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Understanding Hydrogeologic Characteristics of a Well Field of Pyosun in Jeju Volcanic Island of Korea

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Abstract: Hydrogeologic properties of a well field around middle mountainous areas in Pyosun, Jeju volcanic island were examined based on water level monitoring, geologic logging and pumping test data. Due to the alternating basaltic layers with varying permeability in the subsurface, it is difficult to analyze the hydraulic responses to artificial pumping and/or natural precipitation. The least permeable layer, detrital materials with clay, is found at a depth of 200 m below surface, but it is not an upper confining bed for lower main aquifer. Nevertheless, this layer may serve as a natural barrier to vertical percolation and to contaminant migration. Water levels of the production wells are dominantly affected by pumping frequently, while those of the remote observation wells are controlled by ambient precipitation. Results of pumping tests revealed a possible existence of horizontal anisotropy of transmissivity. However, some results of this study include inherent limitations enforced by field conditions such as the consistent of groundwater production and the set of time periods for the cessation of the pumping prior to pumping tests.

Keywords: Jeju Island, groundwater, water level, basalt, pumping

Introduction

Groundwater is nearly a single source for water supply in Jeju Island due to the absence of no perennial streams or rivers, which only run in heavy rain season (Won et al., 2005). Therefore, groundwater resource has been carefully conserved with the strict restriction on its development (Lee et al., 2007). The island has the unique hydrogeologic characteristics that are distinguished from the main land of Korea due to many volcanic eruptions in the geological past (Won et al., 2006). As such, geology of the island is made up of basalt, trachyte, trachybasalt, and sediments (Won, 2004). The geologic layers occur very heterogeneously with location and depth in the island. Despite this heterogeneity, surface of the island is dominated by basaltic rocks. The basaltic rocks with high porosities (voids and fractures) facilitate rapid infiltration of rainwater. Even when the heavy rain occurs, streams and rivers are generally dried up within a few days.

The quality of groundwater in the island has been famous for its high clarity and good taste. In 1995-1997, the provincial government developed a well field of which groundwater has been extracted for commercial sales across the whole country (JPDC, 1997). According to the Korean groundwater law, groundwater development generally requires an official permit from a relevant authority along with the survey of environmental impact. As 5 years have passed since the first environmental assessment on groundwater impact, a renewal of the permit must be required. A new impact assessment hence resumed in 2004 (JPDC, 2005). As a continuing study, groundwater monitoring and many field tests were undertaken consecutively in the well field.

The objectives of this study are to understand and to characterize· the hydrogeologic properties of the well field through an analysis of geologic logging data, water level monitoring data, and pumping test data. The unique hydrogeology of the island offers a unique opportunity to draw attention of many hydrogeologists.

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Methods and Materials

Well Field

The well field of this study is located in the center of right half of the island and its topographic elevation is in the range of 400-450 m (above mean sea level). A total of 8 wells were installed in the well field (Fig. 1). Three of them are for groundwater extraction and five wells are for groundwater monitoring (Table 1). The three groundwater pumping wells are all 420 m depth below ground surface. Thus bottom of the wells reach the mean sea level and they penetrated various geologic layers including surface soil, basalt, clay-rich scoria, and andesite (JPDC, 1997). Each pumping well has produced groundwater with mean rates of 232-568 m^3/day and total annual amount of groundwater produced from the three wells ranged from 163,000 to 269,000 m^3 (JPDC, 2005).

The monitoring wells within 50 m from the pumping wells have nearly the same depths (400 m). The monitoring wells were constructed to detect changes of water levels and water quality, which might be caused by groundwater pumping of the three wells. Consecutive monitoring of water levels and periodic analyses of water quality has been conducted for both for the pumping and the monitoring wells. There are no known contamination sources around the well field. Thus good groundwater quality has been maintained since installation of the production wells. There only exists a pumping well in a farm, which is 900 m downgradient from the well field and average pumping rate is about 100 m^3/day. This pumping rate was not considered to affect the well field.

Water Levels and Pumping Tests

As described above, there exist 3 pumping wells and 5 observation wells. Each well has equipped with an automatic sensor measuring water level, water temperature and electrical conductivity every hour. Installation depths of the sensors range between 293 and 302 m below ground surface. In this study, these monitoring data are used. In addition, to characterize hydraulic properties of subsurface in the study area, a total of 5 pumping tests were conducted in February-August of 2006. Prior to pumping tests, groundwater production was ceased for about 7 days. The pumping

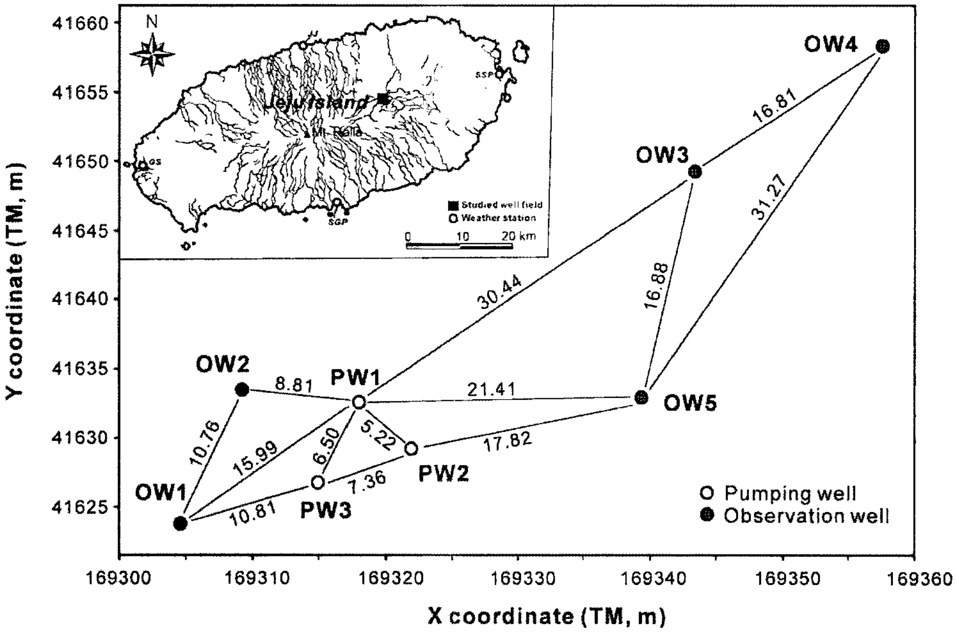

Fig. 1. Location of the studied well field also showing layout of pumping and observation wells. Numerical values above or below straight lines indicate distance between the wells (m).

Table 1. Pertinent well completions in the studied well field. Data are from JPDC (1997, 2005)

Well ID		PW1	PW2	PW3	OW1	OW2	OW3	OW4	OW5
Coordinates	X (m)	169317.95	169321.93	169314.97	169304.58	169309.20	169343.40	169357.57	169339.36
	Y (m)	41632.58	41629.20	41626.80	41623.80	41633.52	41649.29	41658.33	41632.91
	Z (m)	441.399	441.374	441.463	441.254	441.190	440.537	441.525	443.351
Well depth (m)		420	420	420	400	400	400	400	400
Screen interval (m, bgs[c])		321-347.9	257-406.2	284.5-404.6	343-392	332.4-372	361.1-396	NA	NA
Main aquifer (m, bgs[c])	Interval[a]	283-415.5	250-359	301-359	300-385	299-382	310-383	200-296	235-385
	Thickness	132.5	109	58	85	83	73	96	150
Clay layer (m, bgs[c])	Interval	198-200	196-198	198-202	197.5-206	198-200	200-202.5	197-200	198-205
	Thickness	2	2	4	8.5	2	2.5	3	7
Water level (m, bgs[c])	Mean[b]	286.12	257.72	270.40	261.92	271.39	258.25	274.40	263.17
	Max[b]	290.0	274.13	280.79	269.46	287.64	280.59	284.29	264.67
	Min[b]	280.51	239.75	261.66	250.26	260.81	237.73	262.17	260.15
	Max-Min[d]	9.49	34.38	19.13	19.20	26.83	42.86	22.12	4.52

[a] The interval is not fully screened, but intermittently screened within it.

[b] For periods of August 24, 2002-June 30, 2005 (PW wells), February 9, 2001-June 30, 2005 (OW1-3 wells), and January 1-December 31 2005 (OW4-5 wells)

[c] The bgs means below ground surface

Table 2. Summary of pumping tests conducted in 2006

Test no.	Pumping well	Pumping rate (m^3/day)	Test period
#1	PW1	1,338	Feb. 18-Mar. 4
#2	PW2	1,086	Mar. 4-Mar. 18
#3	PW1, PW2, PW3	PW1=1,338, PW2=1,086, PW3=1,321	Apr. 13-May 15
#4	1) PW3->2) PW1 and 3->3) PW1-3	1) PW3=1,321 2) PW1=1,338, PW3=1,321 3) PW1=1,338, PW2=1,086, PW3=1,321	May 19-Jun. 9
#5	PW3	1,321	Jun. 16-Aug. 18

tests were prolonged for 15-64 days (Table 2). In three of five pumping tests, single pumping well (#1, #2, #5) was used while the three pumping wells were all used in the other tests (#3, #4). However, only single test (#3) produced reasonable and interpretable drawdowns mainly due to very high productivity of the pumping wells and the involving aquifer. Thus this study only focused on the test #3.

Results and Discussion

Geologic Condition

The geology of the subsurface is very complex. Below top soil of 2-3.5 m thickness, a variety of basaltic rocks are encountered. The basaltic rocks are comprised of porphyritic pyroxene basalts (PFB), feldspar olivine basalts (FOB), feldspar basalts (FB), and trachytic andesite (TA). These basaltic rocks are repeatedly alternating up to 420 m below ground surface, which appears due to many volcanic eruptions of different ages (Won, 2004). Within the basaltic rocks, volcanic detrital layers consisting of sandy gravel and clay appeared at various depths. Depending on clay content, permeability of this layer is greatly varying and it could function as either permeable or impermeable layer for groundwater flow. It is reported that the least permeable layer occurs at average depth of 200 m (JPDC, 1997, 2005). This layer (0.5-8 m thickness) is composed of the volcanic detrital materials with high clay content. Lateral extension of this layer is not well known and this layer cannot be an upper confining bed for lower aquifer because the water levels occur at depths 60-90 m below this layer (Fig. 2). But it is expected that this layer is partly a barrier to direct vertical percolation of rainfall or contaminant migration into lower aquifer. However,

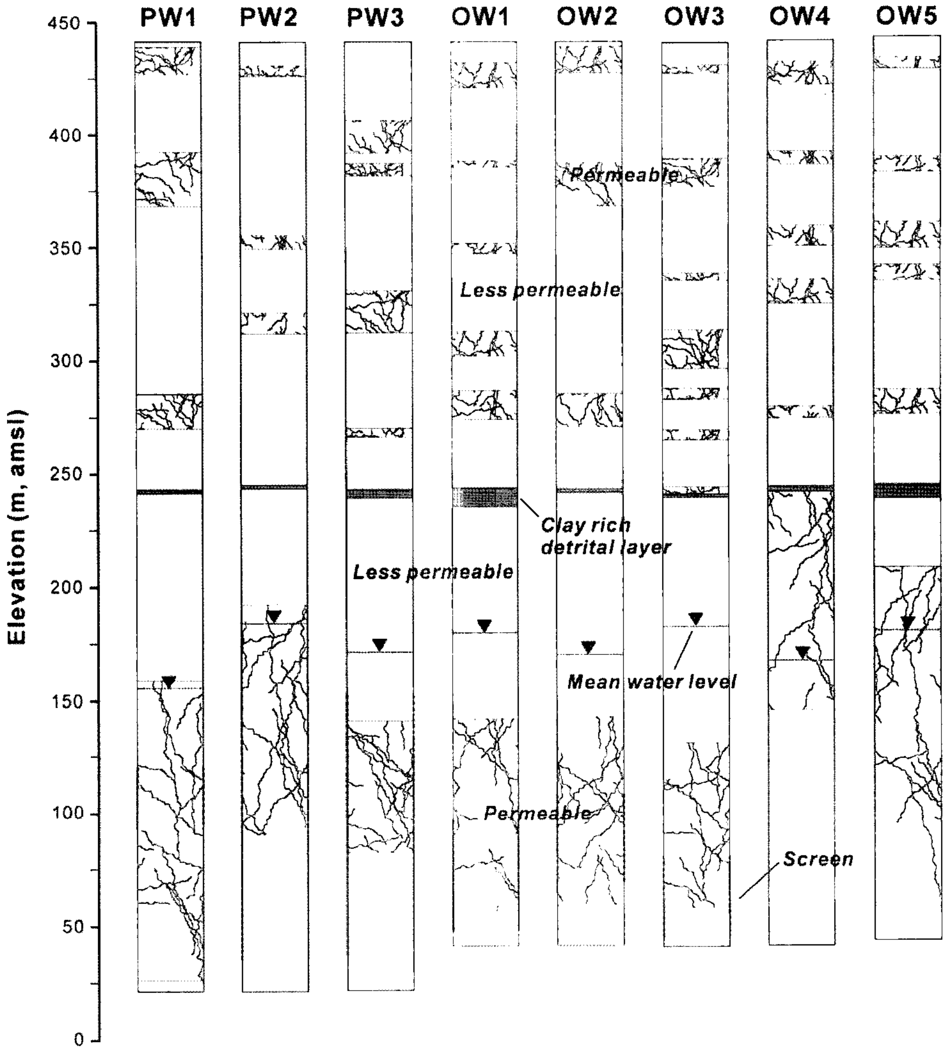

Fig. 2. Simplified hydrogeologic sections at the pumping and observation wells. The permeable layers are variously composed of alternating weathered.

thickness of this layer and its clay content are highly varying with location and thus some flow leakance through this layer may be possible. Repeated occurrence of geologic layers with varying permeability make difficult to define main aquifer zone. Consequently very heterogeneous hydrogeologic layers complicate understanding groundwater flows. But water bearing units having relatively higher permeability at depths 300-400 m are considered as main aquifer in this area (see Fig. 2).

Water Level Fluctuation

In the study well field, the groundwater levels were located at depths of 250-290 m below ground surface (see Table 1). Due to effects of artificial pumping and natural precipitation, difference between maximum and minimum water levels reached 20-40 m since start of the groundwater monitoring in 2001. Only two wells (PW1 and OW5) showed relatively smaller fluctuations within 10 m. Fig. 3 shows water level variation of the period from January 2005 to August 2006. High

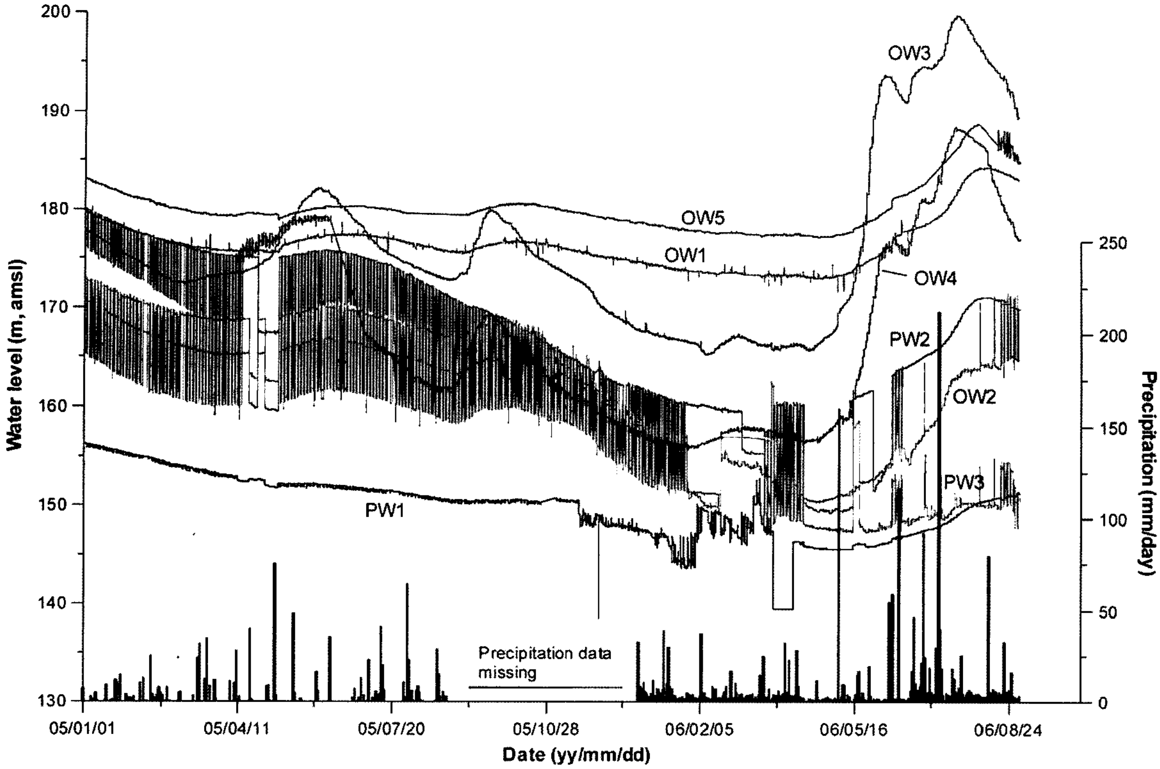

Fig. 3. Fluctuations of water levels at the pumping and the observation wells in the studied well field.

frequency of water level fluctuation is mainly due to groundwater abstraction. Beside of this pumping effect, water levels of the wells can be classified three groups as sensitive (OW3, OW4), intermediately sensitive (OW1, OW2, PW2, OW5) and relatively less sensitive (PW1, PW3) to rainfall events. Pumping wells appeared less influenced by the rainfall because the water levels of the wells are dominated by the direct pumping rather than the ambient rainfall. On the contrary, the relatively remote observation wells (OW3 and OW4) showed a large influence due to rainfall. Furthermore, in these wells, the least permeable clay layer is relatively thinner, thus direct vertical percolation of rainwater can be facilitated at these locations.

Most interestingly, water levels of these wells (OW3 and OW4) were generally lower than those of the other observation wells in dry season while they were mostly higher than the latter in wet season (Table 3). As previously described, these remote observation wells from the pumping wells were largely affected by natural rainfall rather than the pumping. In other sense, high transmissivity of NE direction would result in smaller drawdowns at these wells and rather sensitive response to rainfall. In aquifers where many hydrogeologic layers of different hydraulic properties are intercalating or where development of fractures is irregular, very different response to the outer stress (pumping or rainfall) are not uncommon. In the mean time, an interesting phenomenon was reported that waters from upper wall of the pumping well PW1 were intermittently or continuously dropping into the well (top of water column) (JPDC, 2005). Similar phenomena were also observed at the other pumping wells (PW2, PW3). It is expected that perched groundwater can partly exist above some low permeable layers (above main aquifer zone) because geologic layers are highly varying with depth at this well field. It is also inferred that water from rainfall can partly inflow into pumping well through various

Table 3. Water levels of pumping and observation wells in dry and wet seasons (m, amsl[a])

Wells	Mar. 3, 2005	Jun. 2, 2005	Apr. 16, 2006	Jul. 23, 2006
PW1	154.05	152.11	145.84	149.16
PW2	176.28	175.61	149.89	168.66
PW3	169.49	169.78	147.95	150.08
OW1	176.46	177.11	173.10	181.96
OW2	166.29	166.59	150.62	163.15
OW3	172.53	182.05	165.72	199.68
OW4	169.54[b]	179.00	156.55	188.13
OW5	180.02	180.06	177.28	186.34

[a] The amsl means above mean sea level

[b] Value interpolated from values of nearest dates due to the data missing

joints because highly fractured permeable layers are existed between the less permeable layers.

Spatial distribution of water levels at some times is also of interest. Contour of water levels affected by continuous pumping are highly distorted though the kriging results are calculated automatically by eight observation data and they appeared elliptical shape with a long axis of NE direction (Fig. 4). Even in the neighboring observation wells, water levels were much different by up to several meters. Considering that topographic elevations and depths of the wells are very similar, this abnormal or distorted water level distribution can be partly attributed to different screen interval, vertical permeability variation and difference in hydraulic connectivity among the pumping and observation wells. Because transmissivity of the main aquifer are very large (discussed later) and pumping rates of the three pumping wells are not quite different

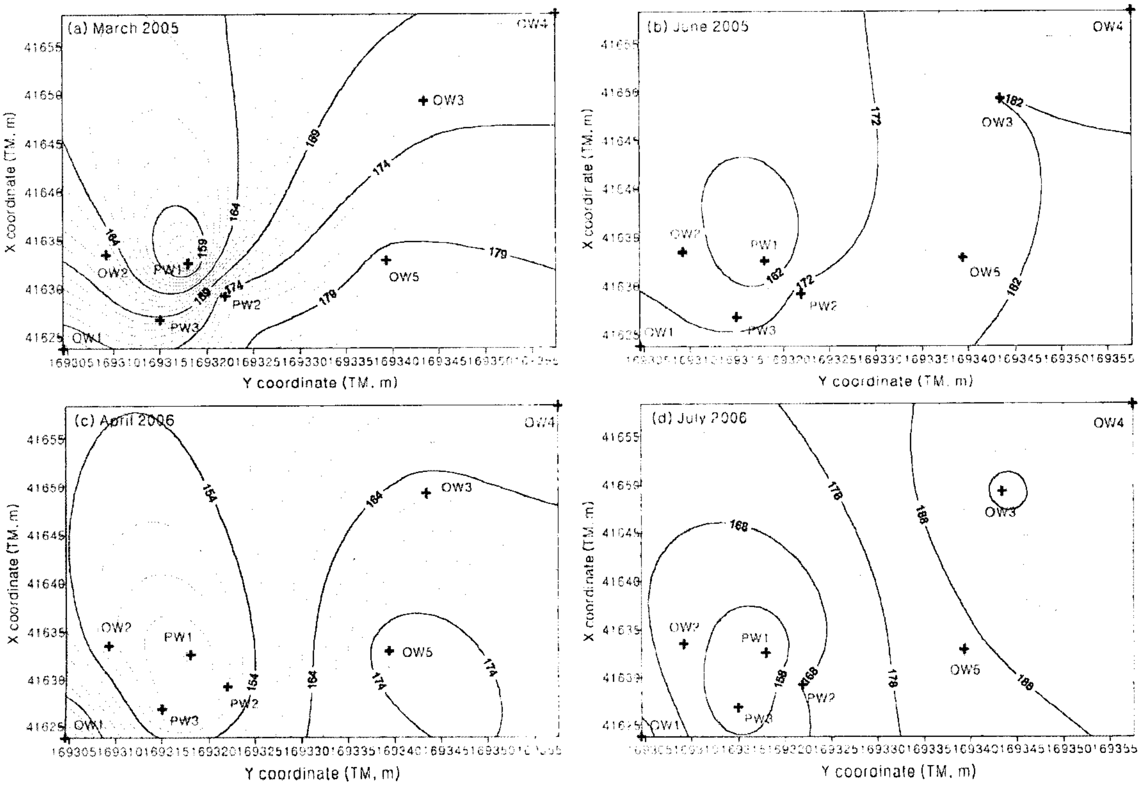

Fig. 4. Distribution of water levels at the well field.

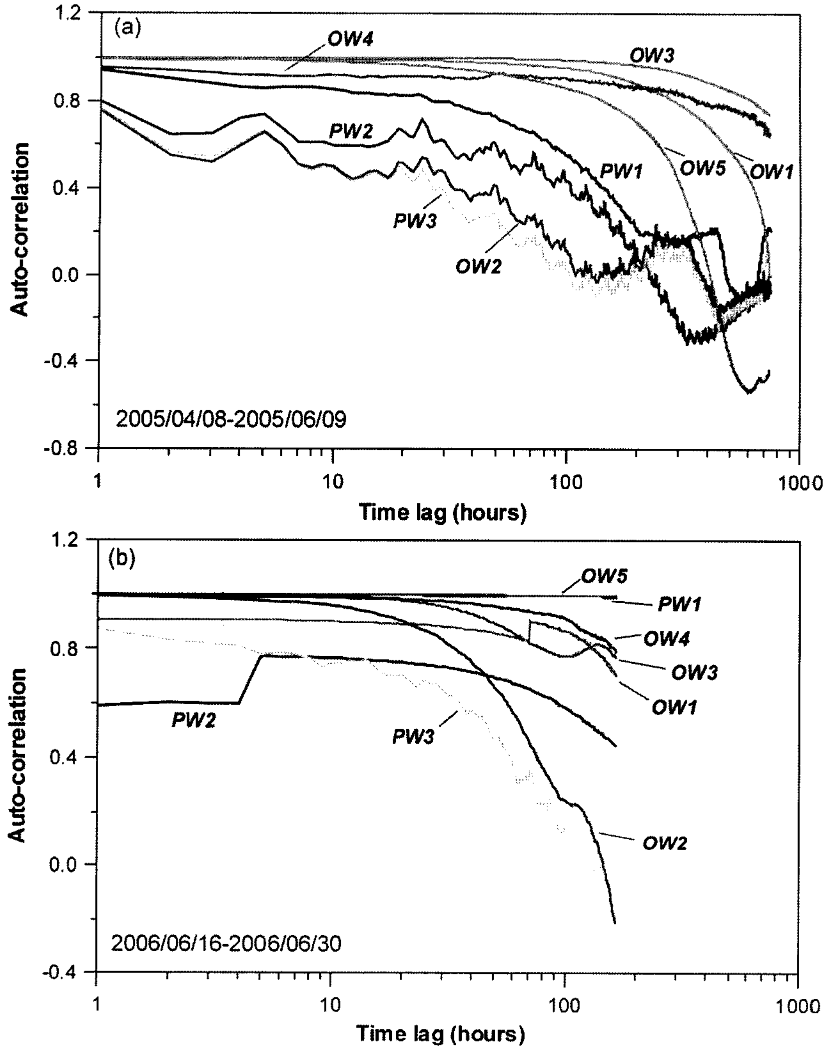

Fig. 5. Auto-correlations of water levels of the pumping and observation wells.

(1,338, 1,086, 1,321 m^3/day), concentrically circular contour of the water levels with respect to the three wells (like single pumping well) was expected. Water levels were lowest at the pumping well PW1 due to the largest pumping rate and groundwaters generally converge toward the well.

Periodic variations of water levels may be analyzed in both time and frequency domains (Lee and Lee, 2000). Like the original water level data (see Fig. 3), OW2 and PW3 showed very similar auto-correlation functions (Fig. 5), which indicates an excellent hydraulic connection between them. In the mean time, the groundwater pumping wells exhibited relatively shorter time lags (refer to Larocque et al., 1998) than those for observation wells (except for OW2, the nearest observation well) due to frequent pumping activity (Table 4). For water levels of OW3 and OW4, their autocorrelations were relatively higher with longer duration because they are largely affected by natural stress (seasonal stress such as rainfall). But these variation characteristics were varying with season or time period.

Spectral density functions of the water levels are presented in Fig. 6. Mostly for the pumping wells, high values at high frequencies are due to frequent pumping and/or pumping test effects (Fig. 6a). Higher

Table 4. Time lags and regulation times obtained from univariate time series analysis for water levels

Well		PW1	PW2	PW3	OW1	OW2	OW3	OW4	OW5
Apr. 2005	TL[a]	481	224	102	740	116	>742	>742	410
	RT[b]	152	17	9	316	34	356	313	190
Jun. 2006	TL	>165	>165	131	>165	146	>165	>165	>165
	RT	83	51	37	75	51	75	80	83

[a] Time lag (hours)
[b] Regulation time (hours)

values of the spectral densities for the observation wells (except for OW2) at lower frequencies are all indicative of stable and longer seasonal water level variation. Also in this case, OW2 and PW3 show similar pattern and remote observation wells OW3 and OW4 did the highest values of the spectral density at low frequencies. Interestingly, the second nearest observation well OW1, showed very stable (see Fig. 3) and longer seasonable water level variation characteristics (Fig. 5a) like the remote observation

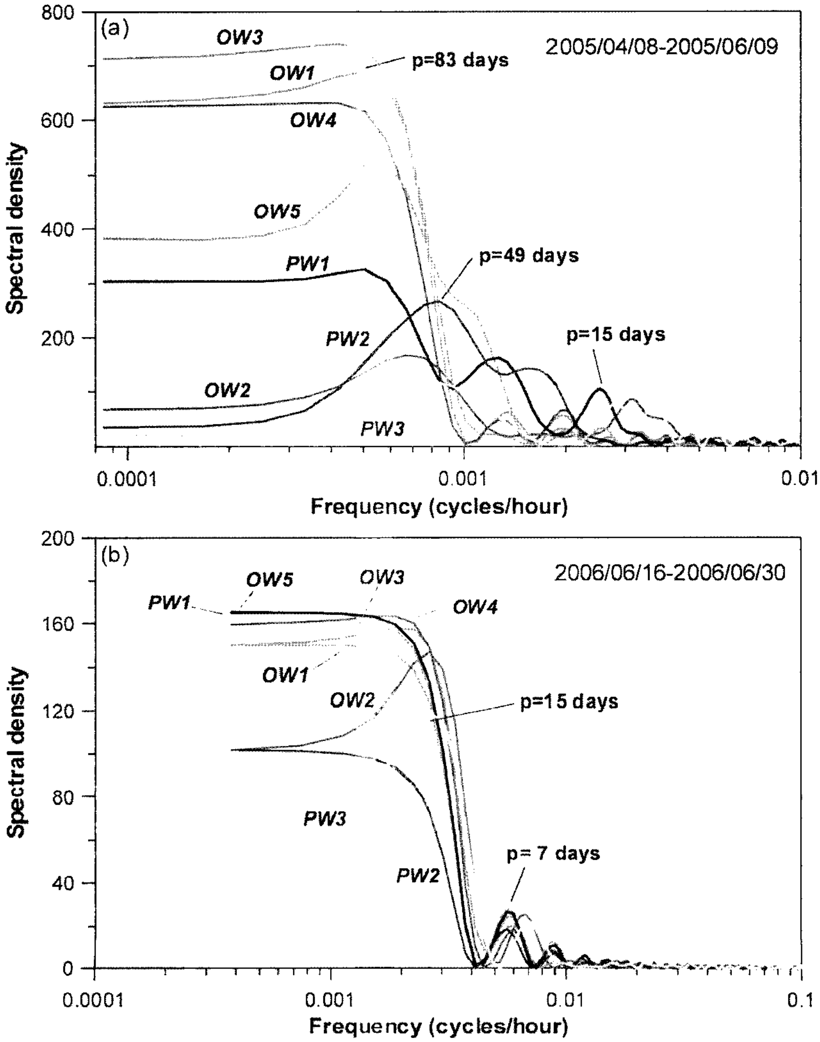

Fig. 6. Spectral density functions of water levels of the pumping and observation wells.

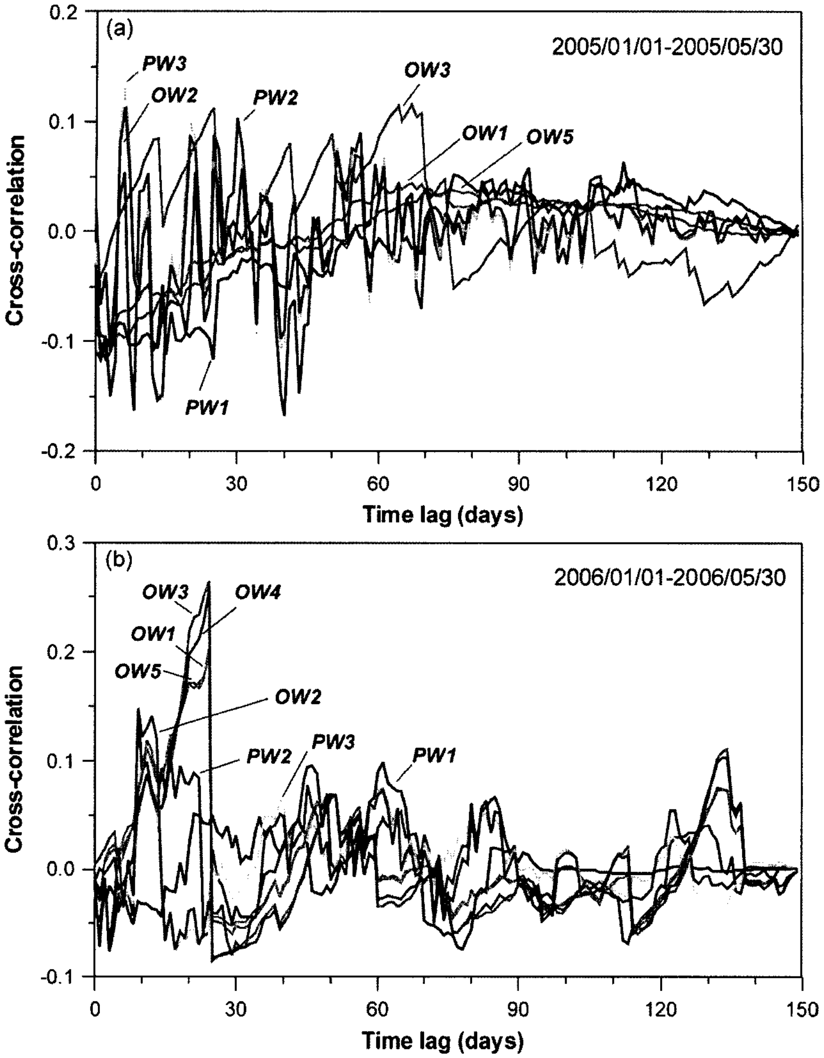

Fig. 7. Cross-correlations of daily water levels with site precipitation.

wells, OW3 and OW4. Rather this well OW1 moderately responded to site rainfall. Very different response of this observation well indicates poor hydraulic connections to the pumping wells (discussed again in the pumping test section). In the mean time, short time period for the analysis may produce different behaviors (Fig. 6b).

Cross-correlation between daily water levels and site precipitation is provided in Fig. 7. The same period of two years (2005 and 2006) yielded very different results. In 2005, no distinctive or discernible correlations between them were found (Fig. 7a) while some interpretable correlations were observed within reasonable time frame in 2006. This difference is partly attributed to intensity and frequency of the site precipitations for the period (e.g., 551.35 mm in 2005 and 900.83 mm in 2006). Most observation wells (OW1, OW3, OW4, OW5) showed moderate cross-correlation with precipitation within 1 month and OW2 well showed quicker response with lowered correlation coefficient. The pumping wells showed only low correlations at substantially longer time lags, which indicates that their water levels are directly dominated by the artificial pumping rather than precipitation.

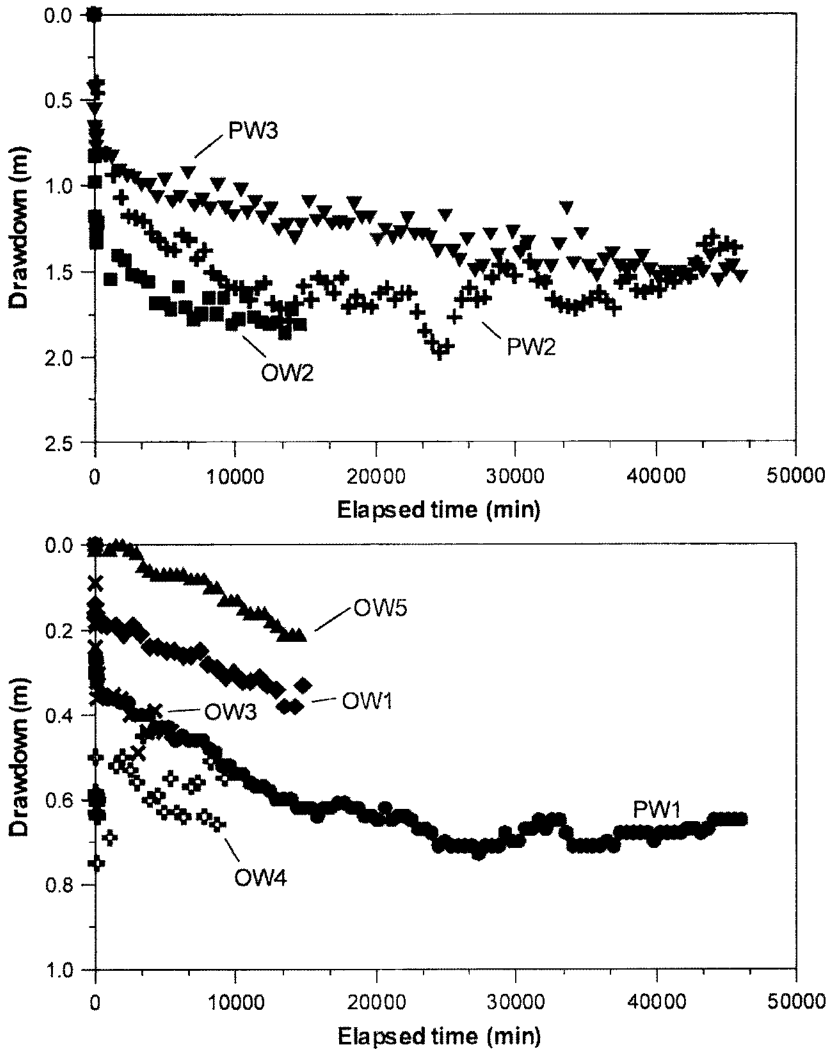

Fig. 8. Drawdowns measured at the third pumping test (pumping wells=PW1-3).

Results of Pumping Tests

As previously described, nevertheless of the several trials of the pumping tests (see Table 2), only single test (#3) produced interpretable drawdowns mainly due to high transmissivity of the adjacent aquifer or high productivity of the well. In most cases, due to relatively low pumping rates (1,086-1,338 m^3/day per well) and effect of preceding frequent pumping (only about 7-day cessation of pumping prior to tests), groundwater levels rose again at some days since pumping start. Occasional site precipitation also complicated the pumping test and their analyses. This study only focused on interpretation of the third (#3) test.

Fig. 8 shows drawdown data of the pumping wells (PW1-3) and observation wells (OW1-OW5). Drawdowns during the test period ranged between 0.2 and 2 m. Interestingly, the pumping wells did not necessarily produce larger drawdowns compared with those of observation wells. Especially, to the contrary of our expectation, the second nearest observation OW1 showed much smaller drawdowns. The well OW5 also showed abnormally smaller drawdowns compared with those of more distant observation wells (OW3 and OW4). Furthermore, even though groundwater pumping at the three pumping wells was continued, water levels of the observation wells rose after 10,000-

Table 5. Estimated hydraulic parameters from the pumping test. For the analysis, Kz/Kh was assumed to be 0.1. Transmissivity (T) is in m^2/min and storativity (S) is unitless

Test no.	Obs. wells	Theis (1935)		Cooper-Jacob (1946)		Neuman (1974)	
		T	S	T	S	T	S
#3	PW1	8.062	5.45×10^{-3}	4.125	1.94×10^{-3}	5.377	2.90×10^{-3}
	PW2	3.646	3.91×10^{-4}	0.583	4.09×10^{-2}	1.962	4.53×10^{-3}
	PW3	4.060	1.94×10^{-3}	1.087	2.09×10^{-4}	2.885	3.33×10^{-3}
	OW1	9.667	8.67×10^{-3}	4.342	4.61×10^{-4}	5.422	4.57×10^{-4}
	OW2	1.542	8.10×10^{-4}	0.618	9.34×10^{-5}	0.858	6.93×10^{-5}
	OW3	4.396	6.95×10^{-3}	1.779	1.40×10^{-3}	2.769	6.50×10^{-3}
	OW4	2.070	4.41×10^{-4}	0.754	1.54×10^{-4}	0.516	1.99×10^{-3}
	OW5	19.97	8.91×10^{-3}	8.066	5.41×10^{-3}	11.15	4.70×10^{-3}
Geometric mean		4.883	2.30×10^{-3}	1.718	9.77×10^{-4}	2.625	1.74×10^{-3}

12,000 minutes (6.94-8.33 days) since pumping start and these rising trends were sustained. For the analysis, the rising water level intervals were truncated.

Table 5 shows hydraulic parameters estimated using three solutions for confined and unconfined aquifers. As previously described, the tested aquifer is not a confined one in theoretically strict sense but vertical variation of rock permeability would produce a confined aquifer characteristic (Lee and Farmer, 1993). The three solutions did not yield very different results. Estimates of transmissivity are between 0.516 and 19.97 m^2/min. The smaller drawdowns at OW5 and OW1 (see Fig. 8) resulted in very larger transmissivity estimates. But these higher values are somewhat open to doubt. No prominent hydraulic connection (revealed by hydraulic resonance) between the pumping wells and the observation wells (OW1 and OW5) (see Figs. 3, 5-7) was observed, thus smaller drawdowns at these wells rather poor hydraulic connection between them, to the contrary (Lee and Lee, 1999). To complete this interpretation, in addition to pumping tests, single well slug tests are further required. In the meanwhile, the estimates are admitted as actual or reasonable, the anisotropic ratio of transmissivity with respect to principal axes (X-Y TM coordinates) is 12.4:1 (76.1° NE direction) (Fig. 9). The anisotropic ellipse was optimized using an algorithm, minimizing residuals in 2-D space.

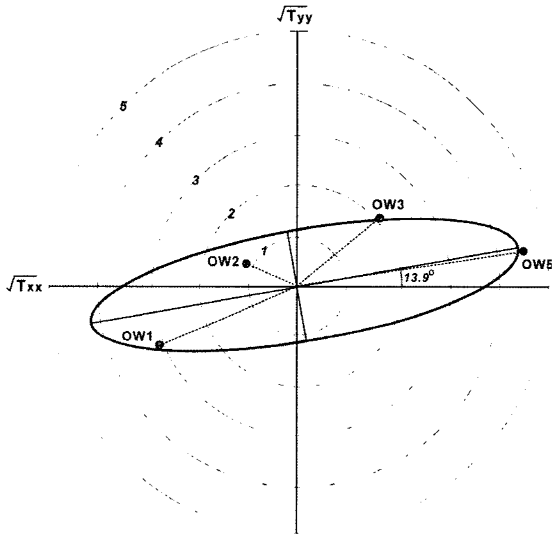

Fig. 9. Horizontal anisotropy ellipse of transmissivity. Anisotropy ratio was estimated as 12.4:1.

Resultant storativity values are also interesting (see Table 5) and they ranged between 6.93×10^{-5} and 4.09×10^{-2}. Their geometric means are between 9.77×10^{-4} and 2.30×10^{-3}, which are somewhat intermediate values for confined and unconfined aquifers. Consequently, the main aquifer of this study is characterized by a mixed one of confined and unconfined conditions, which is mainly due to alternating many geologic layers and their varying permeabilities.

Summary and Conclusion

This study examined hydrogeologic characteristics of a well field around middle mountainous areas of Pyosun in Jeju. Various hydrogeologic layers in the subsurface complicate analysis of hydraulic responses to artificial pumping and natural precipitation. Moreover, this study showed some inherent limitations mainly enforced by field conditions. Due to the groundwater production, appropriate time periods for cessation of the pumping prior to pumping tests cannot be readily secured. Thus effects of preceding and frequent pumping on the pumping test data are inevitable.

Based on time series analysis of water levels and analysis of pumping tests, some main conclusions were drawn.

1. The least permeable layer is found at a depth of 200 m below surface but it is not an upper confining bed for lower main aquifer. Nevertheless, this layer may function as a natural barrier to vertical percolation and contaminant migration.
2. Water levels of the production wells are dominated by frequent pumping while those of the remote observation wells are controlled by ambient precipitation.
3. Results of pumping tests revealed a possible existence of horizontal anisotropy of transmissivity but it deserves further investigation including single well slug tests.

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