# Dynamic freshwater–saline water interaction in the coastal zone of Jeju Island, South Korea

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**Abstract** Freshwater–saline water interactions were evaluated in a coastal region influenced by external forces including tidal fluctuations and seasonal rainfall variations. Five different coastal zones were considered on Jeju Island, South Korea, and electrical conductivity (EC) profiles from the monitoring wells were examined to identify the configuration of the freshwater–saline water interface. There appeared to be discrepancies among EC profiles measured at different points in time. To analyze the dynamic behavior of freshwater–saline water interactions, groundwater level measurements and multi-depth EC and temperature probes were used to obtain time-series data; the data showed that water level, EC and temperature were influenced by both tidal fluctuations and heavy rainfall. The effects of oceanic tide on EC and temperature differed with depth due to hydraulic properties of geologic formations. A spectral filter was used to eliminate the effects of tidal forces and provide information on the influence of heavy rainfall on water level, EC and temperature. Heavy rainfall events caused different patterns and degrees of variation in EC and temperature with depth. The time-series data of EC and temperature in the subsurface at various depths enable greater understanding of the interaction processes between fresh and saline water.

**Keywords** Coastal aquifers · Salt-water/freshwater relations · Spectral analysis · South Korea

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## Introduction

Seawater intrusion has been reported in almost all the coastal aquifers around the globe. The shape and degree of seawater intrusion in a coastal aquifer depend on several factors. Some of these are natural and cannot be controlled, while others are manmade and could, thus, be managed (Sherif and Kacimov 2007).

Understanding the mechanisms of freshwater–saline water interactions has become an important issue for studies in hydrology as well as water management in coastal areas. Recently, Beddows et al. (2007) studied the behavior of groundwater circulation in a coastal aquifer using specific electrical conductance and groundwater temperature as tracers. Numerical models have been widely used for evaluating seawater intrusion in coastal regions (Zhang et al. 2004; Qahman and Larabi 2006). Regarding methods to locate freshwater–saline water interface, Kim et al. (2007) proposed a method using pressure data from the fresh and saline zones within a single borehole.

Submarine groundwater discharge (SGD) is another principal topic related to behavior of coastal aquifers. SGD is recognized as a significant water and material pathway of water to the ocean (Moore 1996; Burnett et al. 2001). Recently, Kazemi (2008) remarked that analysis of groundwater flow dynamics in coastal aquifers can improve SGD studies. Taniguchi et al. (2007) investigated SGD and freshwater–saline water interactions with the use of seepage and resistivity measurements.

The Intergovernmental Panel on Climate Change (IPCC) estimates a global average sea-level rise of about 0.6 m for the coming century under the "Year 2000 constant concentrations" scenario, with a likely range of 0.3–0.9 m (IPCC 2007). Thus, considering the sea level rise and change of rainfall distribution by climate change anticipated in the future, it is essential to understand the subsurface process in coastal aquifers. Melloul and Collin (2006) reported hydrogeological changes in coastal aquifers due to sea level rise, and Masterson and Garabedian (2007) presented the effects of sea-level rise on the depth to the freshwater–saline water interface by using a numerical model.

On Jeju Island, located 140 km south of the Korean Peninsula (Fig. 1), groundwater is the principal source of


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freshwater for the population of 560,000. As the island is surrounded by sea on all sides, seawater intrusion is a generalized phenomenon in the coastal zone, and thus the coastal aquifer needs to be managed carefully. Many

**Fig. 2** Profiles of electrical conductivity (EC) measurements at the monitoring wells at different dates (yyyy/mm/dd); the depths are relative to mean sea level. Wells **a** HL-1, **b** JC-1, **c** JD-1, **d** SS-1, **e** HC-1

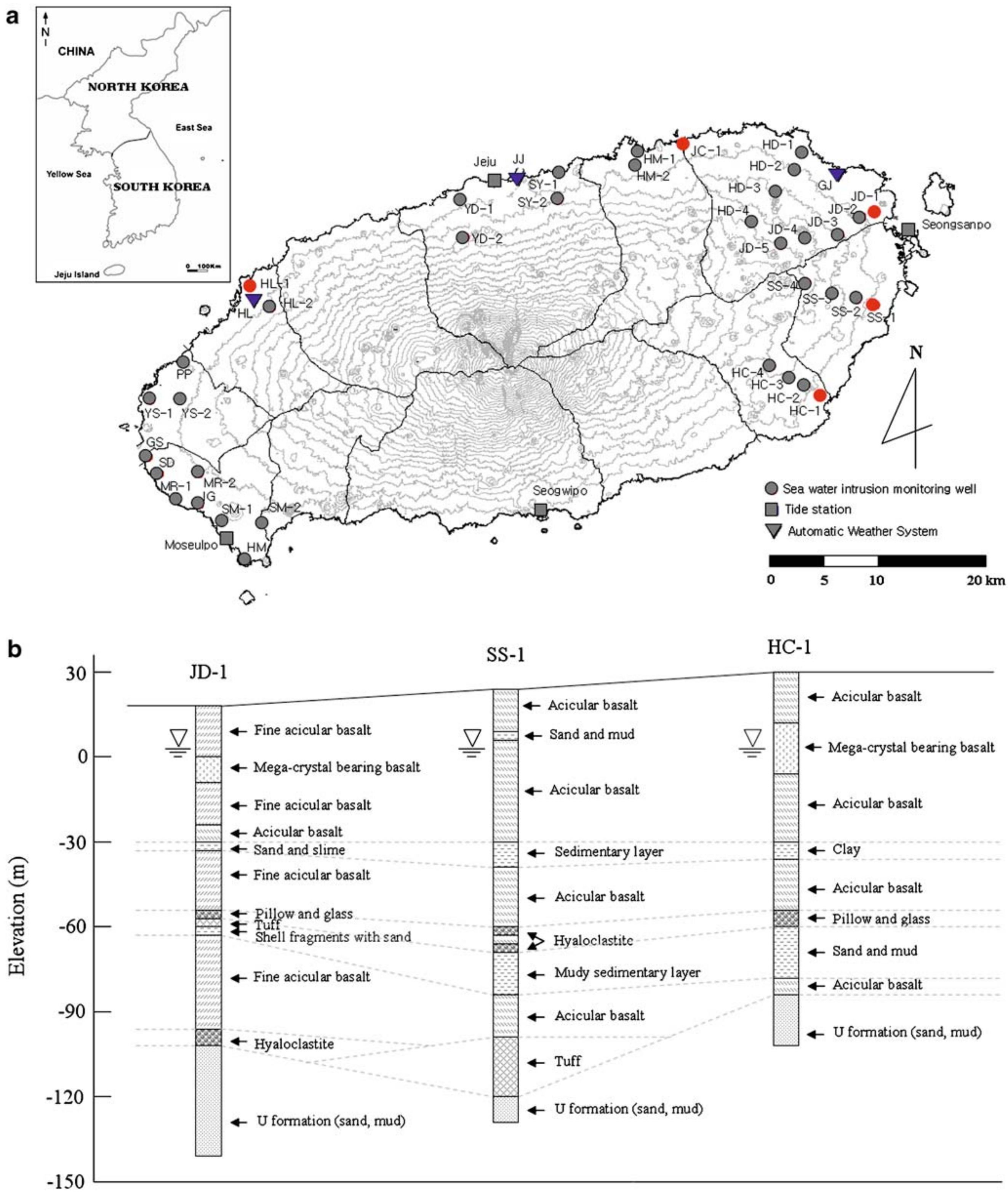
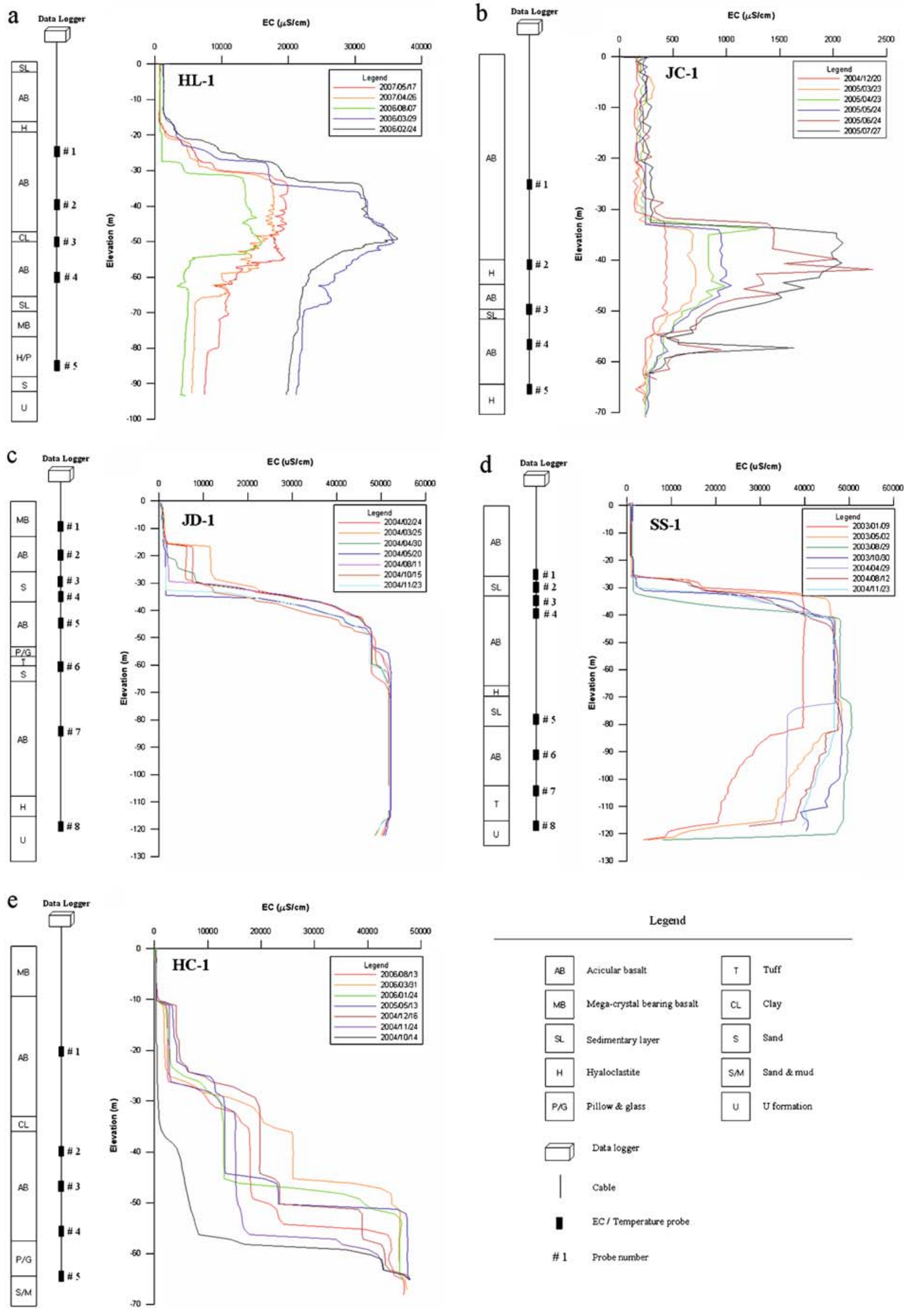



**Fig. 1** **a** The location of the monitoring wells and automatic weather system on Jeju Island. *Red circles* indicate where multi-depth monitoring systems are installed. The topographic contour lines are drawn every 50 m. **b** Geologic cross section for JD-1, SS-1, and HC-1





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hydrogeologic studies on Jeju Island have been conducted. Won et al. (2006) summarized several studies on the occurrence and features of groundwater resources on the island. Kim et al. (2006) proposed a conceptual model of fresh-saline interactions for the eastern part of Jeju Island by combining the results of EC and temperature log and the flowmeter tests. On the extension of the study, Kim et al. (2008) analyzed the interaction of freshwater–saline water influenced by tidal fluctuations with EC data and end-member mixing analysis.

In nature, a freshwater–saline water interface seldom remains stationary. Changes in aquifer stresses result in the movement of the interface. The objectives of this study are to identify the temporal variations of freshwater–saline water interactions at coastal aquifers and to evaluate the influence of tidal fluctuations and seasonal rainfall. In order to reach these objectives, five coastal regions were considered around volcanic Jeju Island and time-series data of EC and temperature were obtained with the multi-depth monitoring system.

## Study area

Jeju Island is 73 km wide and 41 km long with a total area of 1,848 km$^2$ (Fig. 1a). Mt. Halla rises in the center of Jeju to 1,950 m above sea level (m asl), and the rest of the island slopes down from its summit. The island is formed through multiple volcanic activities and mainly consists of volcanic rocks, including very permeable basalts. Topographic profiles and geologic cross-sections for monitoring wells JD-1, SS-1, and HC-1 are given in Fig. 1b. The basement underlying the island consists of Cretaceous welded tuff and granite covered by unconsolidated formation (the U Formation). The U formation is a sedimentary layer composed of mud, fine sand, shell fragments, and quartz particles. The major aquifers on Jeju Island include hyaloclastite, clinker layers, and lava tubes. Hyaloclastite was formed during rapid cooling of lava by water.

The Jeju special self-governing province has established monitoring wells around the coast in order to understand the subsurface geology, to observe water-level fluctuations, and to investigate the EC variations. In this study, five monitoring wells—HL-1, JC-1, JD-1, SS-1, and HC-1—were selected for the installation of a multi-depth monitoring system (Fig. 1a). The distance from coast to the monitoring wells ranges from 0.6 to 1.7 km.

## Methodology

Seawater intrusion monitoring wells were installed around Jeju Island to monitor groundwater level and saline water intrusion. The location and configuration of the freshwater–saline water interface were examined with EC logs, which were obtained at several points of time for each monitoring well in order to investigate the temporal variation. Although these profiles provide valuable information on freshwater–saline water interactions, monthly logging data are unable to analyze short-term variations influenced by tidal oscillations and the effect of rainfall events on interactions between fresh and saline water. Thereafter, the EC and temperature probe system, which can monitor at multi depths, was installed at each monitoring well. The measuring range of the EC probe was 0–60,000 μS/cm (accuracy ±1% full scale, resolution 0.1 μS/cm) and the temperature probe measured from −5 to 50°C (accuracy ±1°C, resolution 0.01°C). Continuous measurements of groundwater level, EC and temperature were made at 30-min intervals.

Considering the hydrogeologic formations identified from geologic log and EC profiles, the sensors were installed at eight points for two monitoring wells, JD-1 and SS-1, and at five points for three monitoring wells, HL-1, JC-1 and HC-1 (Fig. 2). The EC and temperature probes were identified as EC and Temp series, respectively, and numbered in order from shallow to deeper depths. The monitoring wells are installed to a depth of approximately 150 m below the sea level, and are fully screened.

For precipitation, data were obtained from the automatic weather system (AWS). A number of AWSs are operated by Korea Meteorological Administration to monitor various weather data including precipitation. Among the 24 AWS installed on Jeju Island, three stations—Hanlim (HL), Jeju (JJ), Gu-Jwa (GJ) stations—near the monitoring wells were selected (Fig. 1a).

Fourier-transform based spectral analysis was applied to analyze the signal properties by obtaining information of which frequencies are present. Applying a spectral filter to the frequency domain, data eliminates all identified periodicities. In this study, a low-pass fast Fourier transform (FFT) filter was applied to the groundwater level, EC and temperature data to remove the diurnal and semidiurnal fluctuations and the noise from the monitoring system.

## Results

### Freshwater–saline water interface

Coastal groundwater tends to have a definable interface dividing the fresh and saline zones according to density difference. Figure 2 represents geological log and EC profiles measured at various points of time from five monitoring wells. The geology of borehole HL-1, is composed of acicular basalt, sedimentary layer, hyaloclastite and U formation. EC logging was carried out three times in 2006 and two times in 2007. EC started to increase from –25 m and reached up to 35,000 μS/cm. The EC profile shows a tendency of decrease from a depth of –50 m. Based on geological and EC log profiles, five measuring points, –25, –40, –50, –60, –85 m, were selected (Fig. 2a).

The depth of JC-1 borehole is 70 m and the geology is mostly composed of acicular basalt and hyaloclastites. The freshwater zone had an EC value of 200 μS/cm and EC

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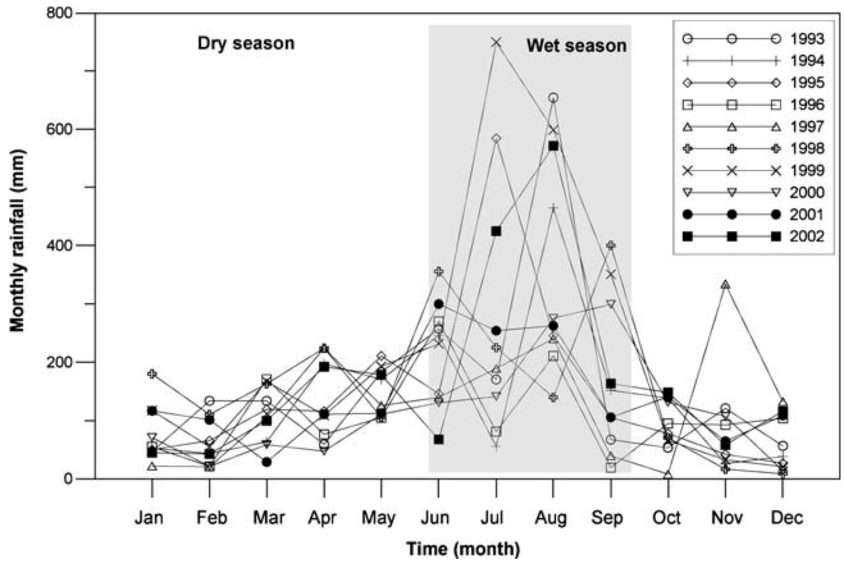


**Fig. 3** Monthly rainfall over Jeju Island during 1993–2002

increased from −32 m. EC tended to decrease at the lower part. The maximum value of EC was detected between −40 and −45 m. Multi-depth probes were installed at depths of −25, −40, −50, −57, and −65 m (Fig. 2b).

The geology at JD-1 is composed of acicular basalt, hyaloclastite, U formation and sedimentary layers. The profiles show that EC at freshwater and saline water zone is ~1,000 and ~50,000 μS/cm, respectively and that the freshwater–saline water interface varied between −15 and −30 m. The monitoring probes were installed at −10, −20, −30, −35, −45, −60, −85, and −119 m (Fig. 2c).

The subsurface system around SS-1 consists of acicular basalt, hyaloclastite, U formation and sedimentary layers. The EC profiles presented two types of interface patterns for different points of time. One is an interface lying at a depth of −30 m, dividing freshwater and saline water zones. The other case shows another interface existing at a lower part and relatively low total dissolved solids (TDS) water flows in this zone. Multi-depth probes were installed at −25, −30, −35, −40, −78, −91, −104 and −117 m (Fig. 2d).

The geology at HC-1 is composed of acicular basalt, hyaloclastite, U formation and sediments lies between layers. According to the EC profile, EC starts to increase from −25 m reaching to 20,000–25,000 μS/cm and the second increase was observed at −45 m. The monitoring probes were installed at −20, −40, −47, −55 and −65 m (Fig. 2e).

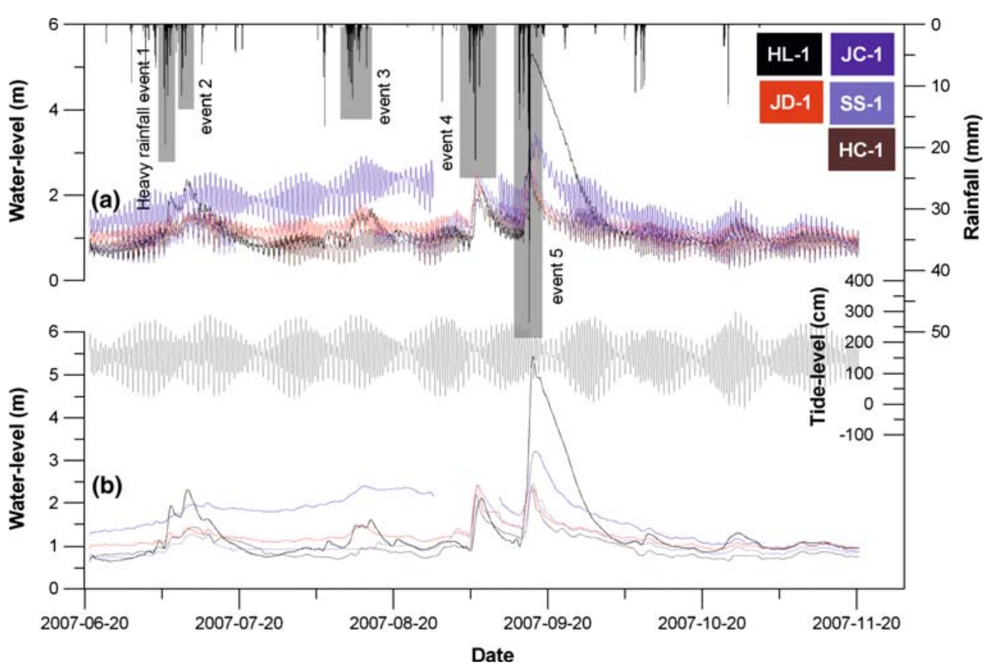


**Fig. 4** **a** Time series data of the 30-min rainfall intervals observed at JJ station and the groundwater level at the monitoring wells. **b** Low-pass filtered signals from the groundwater level data

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**Table 1** Heavy rainfall events observed during 20 June–20 November 2007

| Heavy rainfall event | Duration | Date | Station | | |
|---|---|---|---|---|---|
| | | | HL | JJ | GJ |
| 1st | 39 h | 5 Jul–7 Jul | 93.5 mm | 122.5 mm | 144.0 mm |
| 2nd | 26 h | 9 Jul–10 Jul | 72.0 mm | 55.5 mm | 90.5 mm |
| 3rd | 82 h | 10 Aug–14 Aug | 110.5 mm | 155.5 mm | 139.0 mm |
| 4th | 71 h | 4 Sep–7 Sep | 130.0 mm | 244.5 mm | 340.0 mm |
| 5th | 59 h | 14 Sep–16 Sep | 411.5 mm | 590.0 mm | 358.0 mm |

## Precipitation

The monthly rainfall over Jeju Island from 1993 to 2002 is illustrated in Fig. 3. The average annual rainfall during this period was 1,820 mm (Jejudo and Korea Water Resources Corporation 2003). The highest annual rainfall recorded was 2,693 mm in 1999, while the lowest amount of rainfall was observed in 1996 at 1,304 mm. The wet season starts in June and ends in September while October to April is the dry season.

Figure 4 a presents the time-series of the 30-min rainfall intervals observed at JJ station from 20 June to 20 November 2007. The study period includes both the wet and dry season.

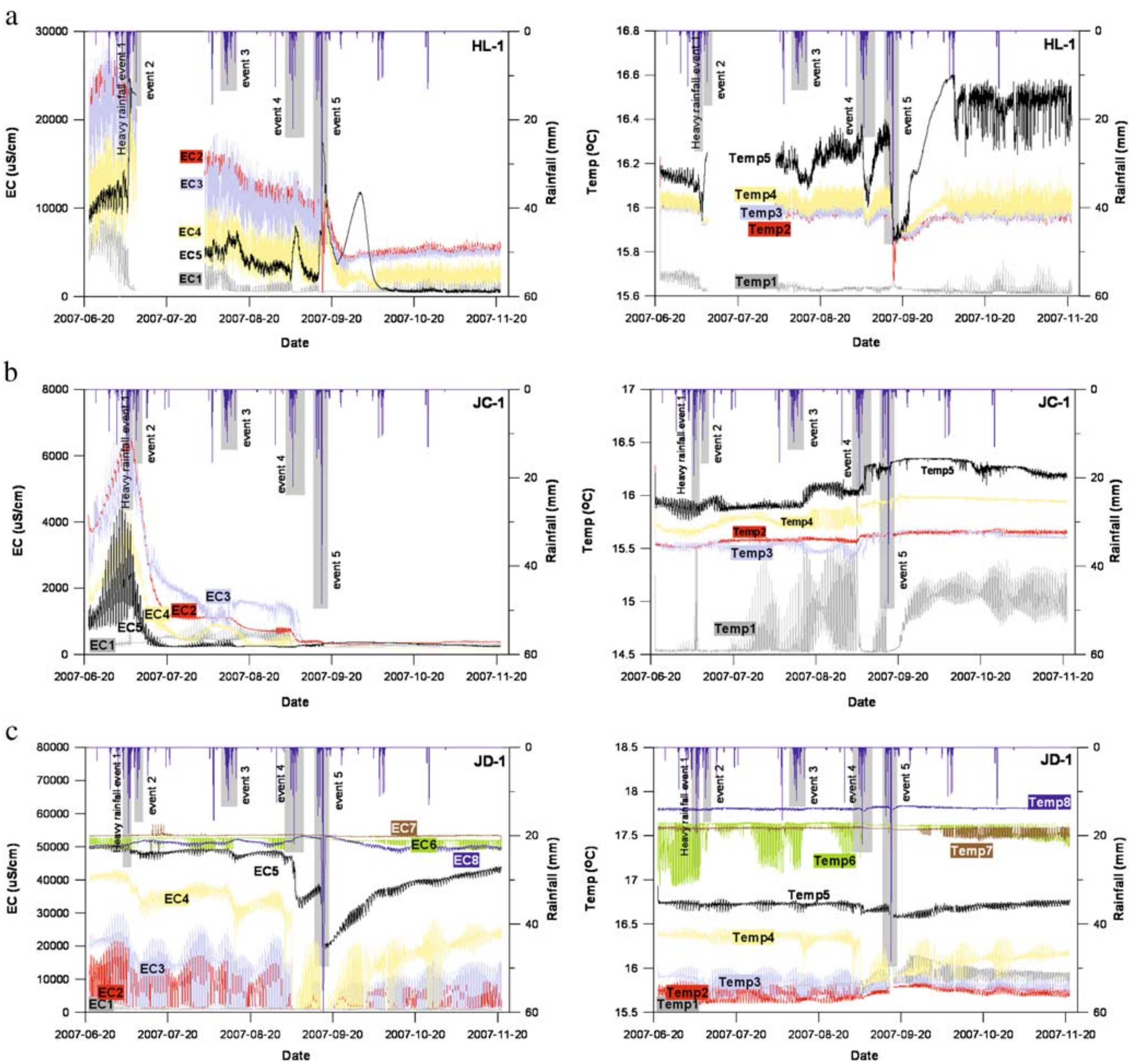


**Fig. 5** Time series data of the 30-min rainfall intervals observed at JJ station and the EC (*left panel*) and temperature (*right panel*) at the monitoring wells. Wells **a** HL-1, **b** JC-1, **c** JD-1, **d** SS-1, **e** HC-1


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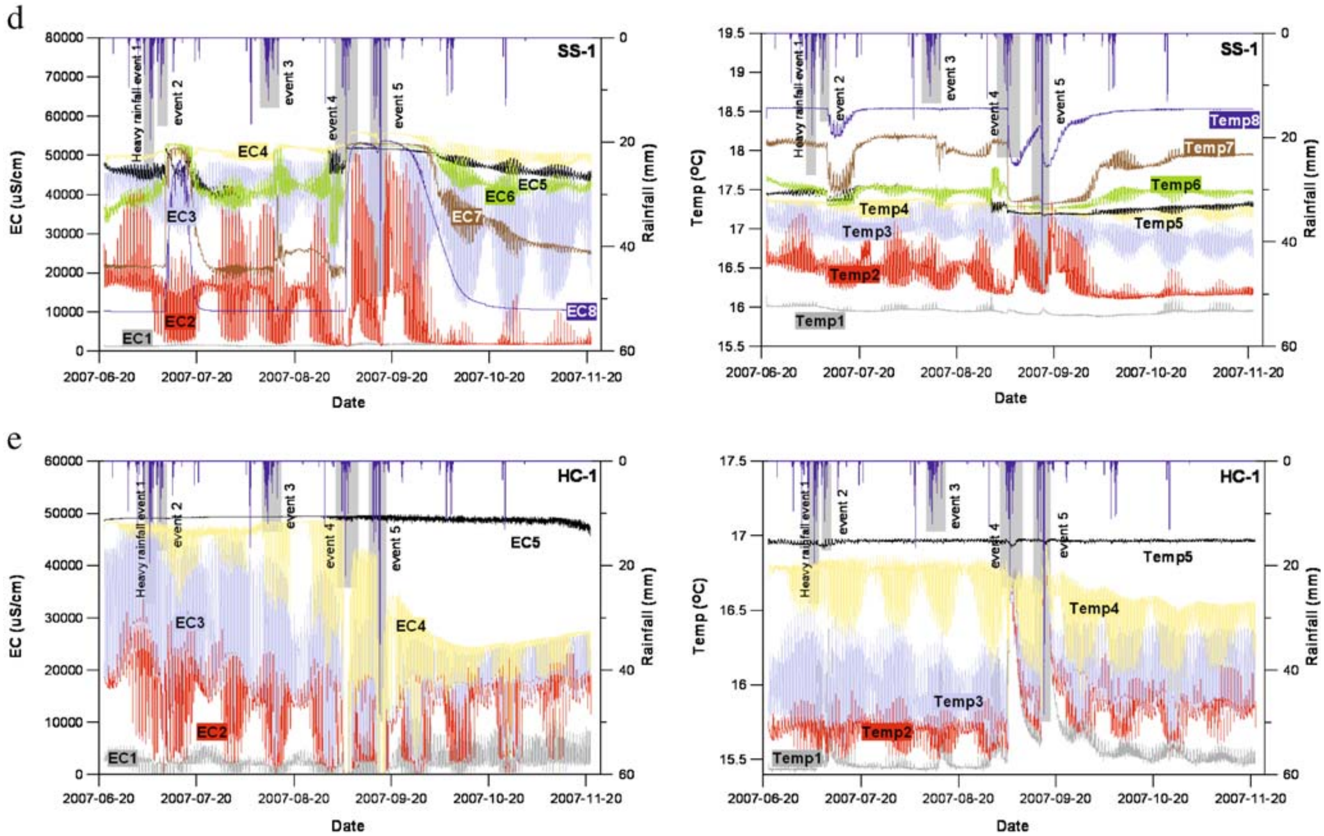


**Fig. 5** (continued)

Although there were some discrepancies of rainfall amount among the three stations of AWS during the monitoring period, the periods of time of heavy rainfall were similar. The total amount of rainfall at the three stations during the study period was 1,281 mm (HL), 1,605 mm (JJ), and 1,634 mm (GJ), respectively. During the wet season, five heavy rainfall events were observed. The first event occurred between 5 July and 7 July with 93.5 mm (HL), 122.5 mm (JJ), and 144.0 mm (GJ). The largest rainfall was recorded during 14–16 September with 411.5 mm (HL), 590.0 mm (JJ), and 358.0 mm (GJ). The duration and amount of rainfall for each event are presented in Table 1.

## Water level, EC and temperature time series

The tide and groundwater level variation from the monitoring wells observed during the study period are given in Fig. 4a. The tide-level fluctuates from −1.5 to 1.5 m, and the groundwater level is influenced by tidal fluctuation. According to the time-series data observed at four tidal gauge stations, there were no specific tidal variations during the storms. The groundwater level varied in the range of 0.5–1.5 m during most of the period, and showed a rise of water level after heavy rainfall events.

Time series data of EC and temperature from five monitoring wells are illustrated in Fig. 5. The uppermost EC probe installed at HL-1 read 700–9,000 μS/cm. While the data obtained from EC1 varies with the tidal period, the EC from probes EC2–4 show irregular patterns without reference to tidal fluctuations. In order to analyze this phenomenon, the EC and temperature were observed at 1-min time intervals (Fig. 6a). The variation of EC within a minute reaches up to 2,000 μS/cm, and the temperature varies in the range of 0–0.3°C (Fig. 6b). This unstable flow is also presented in the EC log data (Fig. 2a). The EC profiles measured in 2007 show the unstable value from −40 to −60 m where probes 2–4 are located. The temperature tended to increase with depth ranging between 15.6°C and 16.6°C.

The EC value obtained from JC-1 did not exceed 7,000 μS/cm throughout the entire borehole during the monitoring time, indicating relatively low TDS water. The tidal effect on EC was weakened after September. The temperature at −25 m was ~15.6°C and increased with depth. Temp5 probe read the temperature, ranging from 16.1–16.3°C.

At JD-1 borehole, the EC value at −10 m depth was ~1,000 μS/cm and revealed no significant change during the monitoring period. However, probes EC2 and EC3, which were installed at −20 and −30 m, showed a wide range of EC fluctuations due to tidal variations. The EC value obtained from EC2 ranged from 2,000 to 21,000 μS/cm, and EC3 ranged from 2,000 to 30,000 μS/cm. Temperature above −30 m ranged between 15.5 and 16.0°C and the bottom of the borehole was ~17.8°C. Small changes of temperature were detected by the force of tidal fluctuations.

The most dynamic variations of EC were observed at the SS-1 monitoring well. EC at a depth of −25 m was ~1,000 μS/cm and did not respond to tide and rainfall

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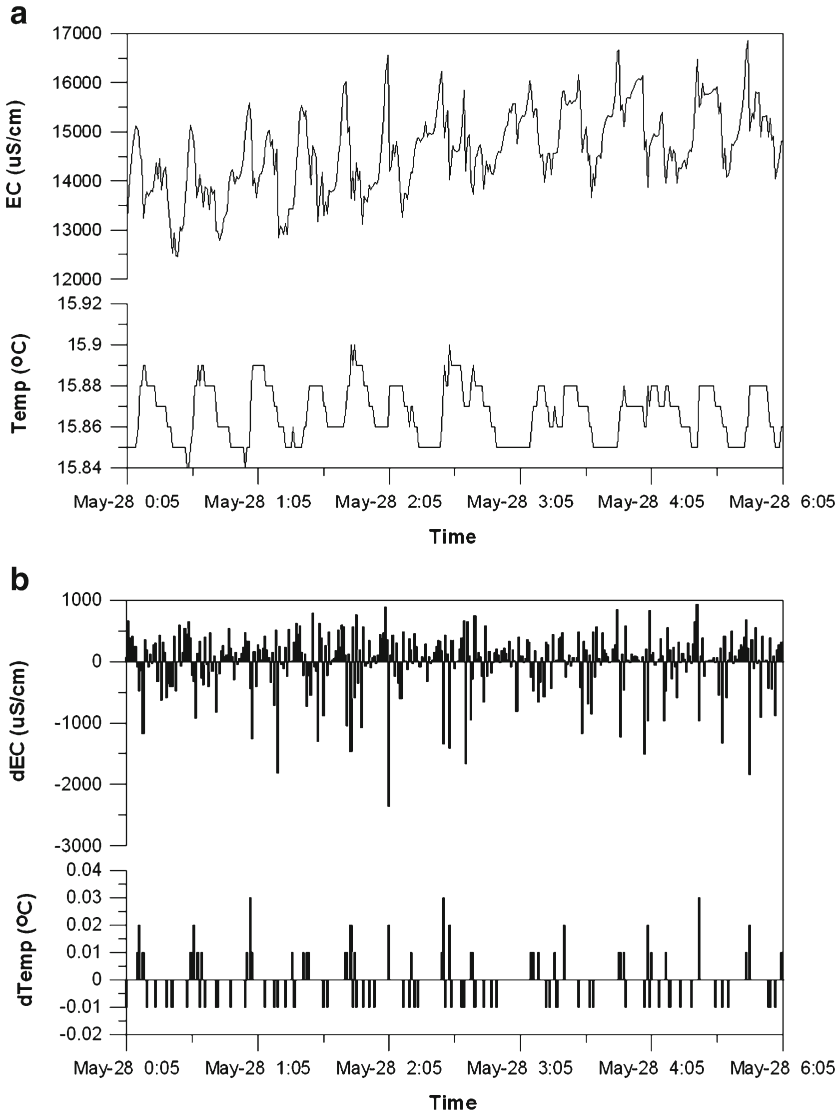


**Fig. 6** **a** Time series data of the 1-min EC and temperature intervals obtained from depth −40 m at HL-1; **b** Differentiated data of EC and temperature

while the EC probe at depth of −30 m read a wide range of EC variation fluctuating from 2,000 to 40,000 μS/cm due to tide. It is interesting to note that the range of EC variations increased from a range of 1,000 to 50,000 μS/cm after the fourth heavy rainfall event. This implies that, in this case, recharge strengthens the tidal effect on EC values. The temperature of the upper part of the aquifer was ~16°C and increased to 18.6°C at a depth of −117 m.

The data from probes installed at HC-1 revealed that EC at a depth of −20 m varied in the range of 500–6,000 μS/cm. EC2 probe which was installed at −40 m showed a wide range of EC varying from 500 to 35,000 μS/cm due to tides. The temperature observed at −20 m was ~15.4°C and increased with increasing depth resulting in ~17.0°C at −65 m.

## Spectral analysis

Spectral analysis was undertaken in order to characterize the periodicity of groundwater level, EC and temperature

**Table 2** The main tidal components

| Nature | Description | Tidal component | Frequency (cph) | Period (h) |
|---|---|---|---|---|
| Diurnal | Principal lunar diurnal | $O_1$ | 0.038731 | 25.819 |
| | Luni-solar diurnal | $K_1$ | 0.041781 | 23.934 |
| Semi-diurnal | Larger lunar elliptic | $N_2$ | 0.078999 | 12.658 |
| | Principal lunar | $M_2$ | 0.080511 | 12.421 |
| | Principal solar | $S_2$ | 0.083333 | 12.000 |

*cph* cycles per hour

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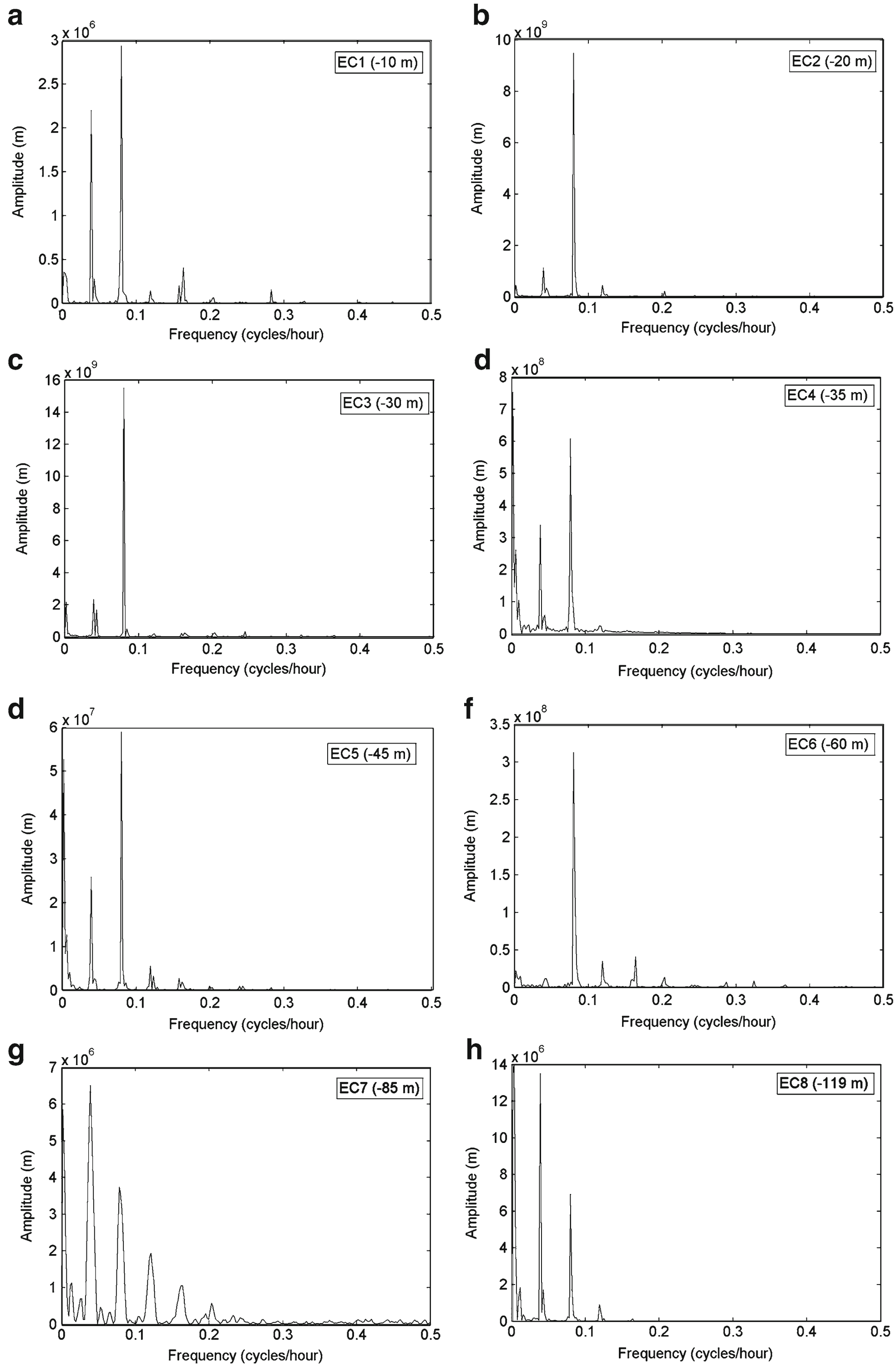


**Fig. 7** Power spectral density of the EC data obtained from each probe installed at JD-1 monitoring well

influenced by external forces such as tidal fluctuation. The various frequencies of astronomical forcing which contribute to tidal variations are called constituents. In most locations, the largest one is the 'principal lunar semidiurnal' constituent, also known as the $M_2$ tidal constituent. Long period constituents have periods of days, months, or years. The main tidal components are listed in Table 2.

Figure 7 delineates the power spectral density (PSD) of the EC data obtained from JD-1 monitoring well. Each figure part shows the PSD for EC data from the depth at which the probes were installed. Power is plotted versus frequency in cycles per hour (cph). Although there were some differences of constituents and amplitude, the results show a strong peak at 0.03 and 0.08 cph from most of the

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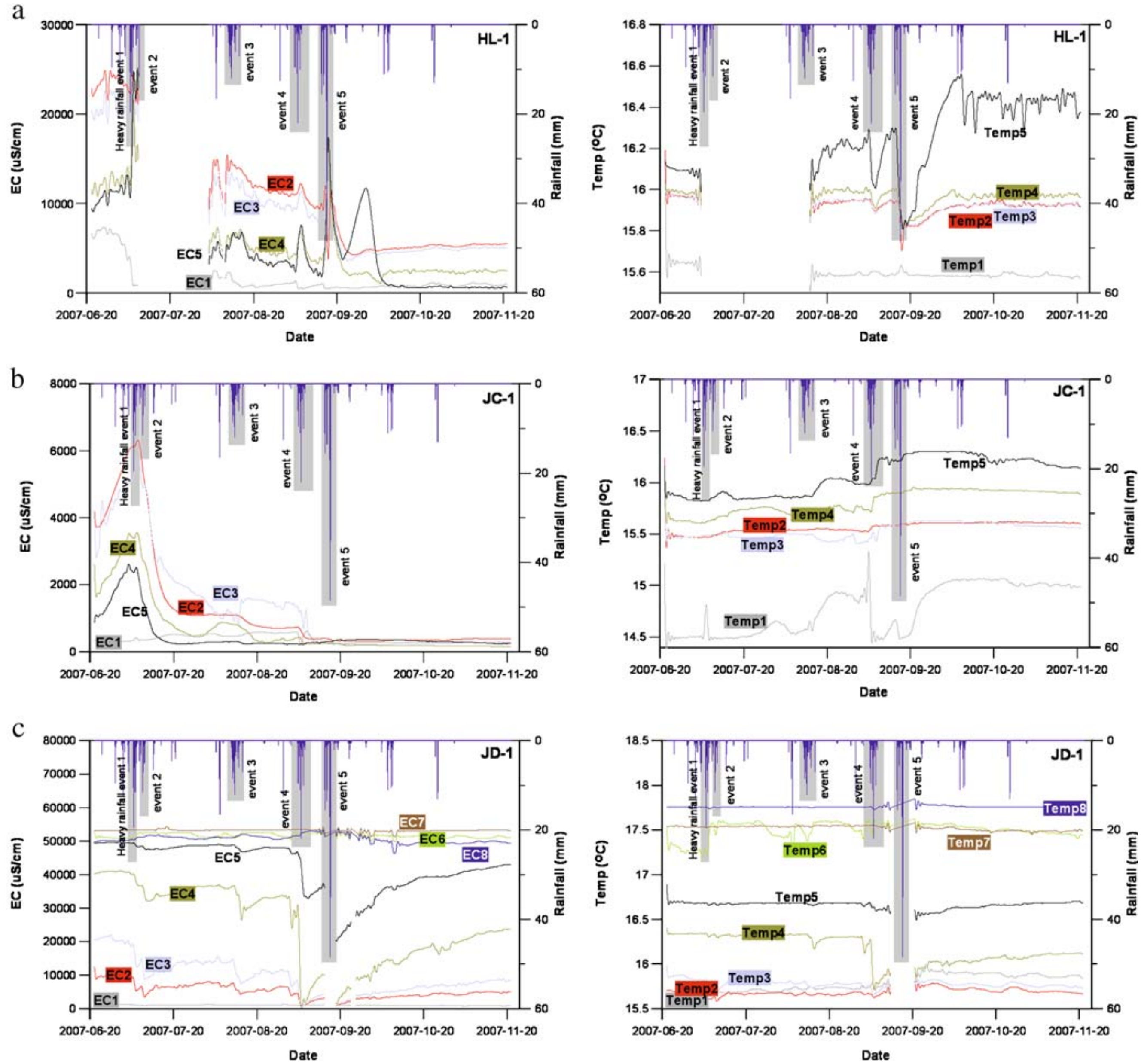


**Fig. 8** Low-pass filtered signals from the EC (*left panel*) and temperature (*right panel*) data at the monitoring wells. **a** HL-1, **b** JC-1, **c** JD-1, **d** SS-1, **e** HC-1

measuring points. In order to analyze the rainfall effect on EC and temperature at coastal aquifers, the tidal effect was removed from the monitored data applying low pass digital filter with a cut-off frequency of 0.03 cph.

## *Effect of seasonal rainfall*

Tide-induced groundwater level was filtered to display the water-level behavior affected by rainfall (Fig. 4b). The water level responded to rainfall events, rising up to 5 m above mean sea level. Among the five monitoring wells, the water level at JC-1 was highest during most of the period, and water-level variation at HL-1 was most sensitive to rainfall.

The results of the filtering of EC and temperature are presented in Fig. 8. The spectral filter analysis of EC and temperature time series data from HL-1 suggest that during the monitoring period, the fourth and fifth rainfall events caused EC decrease at the uppermost probe while EC increased at probes of EC2, EC3, EC4 and EC5. The temperature data of the probes at Temp2–Temp4 were found to decrease slightly due to the fourth and fifth rainfall events. The temperature observed particularly at Temp5 probe was shown to vary significantly decreasing from 16.4 to 15.9°C.

At JC-1, EC decreased to 200–300 µS/cm for all of the probes after the fourth heavy rainfall event. This implies that a large amount of recharge increased the flow of fresh groundwater from inland to seaward and the freshwater–saline water interface moved toward the sea.

Processed data from JD-1 revealed that the fourth heavy rainfall caused EC decrease to 1,000 µS/cm at the

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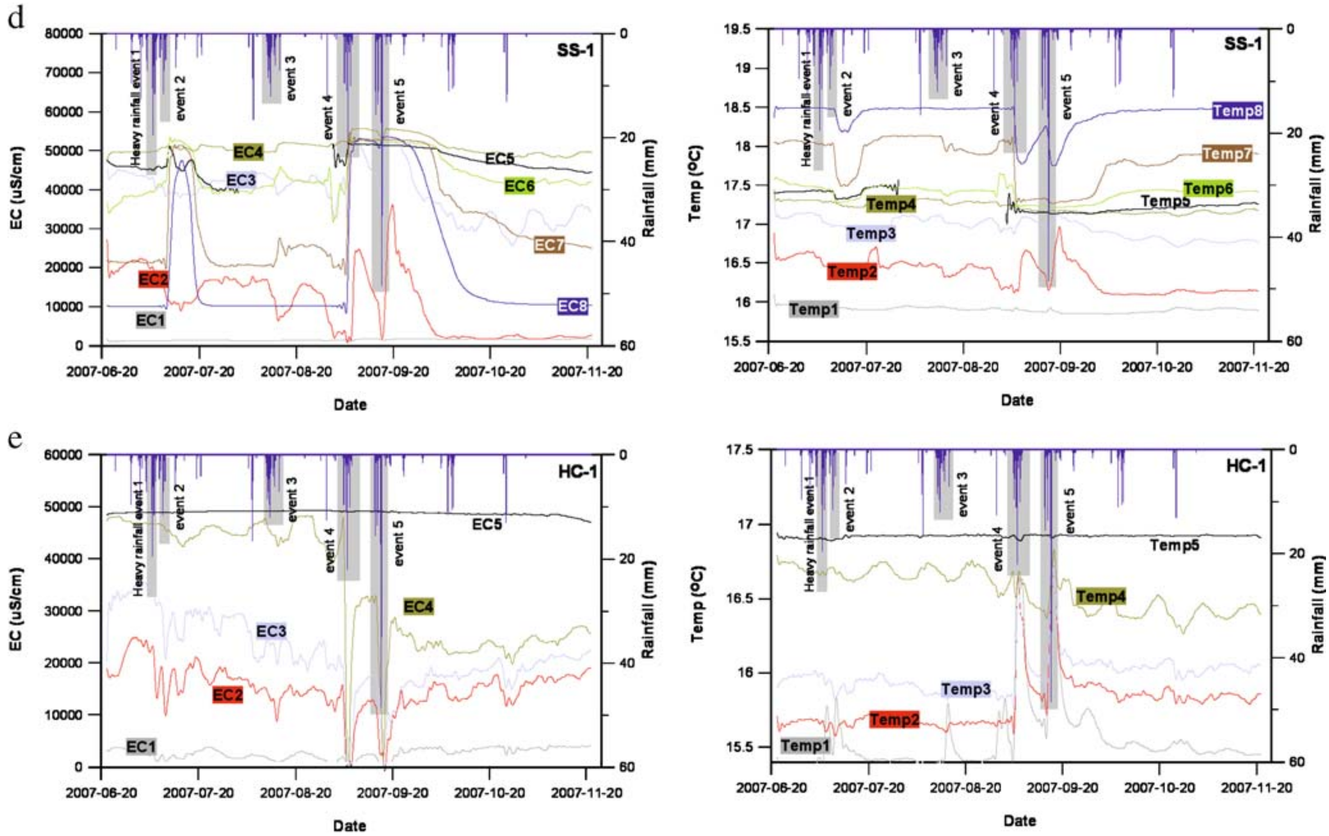


**Fig. 8** (continued)

depth where EC2, EC3 and EC4 were installed. This designates that the freshwater–saline water interface declined down to −40 m. This phenomenon also occurred after the fifth heavy rainfall event and lasted for 3 days. The lower three probes installed at depths of −60, −85, and −119 m did not show a significant change during the monitoring period. Temp4 probe, which was installed at −35 m, showed a variation of temperature due to heavy rainfall decreasing from 16.4 to 15.8°C. The rainfall effect on freshwater–saline water interaction reached down to a depth of about 45 m in this region.

It is interesting to note the effect of rainfall at SS-1. EC7 and EC8 installed at depths of −104 and −117 m read 20,000 and 10,000 µS/cm at ordinary times, but they increased up to 50,000 µS/cm after the heavy rainfall events. The second rainfall event caused this phenomenon which had lasted for 10 days, whereas the fourth and fifth rainfall events, which were heavier than the previous ones, caused an increase of EC for more than 1 month. The temperature from probes of Temp2 and Temp3 showed an increase while decrease in temperature was observed from Temp5 through Temp 8 after the heavy rainfall.

At HC-1 borehole, heavy rainfall events that occurred two times in September caused EC to decrease in the upper part of the aquifer. The data from probes of EC1 through EC4 were ~300 µS/cm, indicating the freshwater–saline water interface dropped to a depth of −55 m. However, the EC value at −65 m was not affected by tidal fluctuations or heavy rainfall events and maintained a value of 50,000 µS/cm. The figures observed at the upper four probes reveal that heavy rainfall caused an increase of temperature indicating a freshwater flow of relatively high temperature.

## Discussion

The groundwater level obtained from the monitoring wells at the study site is the average value from multi-aquifers, since the monitoring wells penetrate multi-layers and are fully screened. Although the monitoring wells were long-screened, and the water level does not present the hydraulic head of a specific depth, it provides valuable information. In general, the hydraulic head in the well which penetrates multi-aquifers primarily reflect the aquifer with the highest transmissivity (McIlvride and Rector 1988).

The water level obtained from HL-1, JD-1, SS-1, and HC-1 monitoring wells ranged from 0.5 to 1.5 m, while the water level at JC-1 showed a relatively higher level. Considering the short distance (~600 m) from the coast, the high water level designates a relatively high hydraulic gradient compared to other monitoring sites. Therefore, it is expected that more freshwater flows toward the sea, and this corresponds with the result of relatively low EC value (<7,000 µS/cm) at JC-1 monitoring well. As a consequence of the fourth and fifth rainfall events, the water

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level rose to 3 m asl and the EC value decreased to 200–300 μS/cm through the overall boreholes. It could be concluded that the toe of fresh-saline interface has recessed towards the coast.

The water level at HL-1 showed a similar height to other monitoring sites. However, the water level at this monitoring well was most sensitive to precipitation, rising to 5 m asl. This implies that the hydraulic diffusivity, the ratio of the transmissivity to the storativity, of the controlling aquifer at this site is small. The EC variation read from probes EC2–4 installed at HL-1 was not the consequence of tidal fluctuations, since the variation was extremely irregular and the change was made in a very short interval (less than 1 min) that did not follow the tidal period. The breadth of EC variation was around 5,000 μS/cm. Combining the time-series data of EC with the results of the EC profile, one could conclude that the saline water flows irregularly below −40 m, and the flow system is unstable in this zone. The results of filtering of EC presented an unusual phenomenon at a depth of −85 m, showing two peaks after the fifth rainfall event. This could be explained by a two-channel system that influences the flow and transport at this depth. The major channel system causes the EC to respond to recharge promptly, and the minor one affects the EC with some delay in time.

The EC profile of JD-1 indicates a freshwater zone above the interface and saline water below it, which is one of the typical features that generally appear in coastal aquifers. A stepwise feature appeared at the EC profiles between −15 and −30 m. The time-series data of EC reveal that the variations at these depths are due to the tidal forces. A wide range of EC variations with tide at these depths may be the result of high permeability layer.

At SS-1 borehole, two distinctive interfaces appeared, one at around −30 m and the other at around −80 m. These interfaces relates well with the geology of this borehole. The geology is mostly composed of acicular basalt and the sedimentary layer is interlayered between the lava flows; the location of the interface matches the sedimentary layer well. These sedimentary layers are assumed to take on the role of a confining layer and separate the hydraulic system into three zones in this coastal zone. These relationships between the EC variations and geology indicate the importance of geology in freshwater–saline water interactions in the coastal zone.

The time-series data of EC and temperature obtained from the muti-depth monitoring system were installed in a fully screened well which may have caused some biased results. Church and Granato (1996) reported a bias in groundwater data caused by well-bore flow in long screen wells. Although there may have been a bias between the aquifer and within the borehole due to a vertical flow, the degree of EC and temperature fluctuations at various depths has provided valuable information. The variation pattern, with or without following the tidal forces, provided some clues about the stable or unstable flow conditions, and a permeable zone. In addition, the dynamic EC and temperature variations caused by heavy rainfall provide information about how the flow systems behave with respect to external forces.

## Conclusions

This study elucidated some cases of dynamic variations of freshwater–saline water interactions at coastal aquifers. The geology of the subsurface system in the coastal zone of Jeju Island is composed of acicular basalts, hyaloclastites, and sandy/muddy sediments. The EC profiles revealed that the EC in the freshwater zone ranged from 200 to 1,000 μS/cm and that in the saline water zone ranged from 1,000 to 50,000 μS/cm, depending on the mixing ratio of freshwater and seawater. The temperature at the upper part of the aquifer ranged from 14.5 to 15.9°C, increasing with depth, whereas the lower part of the aquifer revealed 16.4 −18.6°C.

In order to obtain time-series data of groundwater level, EC and temperature at various depths of the coastal aquifers, a multi-depth monitoring system was set up. The EC and temperature varied mainly by two external forces, tidal fluctuation and rainfall. Most of the monitoring data followed the tidal variation, but the data obtained from well HL-1 showed irregular variation within 1 min, indicating an unstable flow system in the specific zone. The EC variation at some depths in the coastal aquifers was tens of thousands μS/cm due to tidal forces which complicated the interpretation of the effect of rainfall on freshwater and saline water interactions. The influence of heavy rainfall events on EC and temperature was analyzed by applying a digital filter. The low-pass filter enabled presentation of the EC and temperature variations affected by rainfall.

Five heavy rainfall events were observed during the monitoring period. In some cases, recharge strengthened the tidal effect on EC values. In some subsurface systems, there was a decrease of EC following rainfall, whereas in other systems, there was an increase of EC following rainfall. In view of the effect of rainfall on EC and temperature variations, the interactions between fresh and saline water were governed by different hydrological systems.

The time series data of EC and temperature at various depths enabled the interactions between freshwater and saline water in the coastal aquifers to be quantified. The multi-depth monitoring system turned out to be a powerful tool for examining a freshwater–saline water interaction process in a coastal zone. The mixing process of fresh and saline water varied dynamically depending upon tide, rainfall and the hydrogeologic properties of the subsurface layers.

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