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REPORT

Seismically induced changes in groundwater levels and temperatures following the M_L5.8 (M_L5.1) Gyeongju earthquake in South Korea

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Abstract

Hydrogeological responses to earthquakes such as changes in groundwater level, temperature, and chemistry, have been observed for several decades. This study examines behavior associated with M_L 5.8 and M_L 5.1 earthquakes that occurred on 12 September 2016 near Gyeongju, a city located on the southeast coast of the Korean peninsula. The M_L 5.8 event stands as the largest recorded earthquake in South Korea since the advent of modern recording systems. There was considerable damage associated with the earthquakes and many aftershocks. Records from monitoring wells located about 135 km west of the epicenter displayed various patterns of change in both water level and temperature. There were transient-type, step-like-type (up and down), and persistent-type (rise and fall) changes in water levels. The water temperature changes were of transient, shift-change, and tendency-change types. Transient changes in the groundwater level and temperature were particularly well developed in monitoring wells installed along a major boundary fault that bisected the study area. These changes were interpreted as representing an aquifer system deformed by seismic waves. The various patterns in groundwater level and temperature, therefore, suggested that seismic waves impacted the fractured units through the reactivation of fractures, joints, and microcracks, which resulted from a pulse in fluid pressure. This study points to the value of long-term monitoring efforts, which in this case were able to provide detailed information needed to manage the groundwater resources in areas potentially affected by further earthquakes.

Keywords Earthquake · Hydrogeological system · Groundwater level · Temperature · South Korea

Introduction

Earthquakes of magnitude M_L5.1 and M_L5.8 occurred at 19:44:32 (10:44:32 UTC) and 20:32:54 (11:32:54 UTC), respectively, on 12 September 2016 near Gyeongju, a city located on the southeastern coast of the Korean peninsula. It stands as the largest recorded earthquake in South Korea since the advent of modern recording systems, and it caused great damage with a series of aftershocks. The M_L5.8 event and more than 500 aftershocks caused extreme damage across the area, with 80 associated injuries and approximately 1,300 people left homeless. Subsequently, the region was designated as a special disaster area.

The earthquakes produced strong high-frequency ground motions. A subsurface strike-slip fault with a dip of 65° to the east and a strike of N27°E was a major cause for the earthquakes. The ruptured fault occurred at a depth of 11–16 km, resulting in a ruptured surface of about 26 km^2 (Hong et al. 2017; Kim and Lee 2019).

Previous studies have shown that earthquakes can induce changes in medium properties such as permeability, because stress changes created by the earthquake result in water pressure changes due to strain (Manga and Wang 2007). Both static and dynamic stress changes are associated with earthquakes (Lay and Wallace 1995), which produce a variety of hydrologic and hydrogeologic changes such as liquefaction of unconsolidated sediments, changes in groundwater levels, increased stream discharge, and changes in the chemical composition of the groundwater (Elkhoury et al. 2006; Jonsson et al. 2003; Quilty and Roeloffs 1997; Rojstaczer et al. 1995; Wakita 1975).

Hydrogeologists and seismologists have undertaken a variety of investigations to understand the mechanisms of

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earthquake-induced hydrogeological changes (Blanchard and Byerly 1935; Jonsson et al. 2003; Muir-Wood and King 1993; Wang et al. 2009). Most of these changes are associated with physical and hydrogeochemical properties, related to fluid pressure changes and aquifer interconnectivity (Chadha and Pandey 2003; Chia et al. 2001; King et al. 1999; Kitagawa and Koizumi 2000; Koizumi et al. 2004; Matsumoto 1992; Roeloffs 1998; Roeloffs et al. 2003; Shi et al. 2007; Wang and Chia 2008). More specifically, seismic waves travelling through the rock can induce microcracks and facilitate removal or readjustment of microparticles within fractures. Such changes can alter water chemistry by readjustments in groundwater flow, water–rock interaction, and switching in fluid sources (Cleasson et al. 2004, 2007). These kinds of changes can sometimes act as earthquake precursors, revealed as anomalies prior to the earthquake (Ingebritsen and Manga 2014; Skelton et al. 2014; Wakita et al. 1988). Not surprisingly, there have been efforts to integrate groundwater-related monitoring with conventional seismographic monitoring in countries experiencing frequent earthquakes. Beyond their potential value as precursors, analyses of changes in aquifer properties and groundwater temperature and chemistry add valuable information (Matsumoto and Koizumi 2013; Roeloffs et al. 2003; Shi and Wang 2015).

Many previous studies have analyzed hydrogeological phenomena in relation to the Gyeongju earthquake, including the relationship between the 2011 Tohoku earthquake and the 2016 Gyeongju earthquake (Hong et al. 2017), characteristics of spatio-temporal distribution of groundwater-level changes (Kim et al. 2018), responses of alluvial and bedrock aquifers using hydrological and environmental tracer data (Kaown et al. 2019), and groundwater system responses (Kim et al. 2019). Also, the impact of Gyeongju earthquake on the communities of bacteria in the groundwater ecosystem has been investigated with hydrochemical data (Kim et al. 2020).

The purpose of this study is to describe and analyze various changes in groundwater levels and temperature associated with the M_L 5.1 and M_L5.8 Gyeongju earthquakes. The overall goal of the study is to provide new insights into the spatio-temporal hydrogeologic and tectonic processes associated with earthquakes, reflecting localized stress changes, especially those related to the seismic waves. This particular case study is important because it reveals the changes in rock properties in a low-permeability aquifer.

Study area and hydrogeological setting

The study area, Yeongdong County, is located in the central part of the Korean peninsula, covering approximately 846 km^2. The landscape is rugged and mountainous with the highest peak some 1,242 m above sea level (asl). The narrow valleys are floored by partially developed plains. The area lower than 400 m asl in elevation covers about 605 km^2, which is 71.5% of the total region. This topography reflects the distribution of geological formations that have different physical properties.

Within the study area is an important tectonic boundary fault separating the central southeastern parts of the Ogcheon metamorphic belt and the Yeongnam massif. The Cretaceous Yeongdong basin lies along this boundary as well (Fig. 1). The oldest rocks found there are part of the Precambrian Sobaeksan polymetamorphic gneiss and schist complexes. Somewhat younger, but of unknown age, are rocks of the Okcheon Supergroup. Other key units include the Cambrian Joseon and Pyeongan Supergroups, Triassic and Jurassic granitoids, Cretaceous Yeongdong Group sedimentary rocks, volcanic rocks, and intrusive igneous rocks. Quaternary unconsolidated sediments unconformably overlie older bedrock along the rivers. The primary geologic structures are crosscut by faults and thrust faults trending NE–SW.

This rather complex setting is simplified into six hydrogeologic units. Unconsolidated clastic sediments with developed primary porosity comprise the main aquifer that directly determines patterns of groundwater flow. These sediments are associated with the Quaternary alluvium. The other units are all crystalline rock units with permeability and porosity developed due to fracturing, especially at shallow depths. The nonporous igneous rocks already noted are widely distributed, as well as the clastic sedimentary rocks of the Yeongdong Group, as shown in Fig. 1. The volcanic and carbonate rocks are local in extent. The metamorphic rock unit is extensive and includes the collection of Precambrian units. Generally, the permeability of the crystalline rock units is low but highly variable; consequently, wells are usually not productive.

According to the Koppen climate classification, the Yeongdong area is considered humid continental with hot and humid summers and cold winters. The annual average rainfall is approximately 1,187 mm, a value that is approximately 90 mm less than the Korean peninsula average of 1,277 mm. Most of the rainfall is associated with the summer monsoon season.

Data and methods

Data for this study came from 13 monitoring wells. Five of these are located in complex geological formations in the northwest part of the study area, another seven are located in a simple geological unit, and the remaining one well (YD-388) was placed on the major fault passing through the area. The well-top elevations of the wells range from 104 to 380 m above sea level (asl) with depth ranging from 5 to 80 m. The groundwater level monitoring started from October, 2015. Water levels ranged from 0.72 to 26.5 m in well depth. Tables 1 and 2 provide construction details for the wells and their aquifer types and summarize the different patterns of

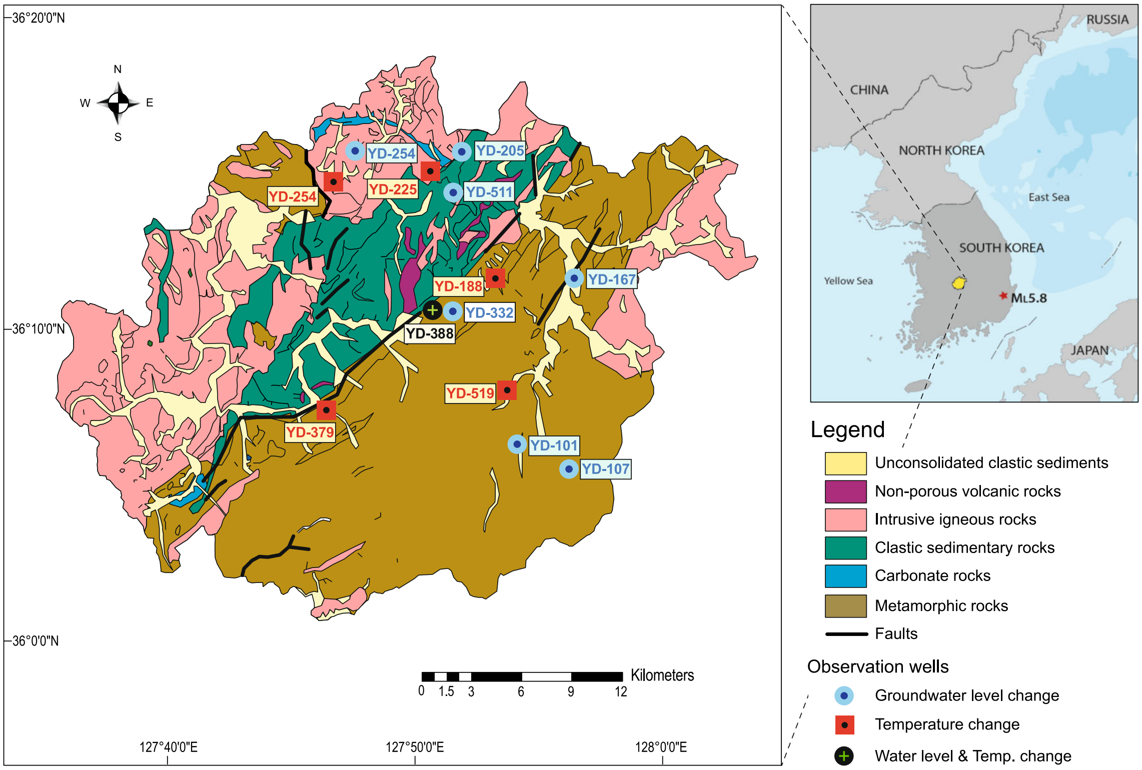

Fig. 1 Maps showing the location of the study area in South Korea and a simplified representation of the geological setting

changes in groundwater levels and temperatures, respectively. Both temperatures and water levels are measured at 30-min intervals using water-level data loggers, including TD-diver automatic transducer and Baro-Diver automatic atmospheric pressure devices in monitoring wells (van Essen Instruments, Netherlands). The TD-diver has an accuracy of ±1.0% full scale and a resolution of 0.4 cm H_2O. Temperature has a range of −20 to 80 °C with an accuracy of ±0.1 °C and a resolution of 0.01 °C. The Baro-Diver has an accuracy of ±0.5% full scale and a range 1.5 m. The monitoring depth of the automatic observation equipment used in this study was installed 10 m below the average groundwater level. The Baro-Diver, for measuring atmospheric pressure, was installed near the YD-511 well to calibrate the groundwater level.

Fluctuations in groundwater levels in this part of the Korean peninsula are due mostly to variability in precipitation. Fortunately, during the times around the earthquakes, there was only modest rainfall. There was 21 mm of precipitation during the 10-day pre-event period of interest (1–11 September). Within the pre-event period, on 2 September, there was one small (10.5 mm) rainfall event, which would not affect any changes in groundwater levels from 3 to 11 September.

Table 1 For each monitoring well, the table lists construction details and three types of groundwater level changes. Also indicated are potential precursors associated with the M_L 5.1 and M_L 5.8 events

ID	Elevation (EL. m)	Well depth (m)	Aquifer condition	DTW (m)	Change type of groundwater level		
					Transient	Step-like	Persistent
YD-332	217.5	70.0	Confined	7.7	√	–	–
YD-254	170.0	70.0		9.5	√	–	–
YD-107	369.5	70.0		26.5	√	–	–
YD-167	185.4	–		13.9	–	Up	–
YD-101	319.8	–		22.8	–	Down	–
YD-388	179.1	–	Semiconfined	4.2	–	Down	–
YD-511	143.3	7.8	Unconfined	6.0	–	–	Rise
YD-205	150.0	18.0		0.7	–	–	Rise

ID observation well, *EL* elevation above mean sea level, *DTW* depth to water

Table 2 For each monitoring well, the table lists construction details and three types of temperature changes. Also indicated are potential precursors associated with the M_L 5.1 and M_L 5.8 events

ID	Elevation (EL. m)	Well depth (m)	Aquifer condition	DTW (m)	Change type of temperature		
					Transient	Shift change	Tendency change
YD-519	242.0	70.0	Confined	10.1	Up	–	–
YD-513	115.1	10.0	Unconfined	3.0	Up	–	–
YD-225	154.9	–	Unconfined	2.0	Down	–	–
YD-188	199.4	60.0	Confined	2.5	–	√	–
YD-379	201.2	20.0	Unconfined	2.5	–	–	√
YD-388	179.1	–	Semi-confined	4.2	–	√	–

ID observation well, *EL* elevation above mean sea level, *DTW* depth to water

Results and discussion

Changes in groundwater levels caused by the M_L5.8 and M_L5.1 Gyeongju earthquakes

Both the M_L5.1 and M_L5.8 earthquakes were continuously recorded on modern seismic systems. The M_L5.8 event followed the M_L5.1 event by 1 h on 12 September. In the study area, approximately 135 km away from the epicenter to the west, various changes in groundwater levels were observed following the earthquakes. Earthquake-induced changes in groundwater levels are often a function of the distance between the epicenter and monitoring well (Montgomery and Manga 2003; Roeloffs 1998; Shi and Wang 2014). The seismic energy density was estimated with knowledge of the magnitude of the event and distance from the epicenter to wells in the near and intermediate fields using Eq. (1) (Wang and Chia 2008):

$$\log r = 0.48\,M – 0.33\log e(r) – 1.4 \qquad (1)$$

where $e(r)$ is the seismic energy density, r is the hypocentral distance (km), and M is the earthquake magnitude. Calculations using Eq. (1) indicated that energy levels of 10^{-2} to 10^{-1} J m^{-3} were associated with the M_L5.8 earthquake.

Earthquake-induced changes in groundwater levels from pressure changes in aquifers and wells are commonly of two types. The first is an oscillation-type response (Brodsky et al. 2003; Cooper et al. 1965; Liu et al. 1989; Wang and Manga 2010), and the second is a persistent type (rise and fall; Roeloffs et al. 2003; Wang and Chia 2008). In the study area, Earth tides and barometric fluctuations also contribute to changes in water levels. Earth tides produce small diurnal variations in water levels because of dilation of the saturated system due to interactions with the moon and sun. Barometric fluctuations occur because changing air pressure acts within the cased well to change hydraulic head. Given that the focus of this scoping study is on the character of water level adjustments directly related to the two events, the Earth-tide data were not quantitatively evaluated. However, the magnitude and shift in the phase of tidal water level signal can be used quantitatively to determine the impact of earthquakes on hydraulic properties (e.g., Zhang et al. 2019).

Figure 2a shows water level hydrographs for wells YD-332 and YD-107 for ~7 days (~10,000 min) before and ~3 days (~4,300 min) after the M_L5.8 event. These wells were completed as open holes with depth of 70 m. Tidal oscillations are evident in the records for both these wells as small sinusoidal fluctuations. At YD-332, near the major fault that bisects the study area, the amplitude of tidal oscillations was 1–1.5 cm before the events and ~3 cm after. At YD-107, far away from the fault, amplitudes increased from ~3 cm before the event to ~6 cm, after. These changes provide indications of changes in rock permeability through the events, since seismic waves can cause microcracks and enhance removal or readjustments of microparticles within rock fractures. The large earthquake increased the permeability and transmissivity of the aquifer due to seismic waves (Elkhoury et al. 2006; Wang et al. 2009; Zhang et al. 2019).

In order to observe changes in groundwater levels due to the seismic events, the two time series were processed to correct for atmospheric pressure changes and to remove relatively low-frequency tidal fluctuations. The modified moving average method involved the following equation:

$$X_t^* = X_t – \frac{X_{t-n} + \dots X_t + \dots X_{t+n}}{2n+1} \qquad (2)$$

where X_t^* is the filtered groundwater level, X_t is the original groundwater level corrected for atmospheric pressure, and n is the number of samples in the moving average before and after X_t. In this study, changes in the groundwater level caused by the earthquakes were evaluated using $n = 1$ in Eq. (2).

Figure 2b shows the two corrected hydrographs to emphasize the earthquake effects. The parallel red lines capture the remaining variability in the two times series, which show small maximum amplitudes of ~0.2 cm for YD-107 and ~0.4 cm for YD-332. The earthquakes produced transient

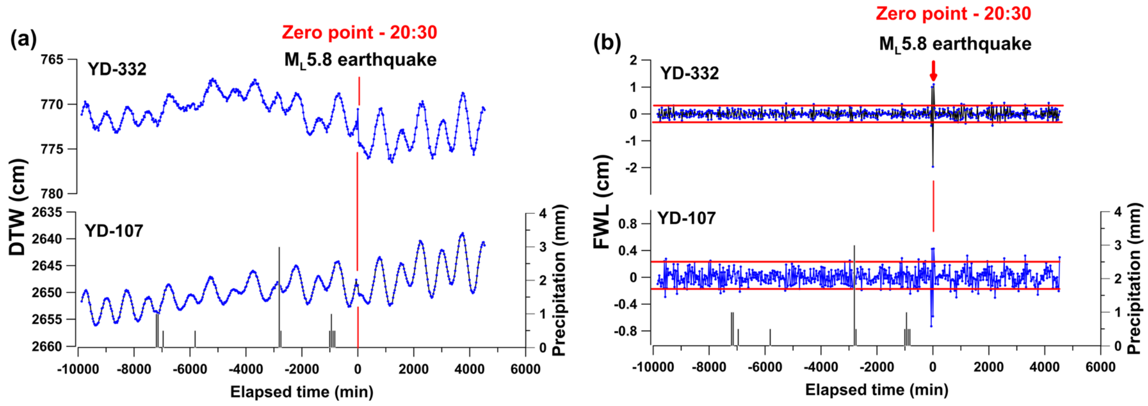

Fig. 2 **a** Transient-type groundwater level changes in the wells associated with the M_L5.8 earthquakes in the study area from 6 to 15 September 2016. **b** The filtered water-level (FWL) hydrograph shows data on groundwater levels processed to remove tidal fluctuations and to correct for changing atmospheric pressures (depth to water, DTW)

maximum upward/downward deviations of ~0.4/0.7 cm for YD-107 and ~1/2 cm for YD-332. Neither of the wells experienced longer-term changes in water level. The true maxima/minima for these wells are not known with accuracy because of the (1) inherent lack of sensitivity in wells with relatively large borehole diameters placed in low-permeability settings and (2) 30-min data sampling, which is not optimal for short-period fluctuations.

Other monitoring wells showed different responses—YD-167 and YD-101 experienced step-like-type responses (Fig. 3) where water levels changed permanently after instantaneous rising or falling, e.g., rising ~4.5 cm (2 cm for M_L 5.1 and 2.5 cm for M_L 5.8) in YD-167 and falling ~8 cm (5 cm for M_L 5.1 and 3 cm for M_L 5.8) in YD-101. These wells also monitor water levels in metamorphic rocks, with YD-167 located adjacent to a small fault zone. Step-like changes of groundwater level were mostly observed in the wells located in the proximity of the faults. This phenomena occurred in YD-101, not located close to the fault zones, and should be studied further in relation to its geology and hydrogeological properties.

Persistent-type responses were also evident. The groundwater levels in YD-511 and YD-205 abruptly reversed their declining trend to rise after the earthquake by ~0.3 and ~ 0.1 cm, respectively (Fig. 4). Both of the wells were completed in clastic sedimentary rocks. Typically, these behaviors reflect an enhancement in rock permeability by removing precipitates and colloidal particles from clogged fractures, which improves the hydraulic connection with a nearby unit with a higher hydraulic head (Brodsky et al. 2003; Matsumoto et al. 2003).

Previous studies used such a permeability enhancement model to explain increases in river flow and changes in water quality (Rojstaczer and Wolf 1992; Rojstaczer et al. 1995). Other examples include discussions of hydrological changes associated with the Kobe earthquake in Japan (Sato et al. 2000), changes in the electrical conductivity of karst aquifers caused by a M_L 5.1 earthquake in France (Charmoille et al. 2005), and increases in permeability due to the groundwater response associated with tidal effects (Elkhoury et al. 2006). All these cases illustrate how an increase in permeability can

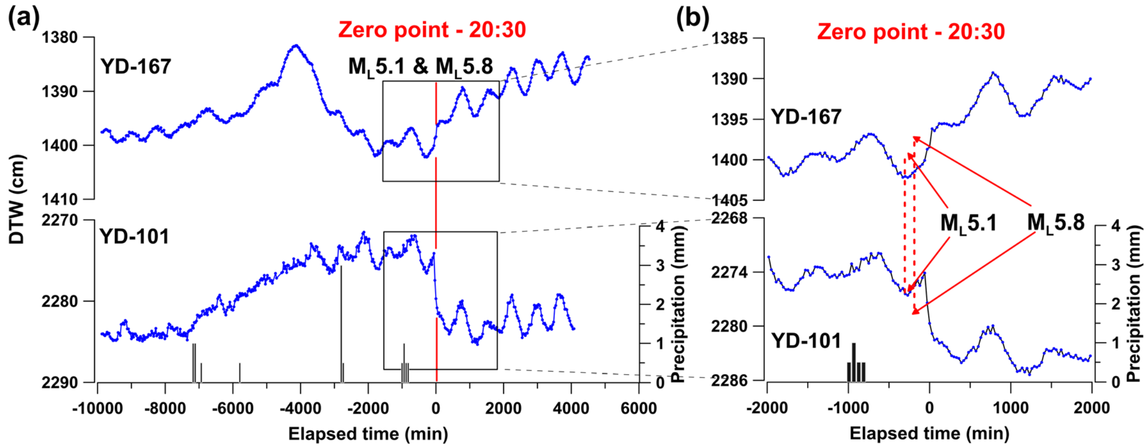

Fig. 3 **a** Hydrograph showing water-level changes in YD-167 and YD-101 throughout the two events. **b** A higher-resolution plot of the two time series. Groundwater levels were corrected for changes in barometric pressure. Both of the wells experienced step-like-type changes in groundwater levels, upward at YD-167 and downward at YD-101

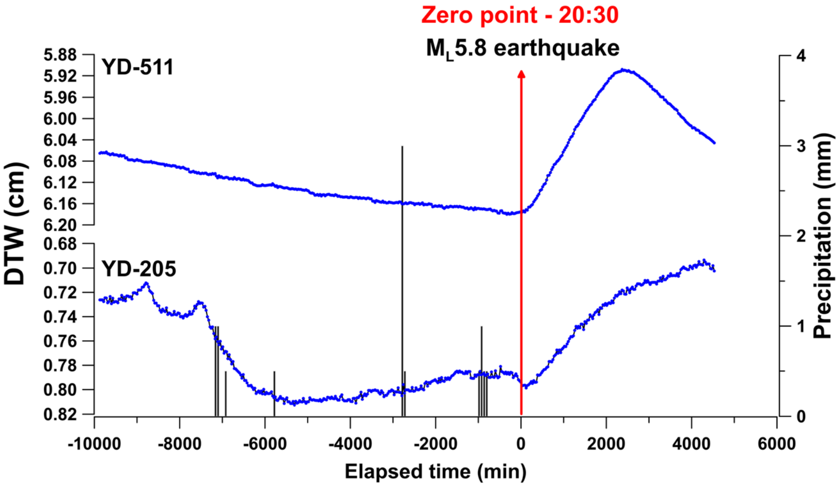

Fig. 4 Persistent-type changes in groundwater levels in wells completed in shallow alluvial aquifers. Groundwater levels have been corrected for changing atmospheric pressures. Notice how both downward trends were reversed to create a slight increase in water levels

lead to changes in the hydraulic gradient of wells, located either up-gradient or down-gradient. The result is positive or negative changes in groundwater levels (Wang and Chia 2008).

The time series data of groundwater level include periodic components such as atmospheric pressure and tidal effects, and the tidal components reflect changes in hydraulic properties of the aquifer (Rahi and Halihan 2013; Sun et al. 2019). The spectral analysis was performed using MATLAB (Mathworks Inc., Natick, Minnesota, USA) to characterize the aquifers of each monitoring well.

The trends in groundwater level data were removed, and Discrete Fourier Transform analysis was performed to determine the periodic components using the detrended data as follows (Shumway and Stoffer 2010):

$$x_t = a_0 + \sum_{j=1}^{(n-1)/2}\left[a_j\cos\left(\frac{2\pi tj}{n}\right) + b_j\sin\left(\frac{2\pi tj}{n}\right)\right] \tag{3}$$

where x is the time series data for the groundwater level (30-min interval), t is the time, a_0 is the coefficient, n is the number of discrete samples, and j/n is the period of the jth frequency component.

When j/n is not 0 and 1/2, the regression coefficients for a_j and b_j in Eq. (3) can be written as:

$$a_j = \frac{2}{n}\sum_{t=1}^{n} x_t\cos\left(\frac{2\pi tj}{n}\right) \tag{4}$$

$$b_j = \frac{2}{n}\sum_{t=1}^{n} x_t\sin\left(\frac{2\pi tj}{n}\right) \tag{5}$$

The presence of the signal frequency at j cycles in n time points in the water-level data may be estimated by the following equation. The scaled periodogram ($P\left(\frac{j}{n}\right)$) is defined as follows:

$$P\left(\frac{j}{n}\right) = a_j^2 + b_j^2 \tag{6}$$

The patterns of groundwater level fluctuation due to the earthquake were classified into transient (YD-107 and YD-332), step-like (YD-101 and YD-167), and persistent changes (YD-511 and YD-205), which reflect different characteristics of the fluctuation patterns. In deep wells, the groundwater level fluctuations were observed with regularity, while the groundwater levels in shallow wells showed no apparent regularity or weak regularity.

As a result of the spectral analysis, the groundwater level changes of each monitoring well were affected by the Earth-tide frequency, and K1 and S2 signals were dominant for the atmospheric pressure (Fig. 5). Both the well YD-107 transient change and YD-101 step-like change in the groundwater level during the earthquake seem to reflect the oscillation changes because the short-period (high frequency) signal (M2 and S2) was dominant. The type of persistent change (YD-511) for the earthquake-induced groundwater level changes showed a weak short-period signal (i.e., S2 component). This behavior reflects the sustained changes in groundwater levels since the long-period (low frequency) signal of less than 1 cycle per day is dominant.

The groundwater levels in the shallow wells contain various noise signals and exhibit various periodic loadings (Sun et al. 2019). The persistent types of water level responses are associated with wells completed in alluvial aquifers with a relatively low surface elevation (104–150 m) and shallow well depth (7.8–18.0 m), with maximum water-level changes of 20 cm, indicating the enhanced flows from nearby mountainous regions with complex geological structures. A similar mechanism explains the increase of stream water flow in mountains after earthquakes (Muir-Wood and King 1993; Wang and Manga 2015).

Changes in groundwater temperature caused by the M_L5.8 and M_L5.1 Gyeongju earthquakes

Various patterns in temperature changes were also observed in the monitoring wells. Figure 6 illustrates the three different

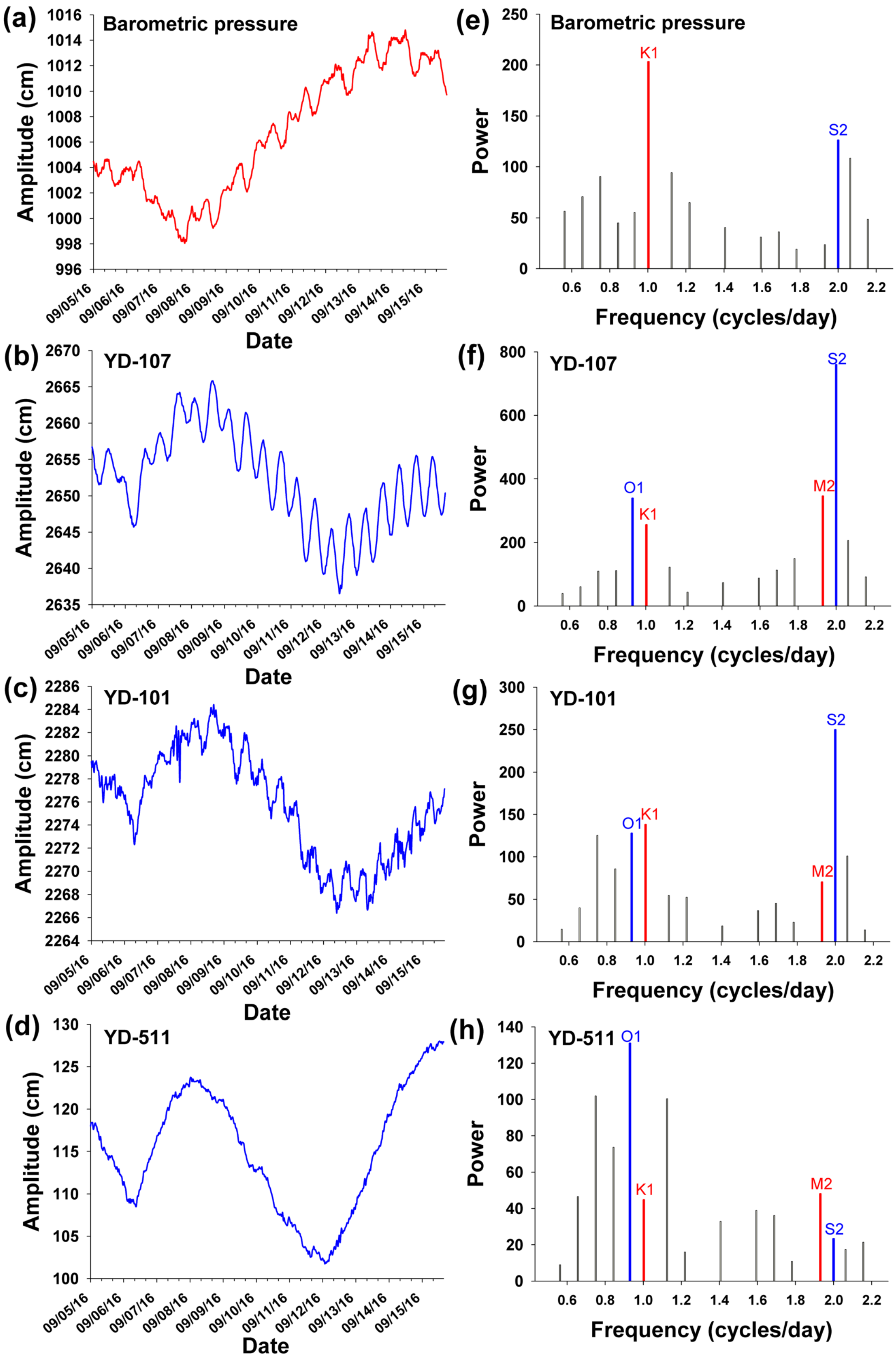

Fig. 5 Comparative analysis of each groundwater change type through spectral analysis of raw groundwater level and barometric pressure data. The four major tide constituents, K1, O1, M2, and S2, have the following characteristics and periods; K1: soli-lunar diurnal 23.93 h, O1: main lunar diurnal 25.82 h, M2: main lunar semi-diurnal 12.42 h, S2: main solar semi-diurnal 12.00 h. **a**–**d** changes of barometric pressure and groundwater level, and (**e**–**h**) periodograms of each groundwater level

patterns: (1) a transient type showing an abrupt, small down/up or up/down shift in temperature (Fig. 6a,b, respectively); (2) a shift-change type showing a permanent jump to a new warmer temperature with a similar declining trend (Fig. 6c); and (3) a tendency-change type showing an abrupt reversal to an existing trend (Fig. 6d). The transient up-type patterns (e.g., Fig. 6b) exhibit a spike-like pattern, thought to occur when high-temperature waters abruptly rise from the well bottom. An instantaneous change in pressure occurred as the seismic waves traveled through the well–aquifer system. Transient down-types (Fig. 6a) represent a decline in temperature caused by oscillation in groundwater levels that was also reported in a study associated with the earthquake events (Shi et al. 2007). The groundwater oscillation occurs with the arrival of surface waves at different times, which results in the mixing of waters in the borehole. It is observed that the temperature continued to drop until the oscillation ended. Shift-change and tendency-change types are associated with the model of enhanced permeability in the shallow crust.

The patterns of temperature increases with the shift-change and tendency-change behaviors (Fig. 6c,d) were also observed in nearby hot springs and again attributed to the removal of clogging materials from fractures due to the impact of seismic waves. Wang et al. (2012) studied vertical changes in the groundwater temperature using advection–diffusion modeling in order to analyze the persistent types of groundwater-level changes after transient changes (up and down) which occurred in alluvial aquifer wells impacted by the Chi Chi earthquake in 1999 in Taiwan (Manga 2001; Manga and Rowland 2009; Wang et al. 2004).

Hydrogeological system changes due to the impacts of earthquakes

Following both of the two large events, rather unique changes occurred in the water levels and temperatures in well YD-388. This monitoring well is located along the major fault bisecting the study area. As shown in Fig. 7, there were two distinct downward moves in groundwater levels, producing a total water level decline of ~7.5 cm. Similarly, there were two contemporaneous decreases in temperature. In both cases, these changes appeared to be permanent. The increases in water levels (i.e., 3.5 and 4.0 cm) were linked timing-wise to the two main earthquake events. Overall, the ~0.02 °C decline was relatively small but well resolved by the monitoring equipment. The largest earthquake events in this area enhanced the fracture permeability through rapid dilatation and contraction that produced new or higher-aperture pathways for flow, or that remobilized fine materials. The net effect was more active flow from shallower depths that raised temperatures slightly and overall drainage that produced lower water levels.

These observations are in line with those from other similar studies suggesting that changes in hydraulic properties (e.g., transmissivity and hydraulic diffusivity) caused aquifers to

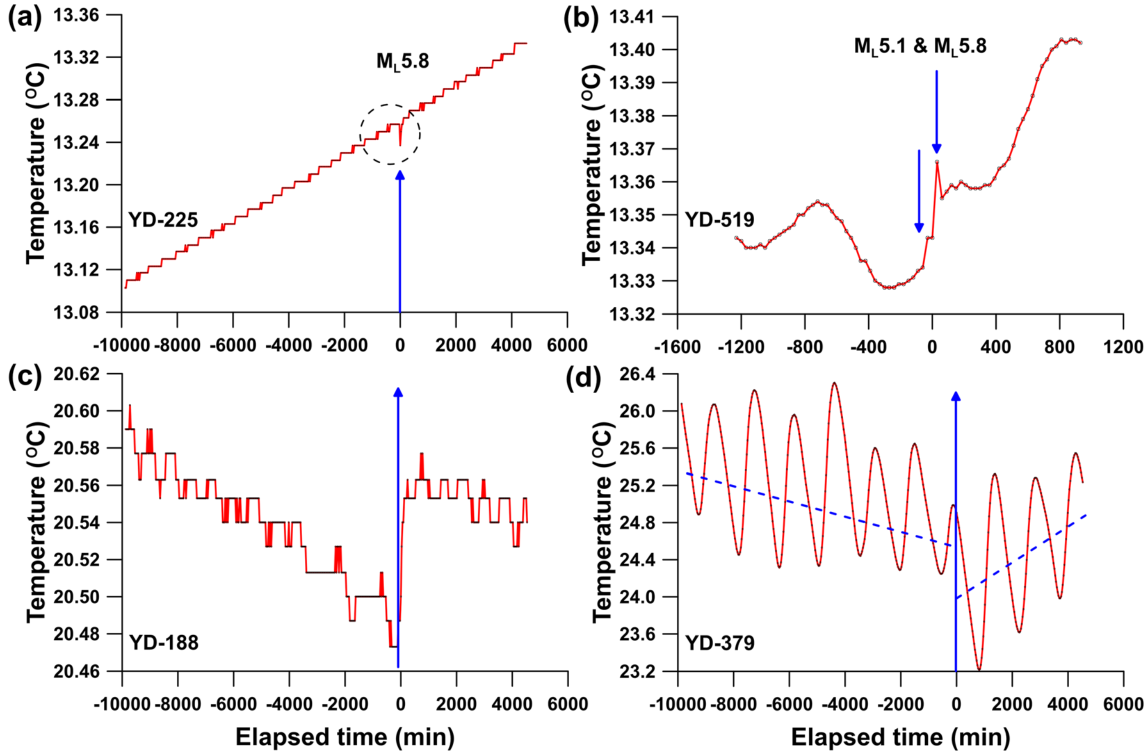

Fig. 6 Different types of groundwater temperature changes in wells associated with the $M_L5.8$ and $M_L5.1$ ($M_L5.8$) earthquakes during the measurement period. **a** Transient type (down), **b** Transient type (up), **c** Shift-change type, and **d** Tendency-change type

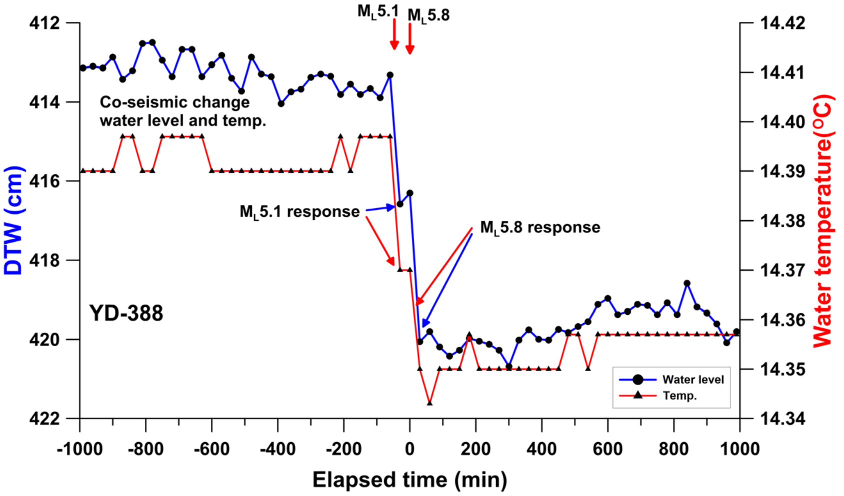

Fig. 7 Step-like-type change and shift change in water levels and temperatures respectively in YD-388, a monitoring well at the boundary of Yeongdong fault. Each of the $M_L5.1$ and $M_L5.8$ events produced identifiable responses in both water level and temperature

change from confined to semiconfined due to seismic waves (Elkhoury et al. 2006; Faoro et al. 2012; Manga et al. 2012; Shi and Wang 2016; Wang et al. 2016). A large earthquake could change aquifer properties including permeability, transmissivity, and storage coefficient by the fluid pore-pressure change and groundwater movement (Jang et al. 2008). Shi and Wang (2016) also focused on analyses of changes in groundwater levels before and after earthquakes. Other studies found comparable results associated with the behaviors of well–aquifer systems (Lai et al. 2014; Liao et al. 2015; Shi and Wang 2015; Yan et al. 2014).

Conclusions

Seismically induced changes in groundwater levels and temperatures were observed in the Yeongdong study area following the Gyeongju earthquakes in 2016. The studies here used high-resolution water level and temperature data from monitoring wells to document the response of groundwater systems to the two largest seismic events as a function of the hydrogeological setting and specifications of the monitoring systems. Clearly in this complex hydrogeological setting, the passage of seismic waves created hydraulic transients in pressure, which affected both the groundwater and the hydraulic properties of the fractured media. More importantly, the variability in the hydrogeological settings so evident in the study area has introduced variability in the observed water level and temperature responses. Typically, relatively deep wells in crystalline rocks exhibited transient behaviors. Step-like changes were mostly observed in a majority of wells known to be placed in close proximity to faults. Finally, persistent changes were evident in the shallowest wells. Similar to water levels, temperatures showed three different types of behavior: transient, shift, and tendency changes.

An important contribution of this study has been to demonstrate the value of highly resolved temperature measurements. Typically, most studies involved with the impact of earthquakes on groundwater work with changes in water levels. Here, similar changes in temperature were observed. Typically, the temperature variations are small but can be categorized into three different modes. Changes in the temperature with categories of shift-change and tendency are interpreted as reflecting permeability enhancements. The temperature data have the potential to identify the character of flows leading to water-level changes. While the efficacy of integrated groundwater and earthquake monitoring systems has been on the rise, more research, especially devoted to monitoring, would be helpful in assuring the stewardship of groundwater resources.

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