



Analysis and quantification of groundwater recession characteristics in regolith-bedrock aquifers: a case study in the mid- and upper-Choshuei river basin in central Taiwan

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Abstract

Investigating the groundwater recession characteristics and its relation with geological conditions is of critical importance to the estimation of groundwater recharge in regolith-bedrock aquifers, which commonly occur in the mountainous areas of Taiwan. This paper examines the role of geological and hydrogeological factors in controlling rainfall-induced recharge processes. Groundwater and rainfall data were compiled from 29 monitoring wells and rainfall stations situated in the mid- and upper-Choshuei river basin in central Taiwan. In light of analyzing the outcome of the groundwater-level response to rainfall, the relation between the effective rainfall and groundwater-level fluctuation tends to be positive, and rainfall events with high intensity firmly control the groundwater recharge process in Taiwan mountainous areas. Permeable geological units likely dominate the groundwater-level variations. Besides, recession rates in the vertical direction varying with geological conditions were obviously found in each well site. To improve the efficiency of the water table fluctuation (WTF) method on extrapolating recession rates, two rating systems for evaluating hydraulic properties of regolith and fractured bedrock, respectively, were proposed and applied to develop the effective techniques linked to the quantification of recession characteristics varying with depths for each well. By regression analysis, the dependence of the hydraulic property rating system on the recession rate was performed, and the derived regression equation for each well can be used to estimate the recession rate with depths. Finally, the recharge estimation with the above techniques in Taiwan mountainous areas was established, and the present method of estimating recharge was compared with the existing method. The difference between the two methods was obviously found. Thus, recharge estimation in mountainous areas should take account of complex geological conditions.

Keywords Regolith-bedrock aquifers · Hydraulic property rating system · Recession rate · Groundwater recharge

Introduction

Groundwater recharge studies in mountainous area are closely related to several practical problems, such as site investigations for spent fuel storage and disposal of high-level radioactive waste, tunnels and underground excavations, groundwater exploration and management in hard rock aquifers, groundwater contamination remediation, and aquifer vulnerability assessment (Adnan et al. 2018; Flint et al. 2002; Gautschi 2017; Gimeno et al. 2014; Jahangeer et al. 2017; Perrin et al. 2011; Plasencia et al. 2015; Yang et al.

2009; Yousif et al. 2018; Yu and Chu 2012). While solving these engineering problems, one of the key works is an analysis of the groundwater flow system that needs input from the characterization of groundwater recharge behavior and quantifications of groundwater recharge. For example, aquifer vulnerability and groundwater recharge are nearly associated because both are concerned with the rainfall infiltration down through the unsaturated zone to the water table (Adnan et al. 2018). Groundwater recharge is, therefore, one of the dominant parameters that are usually taken into account for aquifer vulnerability mapping, such as that proposed in the DRASTIC method (Aller et al. 1978). The significance of this parameter, as compared to other parameters used in the method for assessing groundwater vulnerability, is also highlighted (Babiker et al. 2005; Khosravi et al. 2018).

The significant studies for groundwater recharge are focused on quantifying the amount of groundwater recharge

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or recharge rates into subsurface systems. Although various techniques for estimating groundwater recharge, including stream and borehole analysis, soil moisture budget methods, tracer methods, and empirical methods, have been reported by literature, each of the methods has its limitations in terms of temporal and spatial scales. (Healy 2010; Healy and Cook 2002; Hiscock and Bense 2014; Xu and Beekman 2019). Choosing an appropriate method for quantifying groundwater recharge is of critical importance to increasing the reliability of recharge estimates (Scanlon et al. 2002). Investigation areas underlain by what kind of geological setting (unconsolidated or consolidated media) are another frequently concerned issue (Misstear et al. 2008). According to previous studies, the quantification of groundwater recharge and understanding of its process at fractured rock sites experienced more challenging than those at alluvial plain areas (Cai and Ofterdinger 2016; Cook and Robinson 2002; Risser et al. 2005; Rohde et al. 2015). Meanwhile, studies in such a geological environment of fractured rock are rare as compared to those in an unconsolidated medium.

Nevertheless, groundwater recharge studies based on hard rock aquifers have started to draw more attention as the sustainability of current and future groundwater exploitation from fractured rock aquifers is being considered. Such consideration unavoidably happens in Taiwan as well because the growing demand for adequate water resources supplies during drought conditions urges further understanding concerning groundwater availability in fractured rock aquifers of Taiwan. The potential of groundwater storage is needed to be evaluated by the aid of recharge data. However, groundwater recharge studies in Taiwan mountainous (hard rock) aquifers have only acquired finite consideration to date despite fractured hard rock aquifers underlying over 75% of Taiwan. The first journal article regarding recharge estimation in Taiwan mountainous areas was published by Lee et al. (2006). This study utilized daily streamflow data to estimate the long term mean annual groundwater recharge of Taiwan using a water-balance method coupled with the base-flow record estimation and stable-base-flow analysis. The result showed that the mountainous areas of Taiwan received more recharge rate than alluvial plains of Taiwan, which also implied great groundwater potential. Afterward, the developed technique has become the most widely used method for investigating groundwater recharge in Taiwan mountainous areas. However, this technique may remain the uncertainty of estimating the base-flow index (BFI) because the analyzed data are not from borehole groundwater monitoring directly. Since 2010, the Central Geological Survey (CGS) of Taiwan launched a groundwater monitoring program for the exploration of groundwater resources in mountainous areas (Hsu et al. 2019). The available groundwater data has been collected for up to eight years. These precious data give a new avenue, except for the previous method developed by

Lee et al. (2006), to study recharge using real groundwater dynamic data.

As a matter of fact, employing groundwater monitoring data coupled with the water table fluctuation (WTF) method to estimate recharge in the alluvial plain of Taiwan is frequently found in engineering technical reports, and the determination procedure has been officially recognized in Taiwan (Chiang et al. 2004, 2006). The application of the WTF method requires determination of the groundwater-level rises attributed to the recharge period. The groundwater-level rise is estimated as the height between the low point of the extrapolated antecedent recession and the peak of a groundwater-level rise. The antecedent recession patterns with depths of the subsurface system in plain areas generally do not vary intensively because of uniform porous media as compared to heterogamous fractured bedrock. Based on the characteristics of porous media, Chiang et al. (2004) proposed a stable recession line extrapolated from the dry season (from October to January of next year) recession limb of groundwater hydrograph to calculate the water level rise for each recharge event. The stable recession line was used during the computation of each recharge event throughout the entire year. Such an approach must be evaluated while applied to mountainous areas of Taiwan, where regolith-bedrock aquifers are commonly present. Gleeson et al. (2009) reported the antecedent recession patterns in fractured rock aquifers varying with subsurface hydrogeological conditions at various fractured-bedrock sites (Gleeson et al. 2009). The complicated recession pattern is due to groundwater recharge to regolith-bedrock rock aquifers that dominates by lithology and fracture properties (e.g., granular size of regolith, fracture aperture and frequency, fracture length, fracture orientation and angle, fracture interconnectivity, filling materials, fracture plane features, and so on) (Risser et al. 2005; Rohde et al. 2015). If the computational procedure for plain areas is directly applied to mountainous areas, this may not be appropriate.

As a result of a paucity of research on reporting possible factors that control recession behavior in fractured rock aquifers with overlying regolith and in response to practical concerns on groundwater recharge studies in mountainous areas of Taiwan, the purpose of this study is to analyze and quantify recession characteristics in regolith-bedrock aquifers. Firstly, this study focused on the understanding of the characteristics of recession behavior in response to geological conditions for recharge occurred in regolith-bedrock aquifers. The role of the geological conditions in governing recharge processes was examined through long-term groundwater level data recorded from 29 well sites situated in the mid- and upper-Choshui river basin, central Taiwan. And then, this study demonstrated the variability of recession rate as a function of well depth. Secondly, this study performed correlation studies between recession rates and

regolith-fractured rock hydraulic properties. Meanwhile, the above study outcome incorporated into two hydraulic property rating systems is capable of developing empirical models for estimating recession rates, which can help speed up groundwater recharge calculation and obtain actual recession behaviors in response to intrinsic hydraulic properties of regolith-fractured rock aquifers. Finally, a comparison of recharge estimation between the proposed method and the existing method (Chiang et al. 2004, 2006), which used the constant recession rate appearing in the dry season as a representative recession rate, was conducted.

Study area and material

The long term groundwater data are used to recording in the plain area of Taiwan. Despite most of the groundwater recharge from mountainous areas of Taiwan, all needed groundwater data for estimating groundwater recharge have rarely been monitored. Since 2010, a systematic groundwater monitoring plan for mountain areas has been performed unit now and will be completed in 2021. The mid- and upper-Choshui river basin of Taiwan was selected as the first investigated area for constructing mountainous groundwater monitoring wells. Due to having the longest groundwater monitoring record in the river basin so far, groundwater data collected in this area were used for the analysis of the groundwater recession characteristics in this study.

The Choshui River is the longest river in Taiwan. The elevation of the mid- and upper-Choshui river basin ranges from 21 to 3931 meters above sea level, covers an area of 1530 square kilometers, and contains 23 geological units. The formation age on the west side is younger than that on the east side. The western side dominates sedimentary lithology; the eastern side dominates metamorphic lithology. Figure 1 shows the study area and the locations of the study site and 29 boreholes with at least 100 meters of drilling length per borehole. All boring data indicate the geological conditions of this study area. The predominant lithologies include sandstone, shale, slate, mudstone, siltstone, argillaceous siltstone, quartz sandstone, and alternations of sandstone and shale.

According to borehole drilling and hydrogeological investigation results, the hydrogeological conceptual model of the mountainous region can be considered as a two-part system comprised of the regolith and the underlying fractured bedrock. There is a transition zone between the regolith and the bedrock that groundwater is interconnected to form an unconfined aquifer at the upper formation. Confined aquifers may appear in the deeper formation. Thus, two-level groundwater monitoring systems for 29 boreholes were designed to observe variations of the hydraulic head from the shallow and deep zone,

respectively. Two types of the two-level monitoring system (nested and clustered, respectively) were installed. The type of monitoring system depends on the groundwater potential of well. If the groundwater potential is high, the clustered well is constructed. For this type of system, the diameter of the shallow well, which is 6 inches, is greater than the deep well, which is 2 inches. Inversely, the nested well is installed in a well with low groundwater potential. The groundwater levels from 29 well stations are observed since October 2010 until now. In this study, groundwater data from the shallower wells are only used because the vertical groundwater recharge induced by precipitation is assumed to occur in the shallow wells.

Among 29 well stations, analyzed wells basically depend on historical groundwater data patterns. There are four criteria to exclude analyzed wells in this study. The first one is that the water level fluctuation range is too small (herein, 4.5 meters is assumed). The second one is that the well is situated in the semi-consolidated formation. The third one is that no shallow well was installed because the depth from the ground to groundwater table was too deep. The fourth one is that the water level fluctuation is not significant during rainfall-induced recharge events. After screening out inappropriate wells, only 17 wells were qualified to be utilized in the present analysis. The well stations of BH-12 and BH-13 have no shallow well available, which is against the objective of this study. The water level fluctuations in borehole BH-17 are not significant during recharge events. The lithology in boreholes BHW-03, BHW-14, and BHW-28 is conglomerate and does not belong to the framework of regolith-bedrock aquifers. The water level fluctuation ranges for boreholes BHW-01, BHW-02, BH-22, BH-24, BHW-25, BH-26 are smaller than 4.5 meters. The small fluctuations for these boreholes are not able to perform further correlation analysis. Table 1 shows the observation period, well depth, regolith thickness, lithology of water level fluctuation interval, water level fluctuation range of each well station, and the excluded analyzed wells in this study.

Apart from the groundwater level data, rainfall data also need to be collected in order to understand relationships between the groundwater level and rainfall, which can be a reference for analysis of recession behavior. If the linkage between rainfall and groundwater level does not agree well, recharge sources may come from other natural factors (e.g., lateral recharge) but direct infiltration. The other uncorrelated reason may come from the selected rainfall station and well station that are not paired. This situation is caused by the available rainfall station that is far away from the well station. Thus, the rainfall data and groundwater data should be cautious to check before conducting correlation analysis.

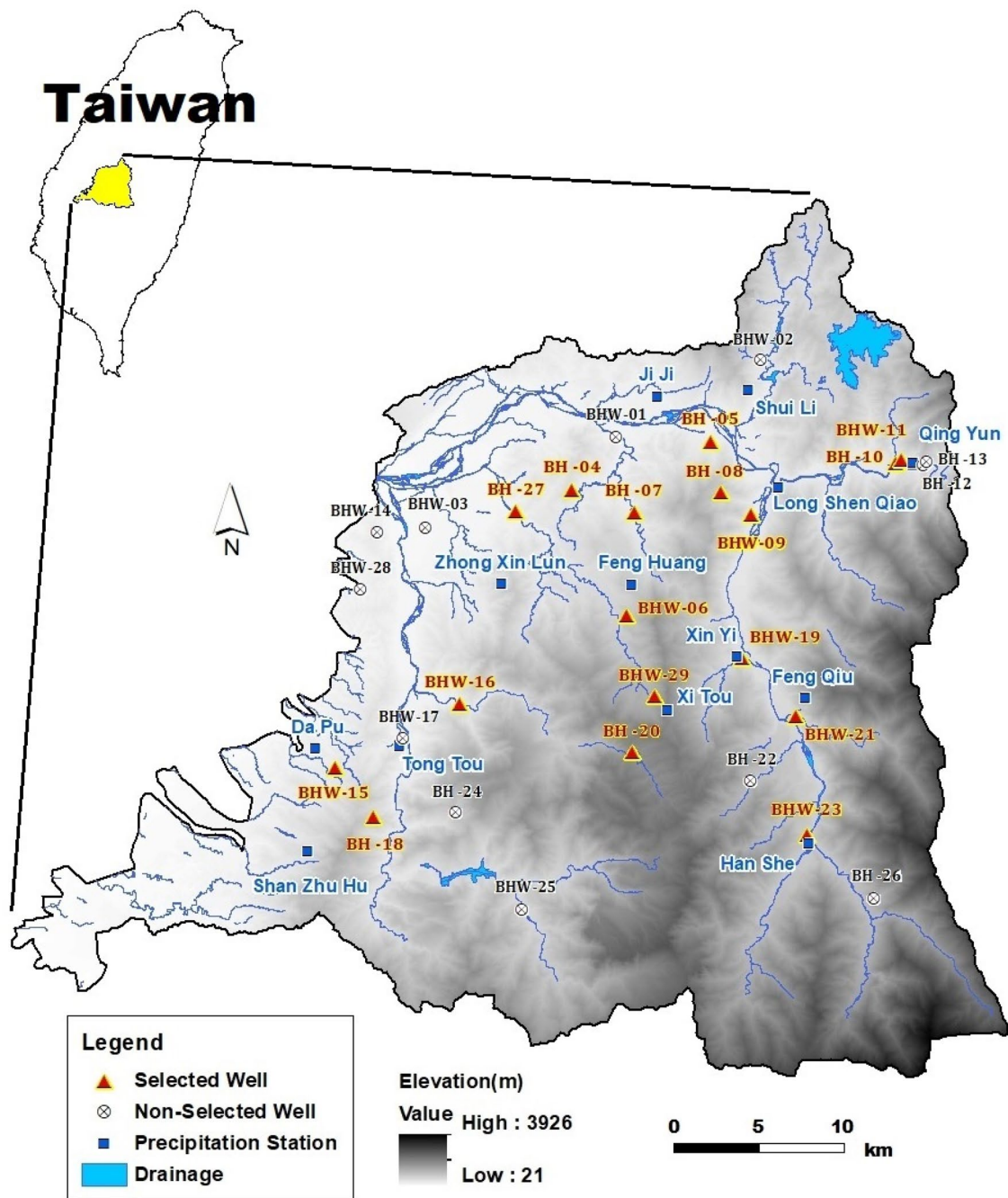


Fig. 1 The study area and locations of monitoring wells

Methods

Groundwater monitoring data can reveal the response of the hydrological cycle, rainfall infiltration, and characteristics of the aquifer system. Groundwater hydrograph can display the behavior of groundwater recharge. Notably, while the recharge process occurs at the regolith-bedrock formation of a mountainous area, complex geological factors may dominate the mechanism of recharge recession. The technique to

deal with recharge estimation in mountainous areas may be different from that in plain areas. It is worthy of evaluating the recharge process and estimation techniques for such a geological environment.

By gathering groundwater level and rainfall data, geological influences on groundwater recession behavior of regolith-bedrock in the Taiwan mountainous region were observed. This study examined the trend of data about relationships between recession rates and geological conditions.

Table 1 Descriptions of collected groundwater monitoring wells

Well number	Observation period	Well depth	Water level fluctuations range	Regolith thickness	Lithology of water level fluctuations interval
^a BHW-01	2010–2017	48 m	3.6–6.6 (3.0 m)	8.5 m	Regolith
^a BHW-02	2010–2017	24 m	3.3–7.5 (4.2 m)	12.8 m	Regolith
^b BHW-03	2010–2017	55 m	3.0–6.9 (3.9 m)	>100.0 m	Conglomerate
BH-04	2010–2016	45 m	0.5–26.8 (26.3 m)	20.0 m	Regolith Sandstone
BH-05	2010–2013	45 m	5.6–14.6 (9.0 m)	42.5 m	Regolith
BHW-06	2010–2017	28 m	2.4–12.1 (9.7 m)	9.4 m	Regolith Sandstone
BH-07	2010–2017	54 m	3.2–9.5 (6.3 m)	9.5 m	Regolith
BH-08	2010–2014	38 m	3.3–16.2 (12.9 m)	19.5 m	Regolith
BHW-09	2010–2017	52 m	15.8–35.8 (20.0 m)	41.6 m	Regolith
BH-10	2010–2017	45 m	0–14.6 (14.6 m)	4.4 m	Regolith Quartzite
BHW-11	2010–2017	59 m	10.4–18.5 (8.1 m)	50.5 m	Regolith
^c BH-12	2010–2011	49 m	–	1.6 m	–
^c BH-13	2010–2013	54 m	–	0.5 m	–
^b BHW-14	2010–2017	129 m	88.0–95.4 (7.4 m)	>150.0 m	Conglomerate
BHW-15	2010–2017	150 m	25.1–32.4 (7.1 m)	1.7 m	Alternation of S.S. and Mudstone Sandstone
BHW-16	2010–2017	42 m	10.2–17.7 (7.5 m)	17.8 m	Regolith
^d BHW-17	2010–2017	50 m	4.4–38.6 (34.2 m)	5.4 m	Regolith Mudstone Sandstone
BH-18	2010–2017	45 m	13.3–37.1 (23.8 m)	20.0 m	Regolith Sandstone
BHW-19	2010–2017	39 m	18.9–25.6 (6.7 m)	20.0 m	Regolith Sandstone
BH-20	2010–2017	70 m	47.5–54.3 (6.8 m)	14.4 m	Sandstone
BHW-21	2010–2017	56 m	34.1–43.7 (9.6 m)	14.5 m	Quartzite
^a BH-22	2010–2013	56 m	15.1–18.6 (3.5 m)	14.5 m	Sandstone
BHW-23	2010–2017	24 m	1.0–9.4 (8.4 m)	11.7 m	Regolith
^a BH-24	2010–2017	39 m	7.1–12.3 (5.2 m)	6.0 m	Sandstone
^a BHW-25	2010–2017	40 m	13.5–18.0 (4.5 m)	17.5 m	Regolith Sandstone
^a BH-26	2010–2017	29 m	7.6–11.0 (3.4 m)	8.0 m	Regolith Sandstone
BH-27	2010–2014	38 m	0.3–9.1 (8.8 m)	5.6 m	Regolith Sandstone
^b BHW-28	2010–2017	42 m	4.4–11.4 (7.0 m)	>100.0 m	Conglomerate
BHW-29	2011–2017	45 m	7.2–21.6 (14.4 m)	>100.0 m	Regolith

^aThe water level fluctuations range is too small

^bThe water level fluctuations range is not in the formation composed by regolith and bedrock

^cNo shallow well

^dThe water levels have no significant fluctuations

Empirical models of the recession rate with the depth of a borehole and recharge estimation procedures were established. The following section introduces the methodology used in this study, including the method of recharge estimation, hydro-potential index, calculation of effective rainfall, and correlation analysis between recession rate and permeability index of regolith-bedrock formation.

Method of recharge estimation

A well hydrograph is a graph reflecting the variation in aquifer storage with time. Recharge in the aquifer for a rainfall event can be revealed and estimated from rises in groundwater tables. A graphical approach known as the water table fluctuation method (WTF) is widely applied to determine the water level rise for each rainfall-induced recharge event (Healy 2010). The antecedent recession curves are manually extrapolated based on a visual examination of the whole data set. Out of antecedent recession data, at least three points, as shown on the left side of Fig. 2, are selected to manipulate recession behaviors. By assuming that recession characteristics are linear, a linear best fit to antecedent recession data is used to compute a recession slope or known as a recession rate. Subsequently, the recession slope can

project groundwater level decline to the point at the time of the following peak groundwater level so as to measure the water-table height for each rainfall-induced recharge event.

As shown in Fig. 2, the lithology and structural geology at the interval I of the groundwater level are different from that at the interval II due to complex geological conditions of the regolith-bedrock system. The recession slope extrapolated at different depths using the WTF method should be different. If a constant recession slope determined from a dry period is applied to each recession period throughout the entire analyzed hydrograph, the constant slope may fail to represent the real recession slope. To accurately estimate recharge in the geological environment of regolith-bedrock, the calculation of the recession slope at different groundwater level intervals needs to be improved. The improved method is to adopt a recession slope value that can represent the recession behavior of the corresponding formation. And then, the recession slope value is determined through a developed relationship between the recession slope and depth interval. More details about the establishment of the relation are described in Sect “Hydraulic property rating system of formation”. Due to the recession rate as a function of depth, recharge estimation can be efficiently proceeded without performing a linear best fit to antecedent recession

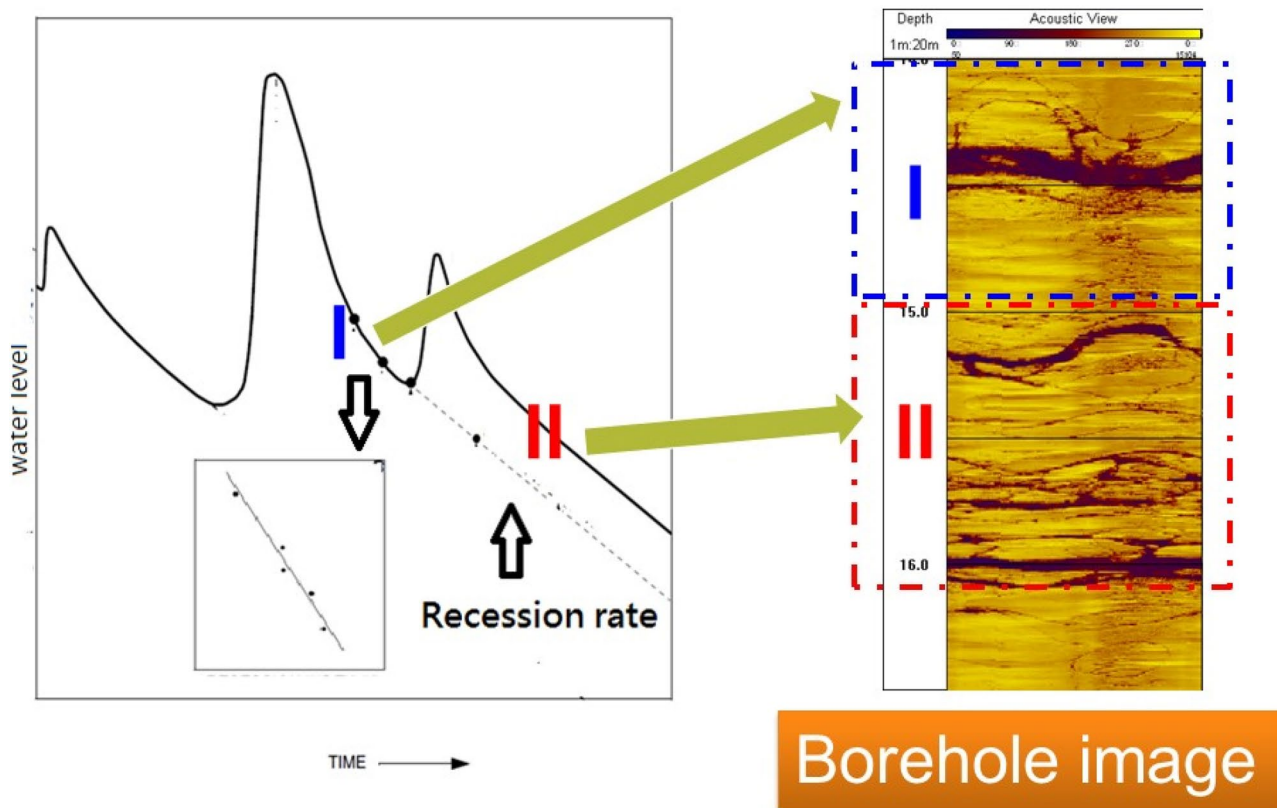


Fig. 2 Schematic of a graphical approach to obtain recession rate and an example of borehole image

data for each recharge event. By introducing the improved technique, the water table height for each recharge event can be easily obtained.

After completing the determination of water-table height, recharge for an individual recharge event can be obtained by the product of the water-table height and the representative specific yield value of an aquifer. The recharge is computed by the following equation.

$$R = A_w \times S_y \times \Delta h \quad (1)$$

In which, A_w is an area of influence around a well station created by Thiessen polygons; S_y is the specific yield; Δh is the groundwater level change during a recharge event. As a matter of fact, the parameter S_y , which may decrease with groundwater levels in an aquifer (Sloto 1990), is another difficulty in employing the WTF method (Healy and Cook 2002; Scanlon et al. 2002). Healy and Cook (2002) reported laboratory (e.g., determination of moisture retention curve) and field approaches (e.g., aquifer tests, water budget methods, geophysical methods, and field capacity tests) to measure the specific yield. Healy and Cook's (2002) study also concluded that S_y obtained from laboratory tests is generally larger than that measured from in-situ tests when estimating recharge through the WTF method. Thus, aquifer (pumping) tests with an observation well were adopted to obtain the specific yield in the present study. Twenty-four hours pumping test drawdown data were used to perform the type curve matching techniques with the theoretical type curves developed by Moench (1997).

Hydraulic property rating system of formation

In mountainous areas, the recession rate occurred in a specific formation/depth interval may be related to the hydraulic property of the specific formation. If the hydraulic property can be quantified through potential geological parameters, the relationship between recession rate and hydraulic property can be constructed. Before developing this relationship, this study proposes hydraulic property rating systems to classify the hydraulic characteristics for any specific geological interval along the borehole.

Since the strata of mountainous areas are mainly composed of the upper regolith and underlying fractured bedrock, the affecting factors on hydraulic properties for the upper and lower stratum are different. Thus, hydraulic property rating systems for different stratum should be considered different affecting parameters to compose its rating system. The first hydraulic property rating system named HPIR-system (Hydraulic Property Index for Regolith-system) is a quantitative model for evaluating the degree of the hydraulic property of regolith based on rock core data and drilling measurement data. The HPIR-system is composed of

three influential parameters (including drilling water return, geostatic stress, and particle size), which are used to classify regolith permeability. Ratings for the HPIR-system are given as the following equation:

$$\text{HPIR} = \left(1 - \frac{\text{WRR}}{100}\right)(\text{GSR})(\text{HPR}) \quad (2)$$

In which, WRR is the water return ratio, GSR is the geostatic stress ratio, and HPR is the particle size ratio. WRR is used to evaluate the loss of drilling fluid, which may indirectly stand for hydraulic properties for drilling a specific formation. As for GSR, the reduction on a hydraulic property (permeability) with depth in regolith commonly connects to the self-weight of soil due to the influence of geostatic stresses. The last parameter HPR represents the hydraulic property of regolith associated with the grain size of a specific formation.

Within this system, the parameter WRR is computed from the following equation:

$$\text{WRR} = \frac{F_{\text{out}}}{F_{\text{in}}} \times 100\% \quad (3)$$

In which F_{out} is the discharge for drill returned water; F_{in} is the recharge for drill water. WRR reflects the capability of stratum to convey groundwater. While increasing permeability, the WRR value decreases. If the WRR value approaches 100%, no drill water will lose. This situation implies the permeability for the drilling formation is relatively low.

The parameter GSR is given by the following equation:

$$\text{GSR} = 1 - \frac{D_c}{D_T} \quad (4)$$

where D_T represents the borehole length; D_c stands for a depth located in the center of a specific recession interval. The GSR value is between zero and one. While increasing permeability, the GSR value increases.

The numerical values of the hydraulic property index for regolith (named as HPR) are given in Table 2. The table is designed on the basis of a particle size classification system published by the Central Geological Survey of Taiwan (CGST) and Hazen's (1930) empirical equation about estimating the permeability of the soil. Since Hazen's (1930) empirical equation describes the permeability that is proportional to the square of effective particle size, this study used a mean particle size (MPS) as an effective particle size (EPS) to quantify hydraulic properties for each type of soil. The mean particle size for each soil type can be designed by referring to CGST's particle size classification system, as shown in Table 3. By combining the suggested MPS and the concept of EPS, numerical values, and their calculated details for different

Table 2 Hydraulic property index for regolith (HPR)

No. (j)	Symbol	Suggested MPS (S_j) for each type of soil	Ratio of mean particle size difference R_{j+1} ($R_{j+1}=S_j/S_{j+1}$)	Square of ratio R_{j+1} (R_{j+1}) ²	Distributed score for each soil type $DS_{j+1} = \frac{(R_{j+1})^2}{\sum (R_{j+1})^2}$	HPR _j (HPR _{j+1} = HPR _j - DS _{j+1}) Note: HPR ₁ =1 for "Boulder(B)"
1	B	500				1.000
2	vcg	250	2.00	4.00	0.020	0.980
3	cg	150	1.67	2.78	0.014	0.967
4	mg	30	5.00	25.00	0.123	0.844
5	fg	6	5.00	25.00	0.123	0.722
6	vcs	1.5	4.00	16.00	0.078	0.643
7	cs	0.75	2.00	4.00	0.020	0.623
8	ms	0.375	2.00	4.00	0.020	0.604
9	fs	0.1875	2.00	4.00	0.020	0.584
10	vfs	0.09375	2.00	4.00	0.020	0.565
11	Z	0.0325	2.88	8.32	0.041	0.524
12	C	0.004	8.13	66.02	0.324	0.200
13	M					0.2–0.524

Table 3 Particle size classification system of soil published by the Central Geological Survey of Taiwan and suggested mean particle size for each soil type

Symbol	Soil names	Mean grain size (mm)		Suggested MPS (mm)
		≥	<	
B	Boulder	500.0		500
vcg	Very coarse gravel	250.0		250
cg	Coarse gravel	50.0	250.0	150
mg	Medium gravel	10.0	50.0	30
Fg	Fine gravel	2.00	10.0	6
vcs	Very coarse sand	1.00	2.00	1.5
cs	Coarse sand	0.5	1.00	0.75
ms	Medium sand	0.25	0.50	0.375
fs	Fine sand	0.125	0.25	0.1875
vfs	Very find sand	0.63	0.125	0.09375
Z	Silt	0.004	0.63	0.0325
M	Mud			0.0325–0.004
C	Clay		0.004	0.004

soil types can be illustrated in Table 2. Scores in the proposed rating system are assigned between 1.0 and 0.2, with a score of 0.2 indicating clay and 1.0 indicating boulder.

The second hydraulic property rating system named HPIB-system (Hydraulic Property Index for bedrock-system) is a quantitative model for evaluating the degree of the hydraulic property of fractured bedrocks based on rock core data and borehole televiewer data. The HPIB-system consists of four affecting factors (including rock quality, geostatic stress, gouge content, and lithology), which are used to classify hydraulic properties of fractured bedrocks.

Ratings for the HPIB-system are given as the following equation:

$$HPIB = \left(1 - \frac{RQD}{100}\right)(GSR)(1 - GCR)(HPB) \tag{5}$$

In which RQD is the rock quality designation, GSR is the geostatic stress ratio; GCR is the gouge content ratio; and HPB is the lithology hydraulic property ratio. RQD represents the degree of fracturing that may bring passages for groundwater flow so as to be treated as a parameter to evaluate the hydraulic properties of fractured rocks. As for the parameter GSR, the decrease in the hydraulic property with depth is generally associated with contraction in fracture aperture due to the cause of geostatic stresses. The parameter GCR can be used to adjust the hydraulic property of fractures that comprise low-permeability infillings (e.g., clay-rich gouges). The last parameter HPB describes the hydraulic property of the rock matrix for each type of rock.

Within the second system, the parameter GSR in Equation 5 is given by the same equation, as shown in Equation 4. The RQD ratio developed by Deere et al. (1967) is computed from the following equation:

$$RQD = \frac{R_s}{R_T} \times 100\% \tag{6}$$

In which R_s is the accumulative length of core pieces larger than 100 mm in a targeted rock core interval; R_T is the total length of the targeted rock core interval.

The gouge content ratio is defined as the following equation.

Table 4 Description and ratings for hydraulic property index of bedrock (HPB)

Lithology	Hydraulic conductivity (m/s)				Range of rating	Suggested rating
	Reference ¹	Reference ²	Reference ³	K _{average}		
Sandstone	10 ⁻⁶ –10 ⁻⁹	10 ⁻⁷ –10 ⁻⁹	10 ⁻⁷ –10 ⁻⁹	10 ^{-7.5}	0.9–1.0	0.92–1.00
Silty sandstone	–	–	–	–	0.8–0.9	0.9
Argillaceous sandstone	–	–	–	–	0.8–0.9	0.85
S.S. interbedded with some Sh.	–	–	–	–	0.7–0.8	0.75
Alternations of S.S and Sh.	–	–	–	–	0.6–0.7	0.65
Sh. interbedded with some S.S.	–	–	–	–	0.5–0.7	0.60
Alternations of S.S and Mudstone	–	–	–	–	0.5–0.6	0.55
Dolomite	10 ⁻⁶ –10 ^{-10.5}	10 ⁻⁷ –10 ^{-10.5}	10 ⁻⁹ –10 ⁻¹⁰	10 ⁻⁸	0.6–0.8	0.70
Limestone	10 ⁻⁶ –10 ^{-10.5}	10 ⁻⁷ –10 ⁻⁹	10 ⁻⁹ –10 ⁻¹⁰	10 ⁻⁸	0.6–0.8	0.70
Shale	10 ⁻¹⁰ –10 ⁻¹²	10 ⁻¹⁰ –10 ⁻¹³	–	10 ^{-10.5}	0.4–0.6	0.50
Sandy shale	–	–	–	–	0.5–0.6	0.60
Siltstone	10 ⁻¹⁰ –10 ⁻¹²	–	–	10 ⁻¹¹	0.2–0.4	0.40
Sandy siltstone	–	–	–	–	0.3–0.5	0.45
Argillaceous siltstone	–	–	–	–	0.3–0.4	0.35
Claystone	–	10 ⁻⁹ –10 ⁻¹³	–	10 ⁻¹¹	0.2–0.3	0.20
Mudstone	–	–	–	–	0.2–0.4	0.30
Sandy mudstone	–	–	–	–	0.3–0.4	0.40
Silty mudstone	–	–	–	–	0.2–0.4	0.35
Granite	–	–	10 ⁻¹¹ –10 ⁻¹²	10 ^{-11.5}	0.1–0.2	0.15
Basalt	10 ⁻⁶ –10 ^{-10.5}	10 ⁻¹⁰ –10 ⁻¹³	–	10 ^{-11.5}	0.1–0.2	0.15
Schists						0.25
Slates						0.35
Quartzite						0.3–1.0

¹Singhal and Gupta (2010)

²Spitz and Moreno (1996)

³https://en.wikipedia.org/wiki/Hydraulic_conductivity [modified from Bear (1972)]

$$GCR = \frac{R_G}{R_T - R_s} \tag{7}$$

where R_G is the accumulative length of gouge content in the interval of $R_T - R_s$.

The ratings of HPB for all kinds of lithology, as shown in Table 4, were designed on the basis of references from textbooks (Bear 1972; Singhal and Gupta 2010; Spitz and Moreno 1996) and available permeability data collected from the mountainous area of Taiwan. In order to distinguish different ratings for the same lithology with varying grain sizes (e.g., sandstone), the concept, as described in Table 2, was also applied to distribute rating values from very coarse sand (vcs) to clay (c). Table 5 lists the ratings for various grain sizes.

Correlation analysis between recession rate and permeability

Since groundwater recharge to regolith-fractured rock aquifers dominates by lithology and fracture properties, this may affect the duration and amount of recharge or recession behavior. Due to the complex geological conditions in spatial (herein pointing out the vertical direction), recession behavior in terms of recession rate is expected to vary with depth. The recession rate may be associated with the lithology and fracture properties or hydraulic properties of recession intervals. By applying two hydraulic property rating systems to corresponding strata as shown in Sect. “Hydraulic property rating system of formation”, the hydraulic property of a given recession interval can be quantified, in which permeability potential for regolith can be estimated by the

Table 5 Grain-size ratings for sandstone with varying particle sizes

Symbol	vcS	cS	mS	fS	vfS	Z	M	C
HPB	1	0.98	0.96	0.94	0.92	0.9	–	0.2

first hydraulic property rating system; permeability potential for fractured rocks can be computed by the second hydraulic property rating system. The WTF method, as described in Section 3.1, can be utilized to obtain the recession rate of each recession interval.

By integrating two quantitative parameters of recession rate and permeability potential, their relationship can be performed through regression analysis to see if there exists any relationship. Once the relation for each well station tends to be positive, its regression equation can be further used to construct the relation between recession rate and depth interval along a borehole. After completing such a relation, the recession rate for each recession interval with similar geological conditions can be classified. In other words, the distribution of the recession rate in the vertical direction of a borehole can be identified. The acquisition of the recession rate for each rainfall-induced recharge event is to identify a recession depth interval firstly. Subsequently, the groundwater level change h during a recharge event through the developed relation can be determined. This outcome can assist in decreasing computational time for identification of recession rate as compared to the WTF method, which needs to obtain a recession rate for each recharge event manually. Therefore, the quantification approach is capable of speeding up groundwater recharge calculation and obtaining actual recession behaviors in response to the intrinsic properties of regolith-fractured rock aquifers.

Results and discussion

Analysis of groundwater-level response to rainfall

Whether or not rainfall is a primary affecting factor of groundwater recharge in Taiwan mountainous areas. To clarify this statement mentioned above, analysis of groundwater-level response to rainfall for each well station has been performed through investigating the relationship between rainfall and groundwater level fluctuation. This study employed regression analysis techniques with both time-series data of rainfall and groundwater level to investigate relationships between groundwater-level fluctuation and effective rainfall during each intensive rainfall event. Prior to conducting correlation analysis, both time series data need to be carefully selected. The first rule is to exclude the groundwater-level fluctuation period caused by an earthquake, which can be done by a cross-check of earthquake database from the Taiwan Central Weather Bureau. The second rule is to select an appropriate rainfall station for each paired well station. Because no rainfall station is available next to each paired well station, this study collected the nearest available rainfall station for each well station as an optimal rainfall station. The third rule focused on the computation

of an effective rainfall for each recharge event. The effective rainfall, as depicted in Fig. 3, is calculated by the summation of (1) the accumulated rainfall during the lowest point to highest point of groundwater level and (2) the antecedent rainfall before the lowest point of groundwater level.

Based on the above three rules, useful rainfall and groundwater level data were screened out and used to perform regression analysis. Table 6 lists regression analysis results for each selected well stations and related information, including the nearest rainfall station with its distance to each well station, R -squared value, hydraulic conductivity of groundwater-level fluctuation interval, regression model, and correlation classification for each well station, in which the classification of correlation was grouped into three classes consisting the following: high correlation with a range of R -squared value between 0.7 and one; moderate correlation with a range of R -squared value between 0.5 and 0.7; and low correlation with a range of R -squared value between 0 and 0.5. As shown in Table 6, the range of R -squared value for 17 case studies was between 0.01 and 0.91. 11 out of 17 cases have a high correlation between the effective rainfall and groundwater level fluctuation. Four cases belonged to moderate correlation. Only two cases, which occupied approximately 12% of all analyzed cases, were a low correlation. Due to carrying the majority of the moderate- and high- correlations, this implies this study area has a better groundwater-level response to rainfall. As for the outcome of regression models from 17 case studies, most of the cases show that the relation between the effective rainfall and groundwater-level fluctuation exists a simple linear relationship.

Figure 4 illustrates long-term rainfall and groundwater-level fluctuations records with three types of correlation intensity, as well as their seasonal variations. For the case

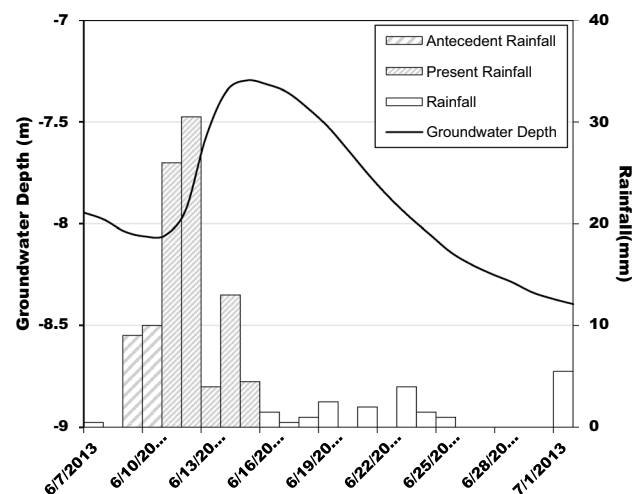


Fig. 3 Schematic of the calculation of effective rainfall

Table 6 Descriptions of regression analysis results for all selected well stations

Well number	Precipitation station	Distance between well and rainfall station (m)	Regression model/ correlation classification	R^2	Hydraulic conductivity of groundwater-level fluctuation interval K (m/s)
BH-04	Ji Ji	5814	Linear/high	0.83	1.22E-05
BH-05	Shui Li	3814	Linear/low	0.27	3.14E-05
BHW-06	Feng Huang	1849	Logarithmic/high	0.70	8.77E-07
BH-07	Feng Huang	4223	Linear/medium	0.68	2.77E-06
BH-08	Long Shen Qiao	3391	Linear/high	0.71	9.42E-06
BHW-09	Long Shen Qiao	2241	Linear/high	0.84	1.22E-05
BH-10	Qing Yun	987	Linear/medium	0.56	1.62E-05
BHW-11	Qing Yun	690	Linear/high	0.88	1.53E-05
BHW-15	Da Pu	1678	Logarithmic/medium	0.56	1.27E-08
BHW-16	Tong Tou	4320	Linear/high	0.89	1.70E-05
BH-18	Shan Zhu Hu	4335	Linear/medium	0.62	8.42E-06
BHW-19	Xin Yi	54	Linear/high	0.80	6.78E-06
BH-20	Xi Tou	3146	Linear/no	0.01	9.15E-07
BHW-21	Feng Qiu	1237	Linear/high	0.84	2.25E-07
BHW-23	Han She	477	Linear/high	0.91	2.44E-05
BH-27	Zhong Xin Lun	4334	Linear/high	0.87	2.93E-05
BHW-29	Xi Tou	1062	Linear/high	0.78	1.09E-05

with the highest R -squared value, two parameters have a very strong linkage with time. Inversely, a very weak linkage between two variables exists in the case with the lowest R -squared value. The statistical outcome revealed that groundwater recharge for high correlation is attributed to direct rainfall. For wells BH-05 and BH-20 with the weak correlation, direct rainfall into the observed well was limited. One of the reasons for the low correlation may be attributed by the selection of rainfall station that is not able to represent real rainfall patterns for the corresponding well. Figure 5 shows the relationship between the R -squared value and distance between each paired stations. While the R -square value is greater than 0.5 (medium-and high correlation), the scattered points (excluding a few outliers, which are not included in the dashed ellipse of Fig. 5) appear to follow a linear trend with the R -squared value of 0.665. The R -squared value indicates a moderate correlation between two variables. The trend also shows that the longer the distance, the lower the R -squared value. This can be proved that the selection of rainfall stations in analyzing this problem should be concerned. Hydrogeological conditions in surrounding wells may attribute the other reason for the low correlation. Figure 6 shows the relationship between the R -squared value and hydraulic conductivity of groundwater-level fluctuation interval for each well station, in which the hydraulic conductivity values were obtained from the in-situ packer hydraulic tests. By excluding the samples with lower R -square value, which is less than 0.5, the remaining scattered points (excluding a few outliers, which are not included

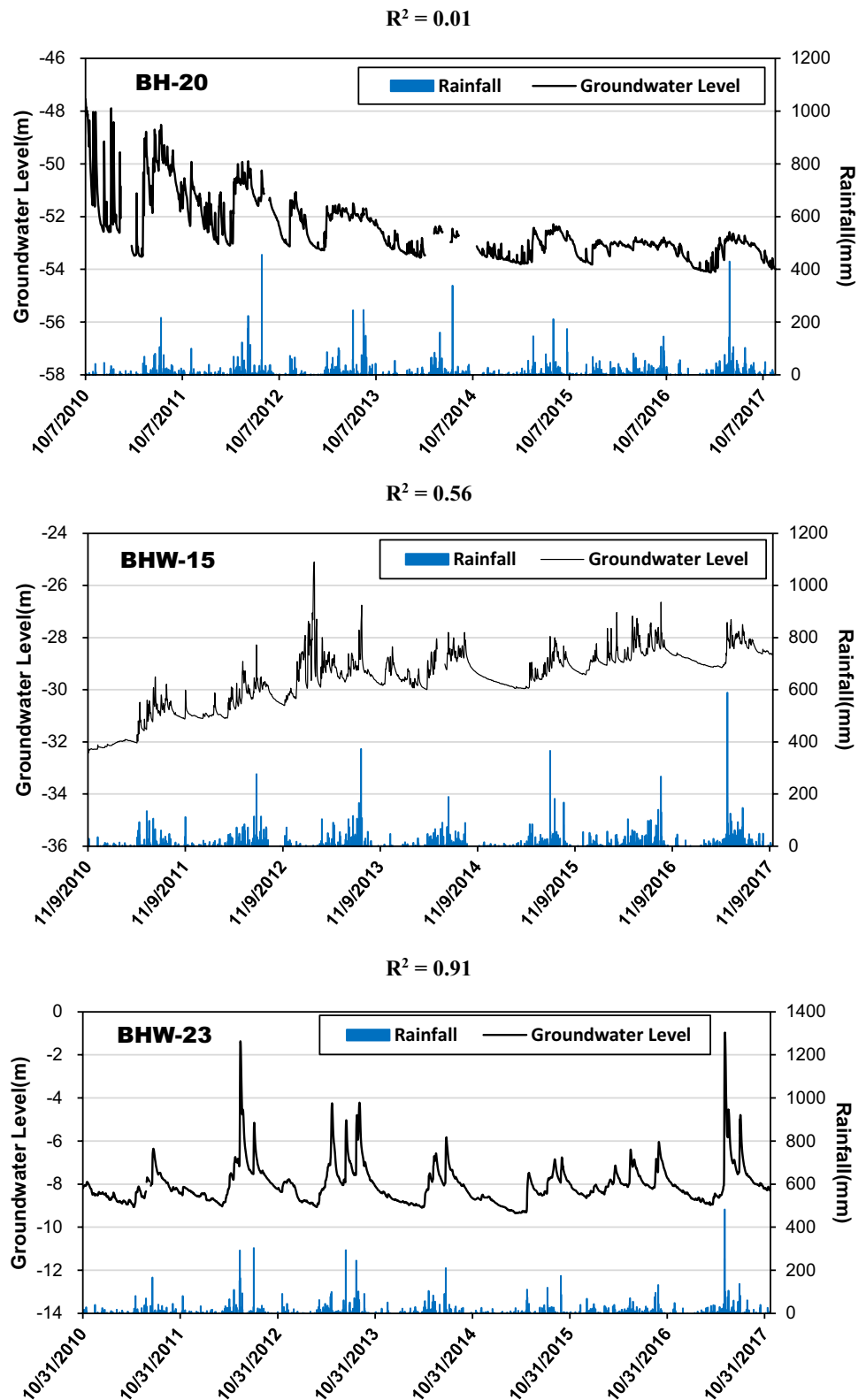
in the dashed ellipse of Fig. 6) appear to follow a linear trend with the R -squared value of 0.772. The R -squared value points out a slightly high correlation between two variables. The resulting trend also shows that the R -squared value slightly increases with hydraulic conductivity. The relationship implies that a better groundwater-level response to rainfall tends to occur in permeable formations.

In light of previous studies, intensive rainfall events may contribute preferentially to groundwater recharge in Taiwan mountainous areas. For most of groundwater monitoring site, the fast responses to rainfall were observed, and the groundwater-level variations are likely dominated by permeable geological units. If the groundwater well does not come with a rainfall station nearby, an appropriate rainfall station should be carefully examined in order to perform an analysis of groundwater-level response to rainfall.

Recession characteristics in regolith-bedrock aquifers

Understanding of recession characteristics in regolith-bedrock aquifers is a prior step to develop a groundwater recharge estimation model in response to hydrogeological conditions of Taiwan mountainous areas. Due to complicated recession behavior in such a geological environment as compared to that in a porous medium, recession patterns varying with depths and aquifer hydraulic properties have been studied. This study examined 17 sets of four to seven-year records of observed groundwater levels and rainfall in

Fig. 4 A comparison of correlation between groundwater level and rainfall time-series data with three types of correlation intensity (low, moderate, and high) over seven hydrological years (October 2010 to September 2017)



four geological environments of Taiwan mountainous areas: regolith, sandstone, alternation of sandstone & mudstone, and quartzite. Recession patterns in terms of recession rate varying with depths were analyzed from the historical

groundwater-level records in each well station. Rules for this analysis include (1) The recession process induced by each recharge event should be selected by different depths, which can take an inside look on all possible recession behaviors

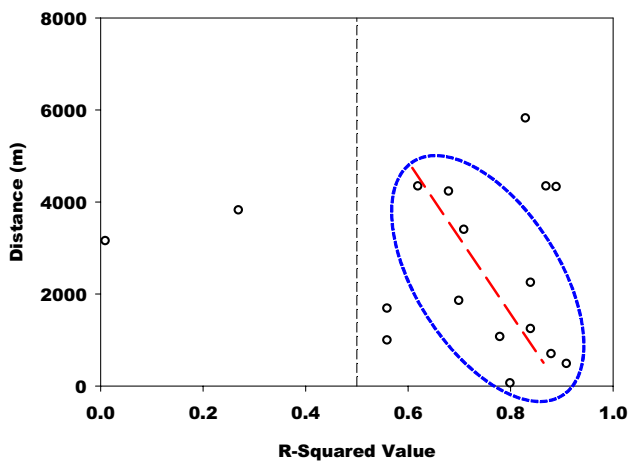


Fig. 5 The relationship between the *R*-squared value and distance between each paired stations (rainfall and groundwater monitoring stations)

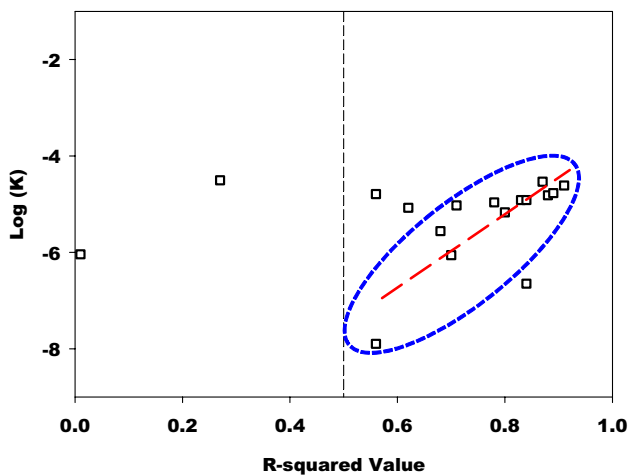


Fig. 6 The relationship between the *R*-squared value and hydraulic conductivity of groundwater-level fluctuation range

for different geological conditions (both lithology and structure); (2) After selecting the recession period for each induced recharge event, the recession rate can be calculated with the method as described in Sect. “Method of recharge estimation”.

Figure 7 shows variations of recession behavior on depth in Well BHW-21. As shown in Fig. 7a, recession patterns in the upper formation drain faster than those in the lower formation. Furthermore, to quantify how fast a recession pattern was, this study utilized a linear best fit to recession data to compute a recession slope in representing its recession pattern and then grouped similar slope values into one value, as shown in Fig. 7b. The grouped recession slope value in the upper formation is approximately two times of that in the lower formation. Figure 7b also marked the locations of

fracture between the depths of 37–44 m below the ground. By comparing geological factors (e.g., depth (geostress), lithology, and amount of fractures) with the group slope values, the recession rate dominated by these geological conditions was obviously found.

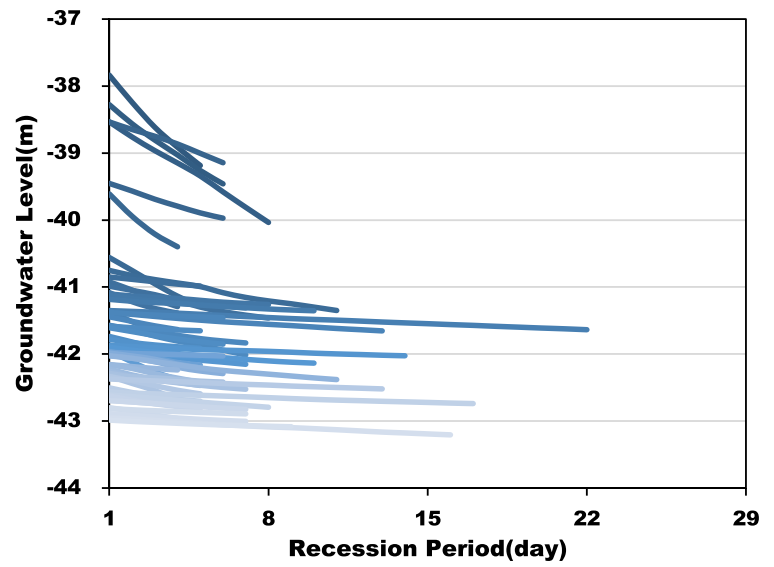
The outcome of recession characteristics observed in Well BHW-21 can also be discovered in the other 16 wells. However, few of wells (e.g., Well BH-04) show that some specific intervals in the lower formation may appear higher recession slopes as shown in Fig. 8, which is slightly different from the previous recession pattern. By checking the borehole logs of BH-04, the fracture density per meter from 20 to 25 m are 2, 4, 10, 5, and 2, respectively. The highest fracture density appears in the interval of 22–23 m. The fracture density is one of the influential factors to control the permeability of rock mass (Hsu et al. 2019; Mizan et al. 2019a,b). Therefore, a faster recession rate is supposed to occur in the interval with a higher fracture density. The outcome observed from BH-04 agreed with the expectation.

Relation between recession rate and HPIR/HPIB

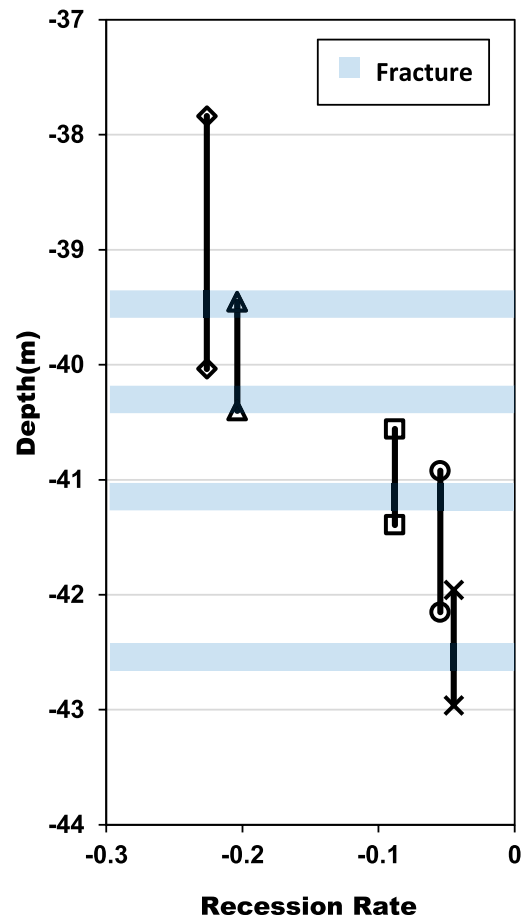
The study results of recession behaviors indicated rainfall-induced recession rates varying with the depth of stratigraphy because of their complex geological conditions in the vertical direction. While applying the WTF method to estimate groundwater recharge within a period, recession rates in different geological units need to be analyzed before performing recharge heights. Unlike the method used in the plain area of Taiwan (Chiang et al. 2004), only one representative recession slope was used during the calculation of each rainfall-induced recharge event at a specific time. Although this study has found the recession characteristics of the Taiwan mountainous area, this needs to repeat the same process to obtain a recession rate that can react to its geological conditions. To ease the loading of computation, this study proposes an alternative approach using recession rate classification. Similar recession patterns in a certain depth can be grouped into one representative value, as seen in Fig. 7b. By using two hydraulic property rating systems of formation as described in sect. “Hydraulic property rating system of formation”, hydraulic properties of each interval can be quantitatively obtained. Finally, regression analysis with both types of data was performed to establish a relation between hydraulic property index and recession rate for each groundwater monitoring well.

Table 7 shows the results of regression analysis for the selected 17 wells, including the relation between recession rate (RR) and hydraulic property index (HPIR or HPIB), correlated lithology for each relationship, and coefficients of determination. As seen in Table 7, BH-04 has two relationships because the fluctuation range of groundwater levels covers two geological units, which are regolith and bedrock,

Fig. 7 Variations of recession rate on depth in Well BHW-21



(a) Recession patterns varying with depth



(b) Grouped recession rate

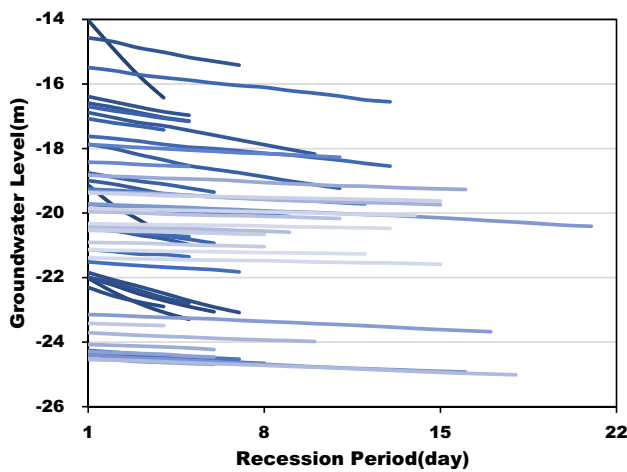


Fig. 8 Variations of recession rate on depth in Well BH-04

respectively. Results from the correlation between two variables indicated the coefficient of determination, apart from that of BHW-09, ranged from 0.58 to 0.98. 14 out of 16 wells have strong correlations with the R-square value of more than 0.7. Therefore, the correlation between the recession rate and the proposed hydraulic property rating system is well. Since the recession rate (RR) is a negative value, the inversely proportional linear relation between HPIR/HPIB and RR (as shown in Table 7) can be obtained.

Table 7 Regression results for constructing relationships between RR and HPIR/HPIB

Well Number	Lithology	The Relation between RR and HPIR/HPIB	R ²
BH-04	Regolith	$RR = -39.714(HPIR) + 21.188$	0.93
	Sandstone	$RR = -1.075(HPIB) + 0.207$	0.93
BH-05	Regolith	$RR = -0.768(HPIR) + 0.518$	0.98
BHW-06	Regolith	$RR = -37.277(HPIR) + 1.341$	0.66
BH-07	Regolith	$RR = -1.434(HPIR) + 0.006$	0.95
BH-08	Regolith	$RR = -4.449(HPIR) + 1.039$	0.83
BHW-09	Regolith	$RR = -0.864(HPIR) + 0.118$	0.35
BH-10	Quartzite	$RR = -0.214(HPIB) + 0.005$	0.72
BHW-11	Regolith	$RR = -0.152(HPIR) + 0.021$	0.74
BHW-15	Alternation of S.S. and Mudstone	$RR = -630.16(HPIB) + 15.135$	0.93
BHW-16	Regolith	$RR = -96.735(HPIR) + 52.071$	0.98
BH-18	Sandstone	$RR = -1.209(HPIR) + 0.355$	0.58
BHW-19	Sandstone	$RR = -134.21(HPIB) + 5.391$	0.91
BH-20	Sandstone	$RR = -0.491(HPIB) + 0.027$	0.88
BHW-21	Quartzite	$RR = -81.701(HPIR) + 5.978$	0.95
BHW-23	Regolith	$RR = -80.71(HPIR) + 36.854$	0.97
BH-27	Regolith	$RR = -2.261(HPIR) + 1.143$	0.76
BHW-29	Regolith	$RR = -3.412(HPIR) + 1.059$	0.63

Estimation of recharge height and comparison of existing and new methods

Based on the previous regression equations as shown in Table 7, a recession rate for a targeted interval can be estimated using the developed equation of each well with hydraulic property rating systems and borehole logs. Table 8 shows an example of a depth-oriented database on the recession rate for each groundwater monitoring station. Once a similar table for a given well station is established, a recession rate, without the traditional computation process, can be obtained through detecting its recession depth interval. Figure 9 illustrates the improved WTF method in obtaining the recession rates for all rainfall-induced recharge events in the Year 2016. Most of the recharge slopes and their recession patterns are visually alike. The total recharge height for the Year 2016, which is 16.56 m, is the sum of each

Table 8 Recession rates for each depth interval in Well BHW-21

Depth	HPIB	RR
37–38	0.0844	-0.920
38–39	0.0761	-0.242
39–40	0.0755	-0.191
40–41	0.0749	-0.141
41–42	0.0743	-0.090
42–43	0.0737	-0.039
43–44	0.0738	-0.048

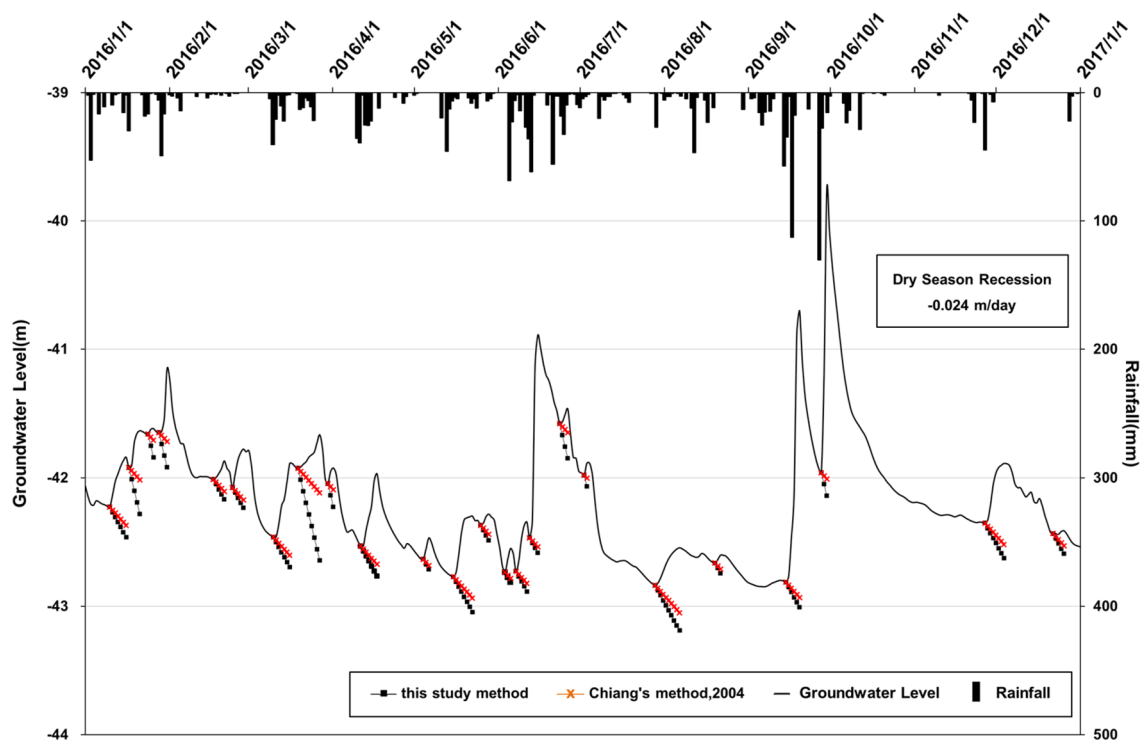


Fig. 9 A comparison of recession slopes obtained by the present method and Chiang's method for hydrological data of the Year 2016

recharge height. Finally, the total recharge amount for the Year 2016 can be computed by Eq. (1) with the calculated total recharge height, the known S_y ($=0.0907$) obtaining from a pumping test, and the known area A ($=69,182,199$ m^2) of influence around the well station created by Thiessen polygons.

In addition to the explanation of obtaining recharge heights, Fig. 9 also shows a comparison of differences between two recession slopes obtained from Chiang's method and present method, respectively. The difference between two recession slopes on a rainfall-induced recharge event can be obviously observed in the Figure. The recession slope determined from the present method is steeper than that obtained from Chiang's method. The gentle slope obtained from Chiang's method is because his method adopts groundwater-level data in the dry season to determine a constant recession slope. The core idea for using data of this dry period is to avoid groundwater-level data that cover the effect of groundwater abstraction (note: little groundwater abstraction for agricultural use during the dry season in Taiwan). Nevertheless, the method ignores recession patterns caused by geological conditions. By contrary, in Taiwan mountainous areas, no groundwater abstraction effect appears in groundwater-level data because groundwater is not utilized for any public-supply water use. Instead, geology-induced recession patterns should be carefully noticed. Thus, using a constant recession rate to determine

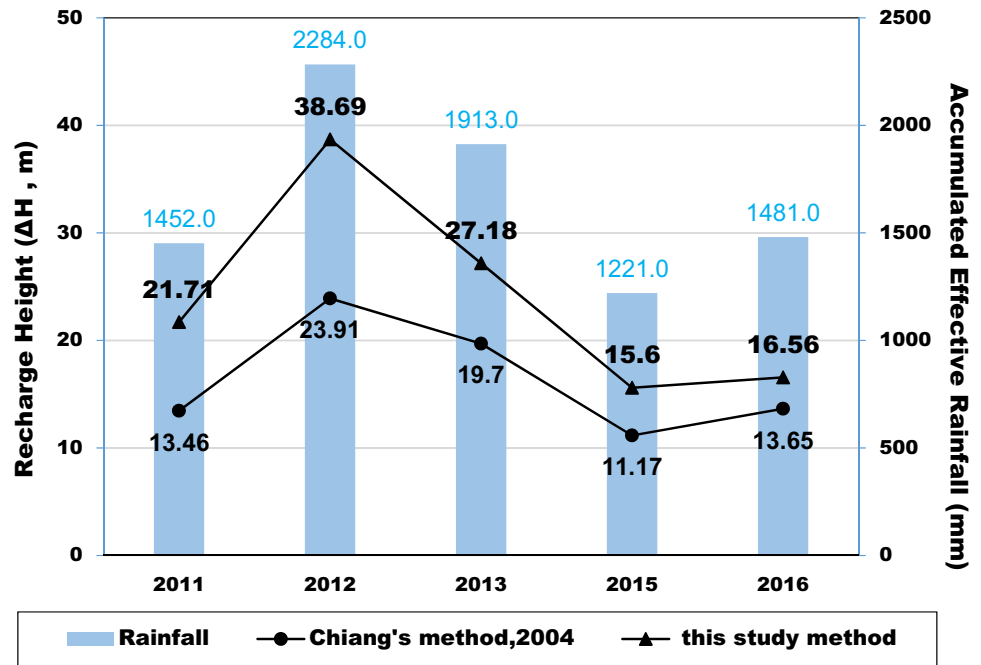
a yearly recharge height in such a geological environment of the mountainous area is not appropriate and may underestimate the actual recharge height as seen in Fig. 9.

Finally, based on the historical groundwater-level data of well BHW-21, this study compared yearly accumulated recharge height for five years (the Year 2011, 2012, 2013, 2015, and 2016), as shown in Fig. 10. The outcome shows that all of the yearly recharge heights obtained from the present method are greater than those from Chang's method. The biggest difference occurred in the Year 2012; the smallest happened in the Year 2016. Additionally, by checking the yearly accumulated effective rainfall and the difference of total recharge height, two variables tend to be correlated. The larger the accumulated effective rainfall, the higher the difference of recharge height. This outcome implies errors for estimating the recharge height of a heavy rainfall event tend to be magnified if Chiang's method applied.

Conclusions

This study investigates rainfall-induced groundwater recharge process in mountainous terrain and develops a practical technique, which can describe recession behaviors in response to intrinsic properties of regolith-fractured rock aquifers, to estimate groundwater recharge. This effort enables to improve the existing method of recharge

Fig. 10. A comparison of yearly recharge height obtained by the present method and Chiang’s method for five years hydrological data



estimation and clarify recharge mechanisms in mountainous geological environment. The primary findings which can be concluded from this study are as follows:

1. Groundwater monitoring data reveal the response of the hydrological cycle, rainfall-recharge processes, and hydrogeologic characteristics of groundwater aquifers. According to groundwater-level data from 29 well stations constructed in the study area, this study finally screened out 17 qualified well stations with a long term of hydrological year’s groundwater-level data for the analysis. The rainfall-induced recharge estimation models for all qualified well stations in Taiwan mountainous terrain have been completed.
2. Instead of using daily streamflow data to estimate groundwater recharge of mountainous geological environment, real groundwater dynamic data are utilized to investigate recession behaviors vertically. The relevant results reveal that the variability of the recession rate in the vertical direction is distinct, and the recession behaviors are controlled by lithology and fracture properties. For most of the analyzed wells, the recession rate in the upper formation is higher than that in the lower formation. However, this statement in a few wells is not valid. Faster recession rate appearing in the deeper formation is due to fracture properties.
3. Overall, results from the analysis of groundwater-level response to rainfall indicate groundwater level fluctuations are linked with rainfall variations in Taiwan mountainous areas.
4. Two rating systems for evaluating hydraulic properties of regolith and fractured bedrock, respectively, were proposed and successfully applied to quantitatively estimate hydraulic properties for a specific depth or recession interval along a given borehole. Based on two proposed systems, the relation between recession rate and hydraulic property index for each well has been found with a strong correlation. Meanwhile, such relations can help speed up groundwater recharge calculation and obtain actual recession behaviors in response to the intrinsic properties of regolith-fractured rock aquifers.
5. By comparing the proposed approach with the existing method (Chiang’s method) to perform recharge estimation in borehole BHW-21 over five years’ hydrological data, utilizing a constant value of recession rate to obtain a yearly recharge height in the geological environment of the mountainous area is inappropriate and may underestimate the actual recharge height. In other words, recession patterns dominated by geological conditions should take into account for recharge estimation.
6. The present approach is underlined with the feature of solving recession characteristics of regolith-bedrock aquifers and improves over the existing method. However, there remain some limitations, including (1) every established relation between recession rate and HPIR/HPIB is not applicable to the depth that is beyond the range of the observed sample data used to build the relation; (2) the disturbance of small rainfall or lateral flow contributed to the groundwater level data in the analyzed

recession period must be cautious while performing the prediction of recession rate.

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