Groundwater occurrence on Jeju Island, Korea

Jong-Ho Won · Jin-Yong Lee · Ji-Wook Kim · Gi-Won Koh

Abstract Jeju Island is a volcanic island composed predominantly of permeable basalts. The island is poor in surface water but abundant in groundwater. No actual perennial streams exist and the water resources on the island are dependent almost entirely on groundwater. The groundwater bodies on the island are classified into three general categories: high level, basal and parabasal groundwaters. The parabasal groundwater is further subdivided into lower and upper parabasal groundwaters due to the position of the Seogwipo Formation, which is made up of sedimentary rocks with a low permeability. The distribution of each groundwater type was evaluated through analyses of the spatial distribution of the Seogwipo Formation and the hydraulic gradient of the groundwater. Basal groundwater emerges extensively along the coast of the eastern sector, less commonly along the coast of the western sector. Parabasal groundwater occurs extensively over most of the island except for the southern sector, where it occurs only locally in the coastal area. This paper presents a summary of several studies on the occurrence and features of groundwater resources on Jeju Island, the largest island in Korea.

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Résumé L'île de Jéhuest une île volcanique, constituée en principal par des basaltes perméable. La ressource en eaux de surface est faible, mais l'île est riche en eaux souterraines. Comme il n'y a pas des cours d'eaux permanente, toute la ressource en eaux de l'île dépend des eaux souterraines. Les hydrosystèmes souterrains sont classifiés en trois catégories: des eaux souterraines de haute niveau, des eaux basales et parabasales. Compte tenu de leur position dans la formation de Seogwipo, constituée par des roches sédimentaires à faible perméabilité, les eaux parabasales sont subdivisées en des eaux de haut et respectivement de bas niveau. La distribution de chaque type d'eau a été évaluée en analysant leur distribution spatiale dans la formation de Seogwipo ainsi que les valeurs du gradient hydraulique. Les eaux basales se déchargent surtout au long de la partie est de la côte et dans une moindre mesure au long de côte ouest. Les eaux parabasales se trouvent en grande quantité sur toute la surface de l'île sauf la partie sud où elles se trouvent localement, au long de la côte. L'article présente une synthèse des études concernant l'occurrence et les caractéristiques de la ressource en eaux souterraine de l'île de Jéhu, la plus grande île de Korè.

Resumen La Isla Jeju es de origen volcánico y se compone de basaltos permeables principalmente. La isla es escasa en agua superficial, pero tiene abundante agua subterránea. No existen verdaderas corrientes perennes y los recursos de agua en la isla dependen casi en su totalidad del agua subterránea. Los cuerpos de agua subterránea en la isla son clasificados en tres categorías generales: De nivel alto, basales y parabasales. El agua subterránea parabasal se subdivide además en aguas subterráneas parabasales superiores e inferiores, debido a la posición de la Formación Seogwipo, la cual se compone de rocas sedimentarias de baja permeabilidad. La distribución de cada tipo de agua subterránea fue evaluada a través de un análisis de distribución espacial de la Formación Seogwipo y del gradiente hidráulico del agua subterránea. El agua subterránea basal aflora en un área extensa a lo largo de la costa oriental, y de manera menos frecuente a lo largo de la costa occidental. El agua subterránea parabasal se encuentra en amplias extensiones a lo largo de la isla, excepto por el

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sector sur, donde únicamente aparece de manera local en la costa. El presente artículo presenta un compendio de varios estudios sobre la existencia y características de los recursos de agua subterránea de la Isla Jeju, la más grande de Corea.

Keywords Jeju Island · Seogwipo Formation · High level groundwater · Basal groundwater · Parabasal groundwater · Korea

Introduction

Jeju Island, the largest island in Korea, is a volcanic island located about 140 km south of the Korean peninsula (mainland; Fig. 1a). The island came into existence seven hundred to twelve hundred thousand years ago when lava spewed from a sub-sea volcano and surfaced above the waters. Then one hundred to three hundred thousand years ago, another volcanic eruption occurred, which formed Mt. Halla (Fig. 1b). A final volcanic eruption took place approximately 25 thousand years ago that created crater lake, Baekrok-dam, at the summit of the mountain (Jeju Provincial Government 2004).

The island is one of the areas in Korea where the highest rainfall occurs. The annual mean rainfall of the island is 1,975 mm, which is 1.5 times as large as the mean value of 1,283 mm for the Korean mainland. Therefore, the extent of the water resources on Jeju Island appears large, but the island has suffered from a water shortage mainly because of the lack of large perennial rivers and streams, which dominate water supply on the mainland. Water on the island occurs mostly beneath the ground due to the island's unique geology. On the Korean mainland, the hydrogeology is mainly dominated by crystalline granitic and metamorphic rocks, which are relatively poor for groundwater yield but excellent for yielding surface runoff. The geology of Jeju Island, on the other hand, is composed predominantly of permeable basalts into which rain and stream waters easily percolate to accumulate and move slowly in accessible and exploitable aquifers, which result in a lack of perennial streams.

Developing a large quantity of water on Jeju Island requires some different approaches from those on the mainland. Some of the waters can be withdrawn from springs and streams only along the coast, so eventually most of them will have to be abstracted from the ground by means of drilled wells, collection galleries and other types of excavations. The successful exploitation and management of groundwater resources on the island is essentially dependent on the understanding of groundwater occurrence and movement dynamics.

Groundwater occurrence on Jeju Island was classified into three general categories: high level, basal and parabasal groundwaters (Mink 1981; KOWACO 1993; Won 1994; Hahn et al. 1997). KOWACO (Korea Water Resources Corporation) first delineated the boundaries among the three groundwater occurrence types. At that time, however, a large part of the delineations had to rely on various assumptions and estimations because of insufficient data.

The main purposes of this study are to evaluate the hydrogeologic features dominating groundwater flows and occurrence and to delineate the boundaries among the groundwater occurrence types more reliably based on reevaluation of the hydrogeologic information including the groundwater level monitoring data accumulated over the last decade since the first delineation.

Hydrogeologic environment of Jeju

Topography

Jeju is a shield volcano with a long axis striking east-northeast (Hahn et al. 1994). Several hundreds of secondary cinder cones disrupt the smooth flanks of the shield and numerous tuff cones are located near the coast. The island is 74 km wide and 32 km long with a total area of 1,828.3 km^2 and an elliptical shape (Koh 1997; see Fig. 1b). In the central part of the island, Mt. Halla rises to a peak of 1,950 m above sea level (Fig. 1c). The rest of the island slopes down relatively gently from its summit to the east and west and moderately to the north and south.

For convenient description and analysis efficiency, Jeju Island has been divided into four principal sectors and sixteen drainage basins based on hydrogeological and topographic conditions as shown in Table 1 and Fig. 1b. No truly perennial streams exist on the island unlike the southern Lihue Basin, Kauai, Hawaii (Izuka and Gingerich 2003). Only in the stormy season, do the waters flow in the streams. Steep and narrow stream valleys radiate from Mt. Halla but over most of the area in the east and west sectors, development of the drainage system is very weak while in the north and south sectors, it is only poorly to moderately developed.

Climate

Jeju Island has a mild oceanic climate throughout the year with the smallest annual temperature variation range in Korea. The mean annual temperature is 14.7°C but the lowest monthly average temperature is 5.1°C in January and the highest is 25.4°C in August. The annual mean rainfall on the whole island is 1,975 mm while it is 1,482 mm at the Jeju station in the north and 1,949 mm at the Seogwipo station in the south. As shown in the isohyetal map (Fig. 2a), however, local variations and orographic effects are so great that the annual rainfall in the southern area is about two times as large as that of the western area and in the mountainous area in the central region it is over two times as large as that of the coastal area (Lee et al. 1999).

Generally the higher the topographic elevation, the more rainfall occurs (Fig. 2b). As shown in the figure, rainfall shows an excellent linear positive correlation with the topographic elevation (r^2=0.85–0.94). The amount of rainfall per unit increase in topographic elevation is greater for the south and east sectors than that for the north and west sectors. Over about 60% of the annual rainfall occurs during the monsoon season from June to September, which is a weather characteristic of eastern Asia (Lee and Lee 2000).

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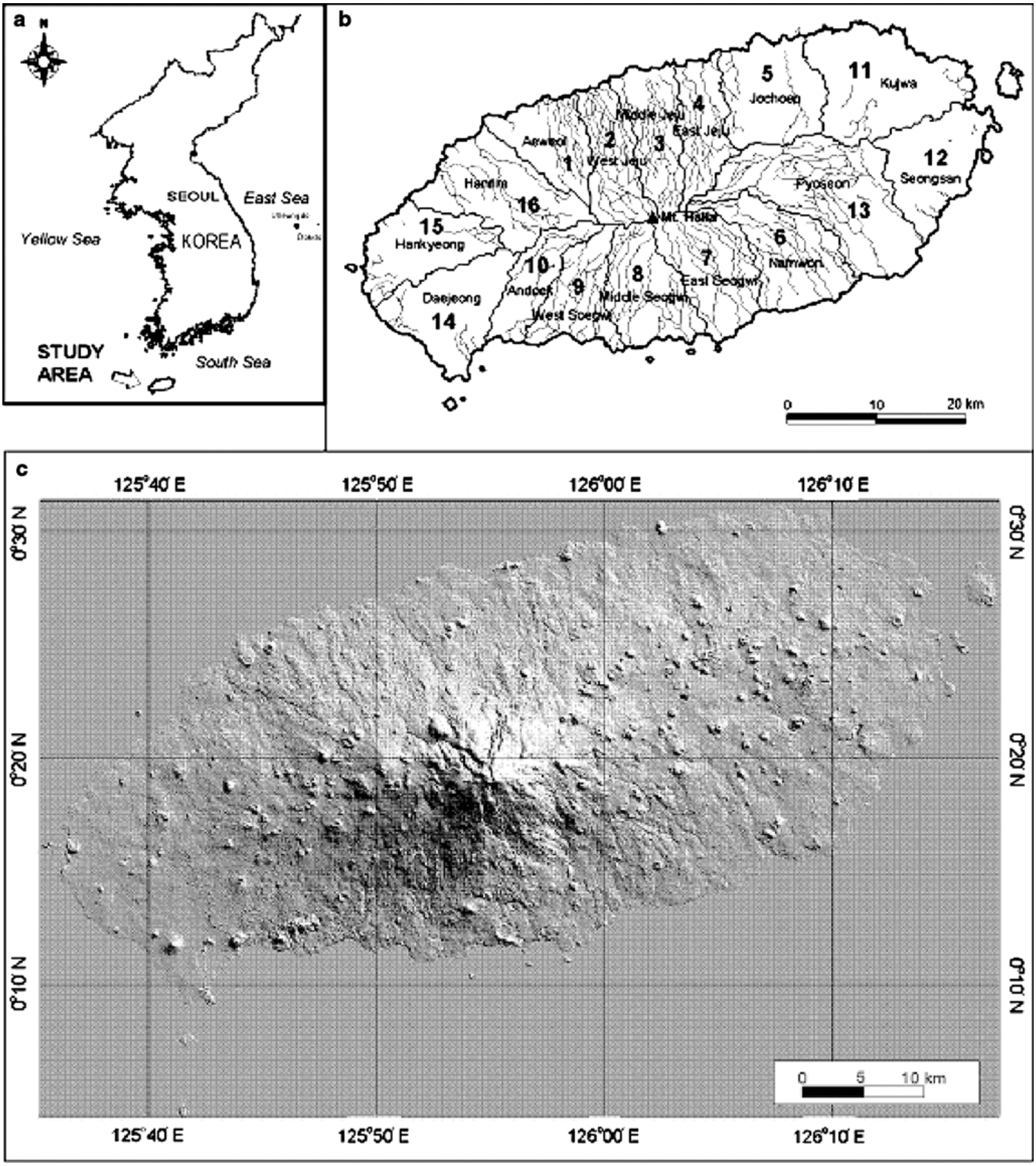

Fig. 1 **a** Location of the study area; **b** division of drainage basins showing streams. No perennial streams exist on Jeju Island. **c** Shadow relief of Jeju Island

Geology

As previously mentioned, Jeju Island is a shield volcano, presently lying on a circa 100 m deep continental shelf off the Korean Peninsula. The island is composed mainly of basaltic lava flows and a subordinate amount of pyroclastic and sedimentary rocks (Fig. 3). The lavas can be roughly divided into early plateau-stage and last shield-stage (Won 1976; Lee 1982; Park 1994). K-Ar age determination of several volcanic rocks showed that the island was formed from 1.20 to 0.025 Ma (Yun et al. 1986; Won et al. 1986). Historic eruptions have also been recorded. The island contains more than 360 pyroclastic cones. Most of them

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Table 1 Principal sectors and drainage basins, Jeju Island (after Jeju Provincial Government 2001)

Sector	Basin Name	No.	Area (km^2)	Drainage length (km)	Drainage density (km/km^2)
North	Subtotal		466.1	666.0	1.43[a]
	Aewol	1	85.3	89.2	1.05
	East Jeju	2	75.3	143.1	1.90
	Middle Jeju	3	89.8	158.3	1.76
	West Jeju	4	89.5	226.4	2.53
	Jocheon	5	126.2	49.0	0.39
South	Subtotal		492.2	719.8	1.46[a]
	Namweon	6	133.5	154.6	1.16
	East Seogwi	7	107.1	184.5	1.72
	Middle Seogwi	8	106.3	181.4	1.71
	West Seogwi	9	82.8	128.3	1.55
	Andeok	10	62.5	71.0	1.14
East	Subtotal		494.7	327.2	0.66[a]
	Kujwa	11	172.5	36.7	0.21
	Seongsan	12	114.9	14.6	0.13
	Pyoseon	13	207.3	275.9	1.33
West	Subtotal		375.3	194.1	0.52[a]
	Daejeong	14	130.8	33.3	0.25
	Hankyeong	15	102.8	46.2	0.45
	Hanrim	16	141.7	114.6	0.81
	Total		1,828.3	1,907.1	1.04[a]

[a]Areal average

are scoria cones and about 10 are tuff cones and rings. The former are largely concentrated in the inland area, whereas the latter are mostly distributed along the coastal regions.

The subsurface geology of Jeju Island has been interpreted by the study of rock fragments in basalts and drilled cores acquired during exploitations of hot springs and groundwater since the 1960s. Granite, tuff and sedimentary rocks are distributed in the subsurface of the island. The unconsolidated sediments called the "U" Formation sits on the basement of granite and welded tuff formed in the late Cretaceous to early Tertiary periods. The formation consists of gray to light gray sand and silt and is regarded as hyaloclastite formed by hydrovolcanism. Foraminifers of the formation indicate that the age is of late Pliocene (Park et al. 2000).

The Seogwipo Formation is stratigraphically located between the U Formation and the basalts (Yoon et al. 1994). The formation crops out only along a cliff wall near Seogwipo City and is present mostly in the subsurface and below present sea level (Yoon et al. 1995). The formation is exposed at only a few sites on the surface but it is widely distributed in the subsurface as identified by the stratigraphic correlation using deep borehole data (Koh 1997; Koh and Yoon 1997; Oh et al. 2000). The formation consists of gravelly sandstone, sandstone, sandy mudstone, mudstone and is characterized by abundant bioclastic shells (Koh and Yoon 1997). The formation also contains angular fragments of basalt, tuffaceous materials and various kinds of fossils. Based on calcareous nannofossils, the geologic age of the formation was estimated to be late Pliocene to middle Pleistocene (Yi et al. 1998). The formation was deposited in the foreshore to offshore environment (Yoon 1988; Kim and Heo 1995; Yi et al. 1998). The formation is classified into aquitards or aquicludes because of the relatively low permeability and is very important in interpreting the groundwater occurrences on Jeju Island (Won 1994; Hahn et al. 1994; Koh 1997; Koh and Yoon 1997).

Hydrogeology

Jeju Island is formed through multiple volcanic activities and mainly consists of volcanic rocks including very permeable basalts. The younger flows especially form high permeability groundwater storage space due to thin lava flows, which facilitate groundwater flow and storage. Factors enhancing permeability of lava flows include clinker layers accompanied by aa lava flows, interstices developed through interface between the lava flows, cooling points, lava tunnels in pahoehoe lavas, unconsolidated scoria, vesicular structures and cavities or interstices formed by collapse of lava tunnels.

Shrink or cooling joints are generally formed in a vertical direction and so vertical permeability of lavas is enhanced. A large number of vesicles are developed in basalts, which enlarge porosity but if they are not interconnected, they cannot provide a significant contribution to groundwater flow. In general, various sizes of interstices are developed in clinker layers, lava tubes and interfaces between lava flows, which are the main paths for groundwater flow. The porosity of clinker layers of aa lava is equivalent to that of well sorted gravel. The lava tubes and lava tunnels are

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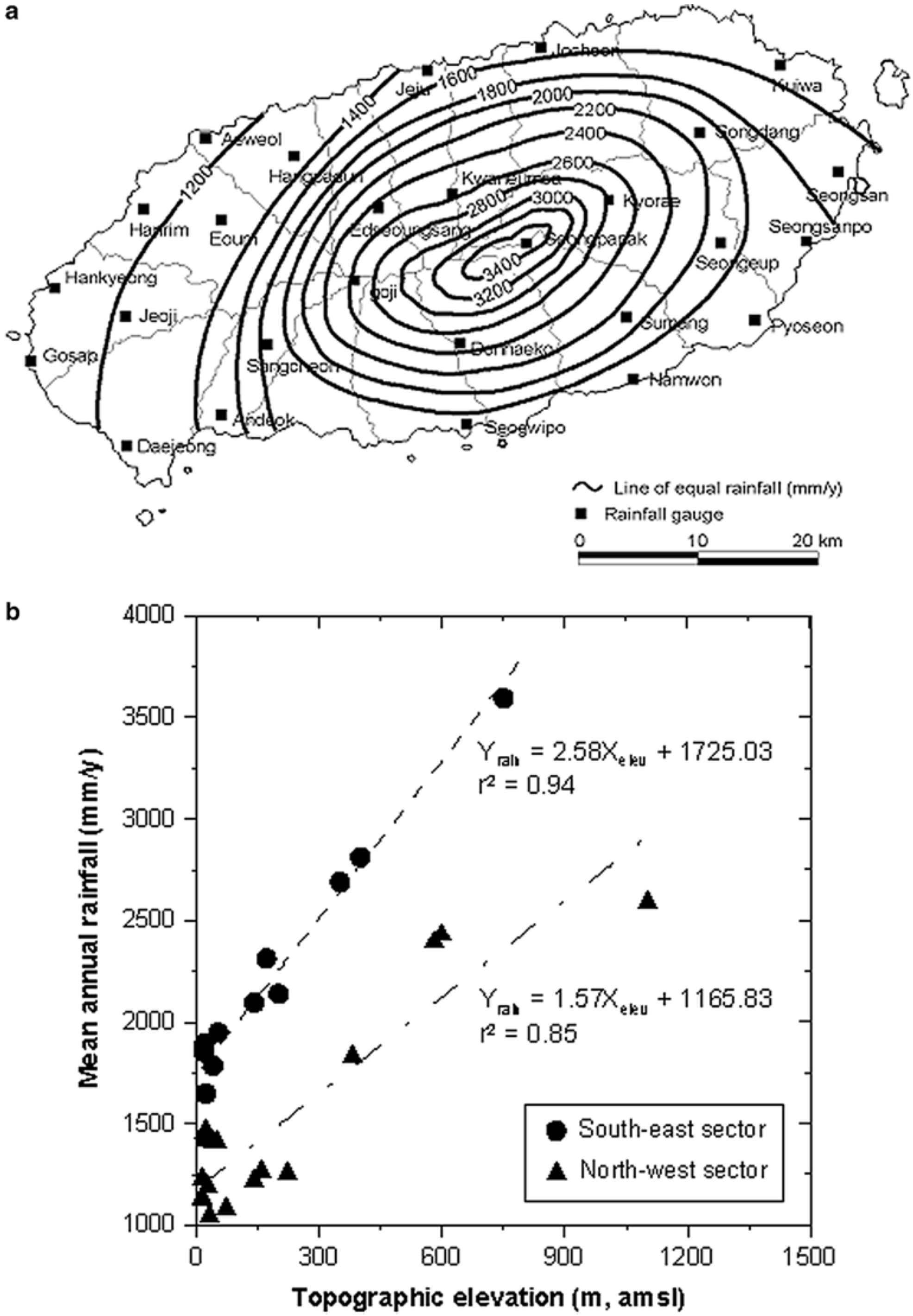

Fig. 2 Isohyetal map of Jeju Island (**a**) (after KOWACO 2003) and plot of mean annual rainfall versus topographic elevation (**b**)

generally developed in pahoehoe lavas, which are widely distributed on Jeju Island.

The volcanic rocks on Jeju Island are classified into basalt, trachybasalt, trachyte and trachyandesite. The trachytes were intruded at the early plateau-stage and late shield-stage (Lee 1982; Chang 1997). The geochemical studies showed that the volcanic rocks have characteristics of oceanic island basalt and the eruption is the hot-spot related to the mantle-plumes (Lee 1982; Park 1994). The most permeable volcanic rocks are the basalts. These formations grew as thin layers (usually less than 3 m thick) of massive to broken vesicular basalt with rubbly interflow breccia (also less than 3 m thick). The rubbly breccia, so called clinker, is often incorrectly reported as pyroclastic material because they are similar to each other. Average values of transmissivity and hydraulic conductivity of the formations were 6,904 m^2/day and 234 m/day, respectively (Table 2).

The andesitic-trachytic rocks are inferior to the basalts in permeability but nevertheless can make adequate aquifers.

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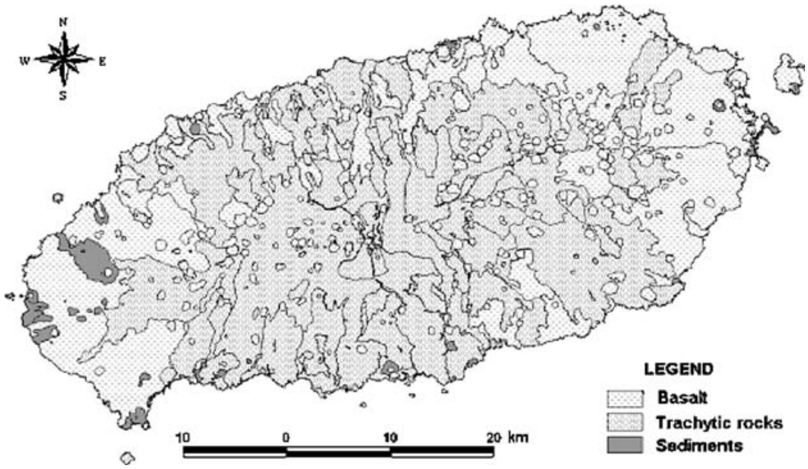

Fig. 3 Geologic map of the Jeju Island (after Jeju Provincial Government 2002)

Table 2 Summary of hydraulic properties of rock types

Rock type	Data	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)
Basalt	No. of data	482	243
	Mean	6,904.3	234.3
	Max	97,700.0	2,400.0
	Min	0.9	0.1
Andestic-trachytic rocks	No. of data	20	6
	Mean	4,369.1	124.9
	Max	54,000.0	685.0
	Min	1.1	0.2
Cinder cone and volcanic sediments	No. of data	18	8
	Mean	2,147.8	10.5
	Max	16,800.0	51.1
	Min	2.0	1.4

Time intervals between deposition of units of these formations were often long enough to allow weathered unconformities to evolve. Also pyroclastic activity frequently accompanied extrusion of the lavas, creating layers of ash and tuffs within the andesite-trachyte column. The most permeable part of the formations is the rubbly breccia between flows that followed one another without an erosional hiatus. Average values of transmissivity and hydraulic conductivity of the formations were 4,369 m^2/day and 125 m/day, respectively (see Table 2).

The pyroclastics of the tuff cones and the volcanic sediments derived from them are usually very poorly permeable. Average values of transmissivity and hydraulic conductivity of the formations were 2,148 m^2/day and

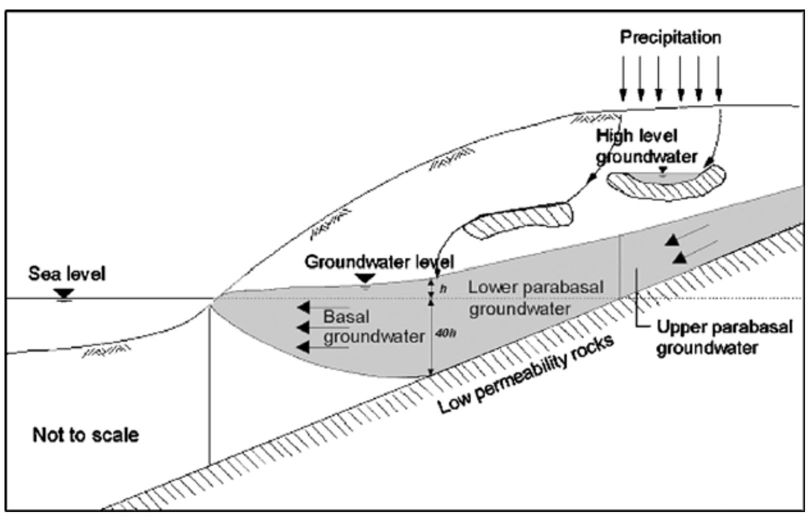

Fig. 4 A schematic showing the groundwater occurrences in Jeju Island

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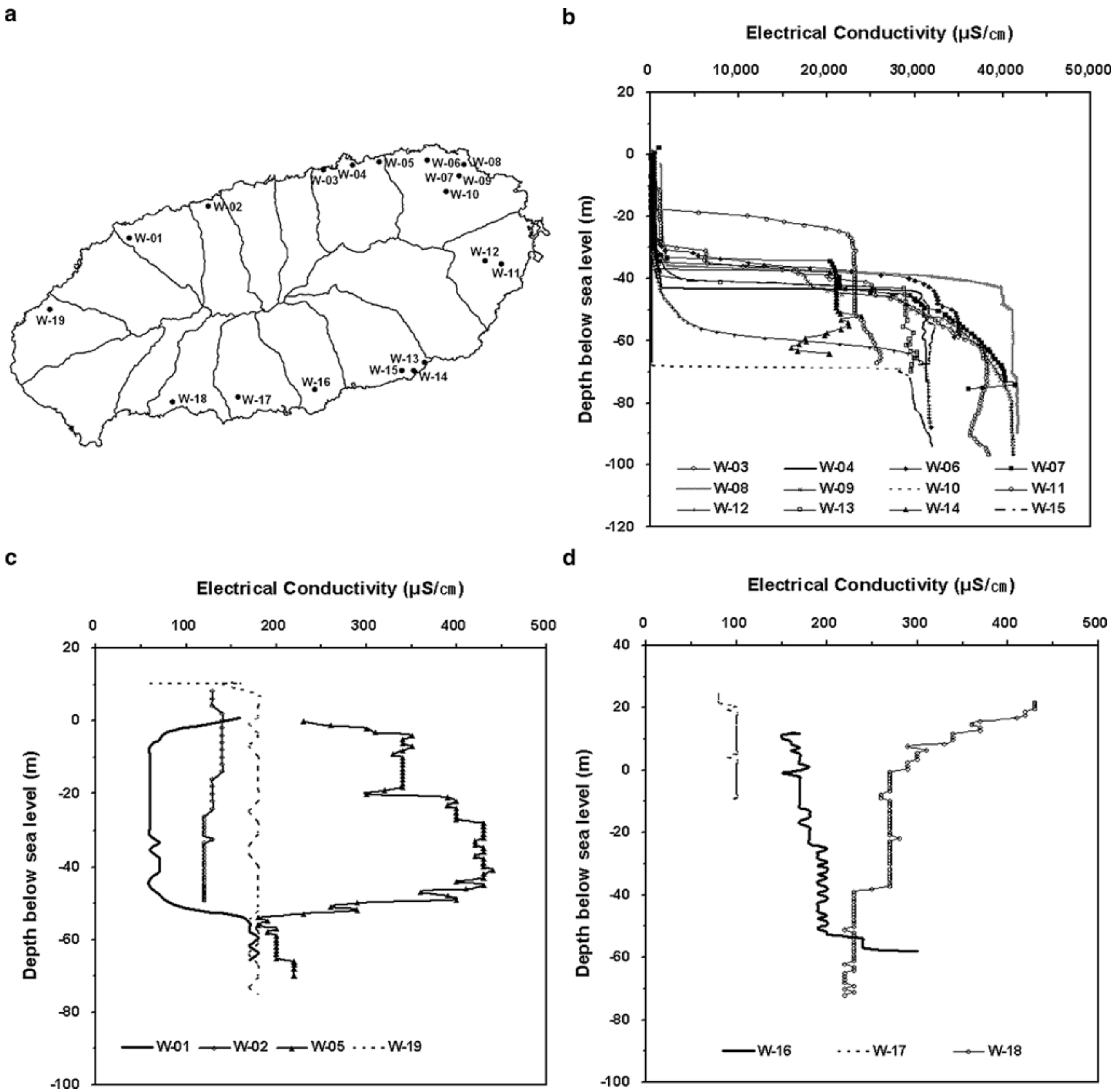

Fig. 5 Location of wells logged for EC (**a**), electrical conductivity logs of wells drilled in basal groundwater (**b**), parabasal groundwater (**c**) and high level groundwater (**d**)

10.5 m/day, respectively (see Table 2). Generally their existence is limited to the vicinity of the cones, but where widespread, such as the Seogwipo Formation, they may have a profound effect on groundwater movement. Scoria cones are extremely permeable but too limited in local area to be important hydrogeologically.

As previously described, the principal extensive aquifer of Jeju is the basalts. The large basal aquifer of the eastern sector occurs in the basalts and the most efficient and productive wells in the other sectors on the island have also been drilled into the basalts. The massive trachytes and Seogwipo Formation are classified into aquitards or aquicludes because of the relatively low permeability (Hahn et al. 1994; Koh and Yoon 1997; Kim et al. 2003).

According to hydrologic budget analyses (KOWACO 1993, 2003; Won 2004), the total amount of rainfall is $3{,}609\times10^6$ m^3/year, evapotranspiration is $1{,}216\times10^6$ m^3/year (33.7%) and direct runoff is 740×10^6 m^3/year (20.5%) in an ordinary year. Therefore, annual groundwater recharge is $1{,}653\times10^6$ m^3/year, which is 45.8% of the total amount of rainfall. Groundwater recharge ratio generally increases with the increase of the topographic elevation because groundwater recharge is affected by rainfall change with elevation, type of vegetation and land use. Stream runoff occurs only when

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rainfall exceeds 40–50 mm and duration of stream runoff is at most 2–3 days.

Groundwater occurrence

Types of groundwater occurrence

The groundwater bodies on the island are basically classified into three general categories: high level, basal and parabasal groundwaters (Fig. 4). Aquifers having no contact with seawater carry high level groundwater because they are normally perched and occur only at considerably high topographic elevations above sea level. The groundwater in aquifers in which fresh water is hydraulically connected to seawater is called basal groundwater when the entire aquifer below the fresh water portion is saturated with seawater, or parabasal groundwater when the lower boundary of the fresh water is not in direct contact with seawater and lies on impermeable or less permeable layers (Won 1994; Hahn et al. 1997). Parabasal groundwater can be subdivided into two types, lower parabasal groundwater and upper parabasal groundwater according to the elevations of the underlying impermeable layer called the Seogwipo Formation (Koh 1997). Figure 4 shows a schematic illustrating the groundwater occurrences in Jeju Island.

High level groundwater

High level groundwater is a perched groundwater not hydraulically interconnected with other aquifers (Koh 1997; Izuka and Gingerich 2003; KOWACO 2003; see Fig. 4). High level groundwater normally is not as voluminous as basal and parabasal groundwaters because ordinarily it is restricted to complicated geological areas in the island interiors (Stearns 1940; Macdonald et al. 1960; Oki 1998, 1999) whereas basal and parabasal aquifers are the subsurface reservoirs where practically all groundwater accumulates before seeping out along the coast and discharging into the sea. Nevertheless, high level groundwater is the most widely distributed form of groundwater on Jeju Island even though its volume may be less than those of the basal-parabasal water resources (Mink 1981; Won 1994).

High level groundwater emerges as springs in stream valleys in high elevations and from subsurface troughs near the shore. An appreciable amount of discharge to stream courses takes place near the southern and southwestern coasts and in the vicinity of Mt. Halla at the center of the island but practically no high level springs occur in the east. The most voluminous discharge occurs in the south.

Basal and parabasal groundwaters

The eastern and western sectors of Jeju are underlain by aquifers containing fresh water floating on saline water in approximately buoyant equilibrium (Mink 1981; Won 1994). When the fresh water is surrounded on all sides by seawater except for the atmospheric interface it is called "basal" groundwater (Meinzer 1930; Hufen et al. 1980; Koh 1997). But when it is continuous with saline water but the interface is truncated, it is called "parabasal" groundwater (NWWG 1998; Hahn et al. 1997; Koh 1997). While the lower boundary of a high level aquifer (groundwater) is fixed and beyond the reach of sea water intrusion, both the lower and upper boundaries in basal/parabasal groundwaters are in motion, making precise mathematical description of the system extremely difficult. Every contraction of a basal lens is accompanied by lateral and vertical seawater movement.

At steady state, fresh water resting on saline water reflects the simple law of buoyancy in which a lighter substance floats on a denser one. The buoyancy relationship between fresh and saline waters is referred to as the Ghyben-Herzberg relationship (Fetter 1988), which gives a good estimate of the thickness of a basal lens. For typical seawater conditions, 40 m of fresh water lie below sea level for every meter above sea level (Cabrera and Custodio 2004).

The Ghyben-Herzberg relationship (Custodio and Bruggeman 1987; Ward and Robinson 2000) assumes the existence of a sharp interface between the fresh and saline waters (Izuka and Gingerich 1998). The interface, however, is diffuse because of hydrodynamic dispersion induced by movement of the interface which result from tidal changes, seasonal difference in recharge rates and withdrawal of fresh water by mechanical means. The diffuse zone of brackish water between the fresh and saline waters is called the transition zone (Cooper et al. 1964; McWhorter and Sunada 1977; Todd 1980). Its thickness depends on the dynamics of flow in the fresh water portion of the lens; if the fresh groundwater velocity is high, the transition zone will be narrow.

The hydraulics of parabasal flow is the same as for basal groundwater with allowances made for the different boundary conditions. But its hydraulic gradient is slightly steeper and heads are higher than those of basal groundwater.

Interface between fresh and saline groundwaters

To compare the vertical distribution of groundwater salinity for each occurrence type and to evaluate the characteristics of the transition zone in basal groundwater, well logging of electrical conductivity (EC) was conducted in 2000–2002 (Jeju Provincial Government 2001, 2002). Figure 5a shows the location of investigated wells. Brief descriptions of the investigation results depending on the groundwater occurrences are as follows.

Basal groundwater

The electrical conductivity logs of 12 wells that penetrated a basal lens are shown in Fig. 5b. It shows a distinct tendency that the electrical conductivity of water increases with depth and shows clearly the location and thickness of the transition zone in each well. Values of the electrical conductivity ranged between 130 and 1,690 μS/cm to a depth of 20–60 m below sea level. These are within a typical EC range of fresh water (Hem 1992). However, below that depth, they drastically increased by up to factors of 40–351. At depths of 50 m for wells W-04, W-06, W-07, W-08,

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W-09, W-11 and W-12, electrical conductivities exceeded 30,000 μS/cm, which is within a range of ECs for a typical seawater in the neighboring coast of Korea (Lee et al. 2004).

Based on the EC logging data and assuming the measured water level is equal to the equilibrium head, the thickness of a basal lens and G-H ratio in the eastern sector of the island were estimated. As shown in Table 3, the thickness of a basal lens (average G-H ratio = 1:23) appears to be thinner than that of a theoretical fresh water lens (G-H ratio = 1:40). Furthermore, the transition zone in Jeju seems to be thin or narrow (see Fig. 5b). Therefore, flow velocity of the fresh water is expected to be high (Won 2004).

Parabasal and high level groundwaters

Vertical profiles of the logged ECs for wells drilled in parabasal and high level groundwaters are also presented in Fig. 5c and d. The parabasal groundwaters showed a narrow range of electrical conductivity between 60 and 430 μS/cm. Average coefficient of variation (CV) for them is 0.15 with a standard deviation of 0.19. In the parabasal groundwaters, no distinctive increasing trends with depth were observed unlike the basal groundwaters (see Fig. 5c). The electrical conductivities of the high level groundwaters ranged between 90 and 340 μS/cm. Also in this groundwater, there was no substantial increase of ECs with depth. Interestingly, electrical conductivity decreased with depth from 340 to 230 μS/cm at W-18 well (see Fig. 5d).

In general, electrical conductivities of parabasal and high level groundwaters are nearly constant only with a small variation independent of depth unlike the basal groundwater. Rather electrical conductivities in some wells decrease with depth.

Fluctuations of groundwater levels

A groundwater level indicates the position where the atmospheric pressure and the hydraulic head are at equilibrium in the aquifer. Any phenomenon that produces a change in pressure on groundwater will cause the groundwater level to vary. Differences between supply and withdrawal of groundwater cause levels to fluctuate. In general, stream flow variations are also closely related to groundwater levels. Other various natural and artificial factors including meteorological, tidal phenomena, urbanization, earthquakes and external loads influence groundwater levels (Todd 1980). Jeju Province established a groundwater monitoring plan and has carried out continuous monitoring of groundwater levels since 1991. In this section, major causes and regional characteristics of groundwater level fluctuation in the island is discussed based on the monitoring data during the last four years (1997–2001).

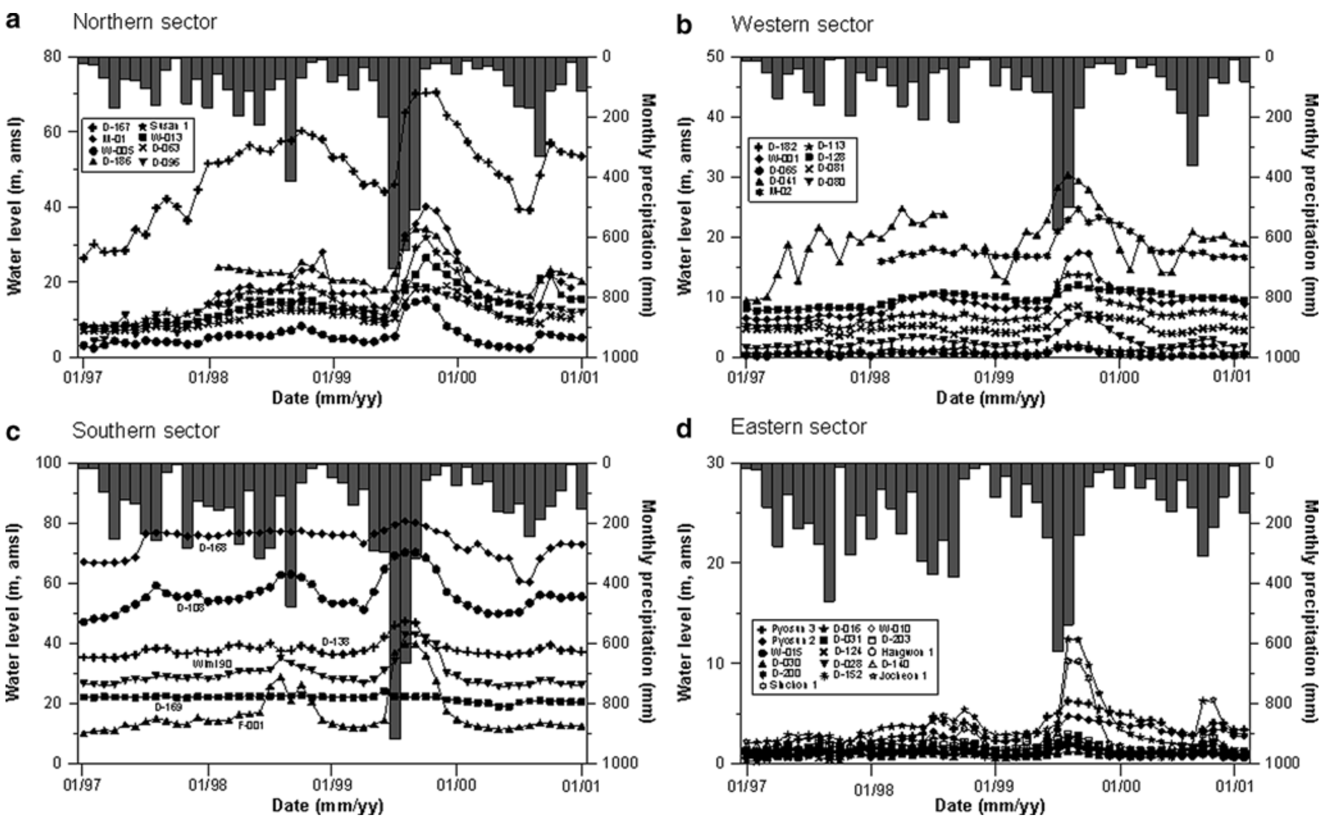

Fig. 6 Fluctuations of water levels at some selected wells and monthly precipitation in each sector

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Table 3 Thickness of the fresh water lens and G-H ratio in the eastern sector of Jeju Island

Well name	Surface elevation (m)	Water level (m, amsl)	Thickness of fresh water lens (m)		G-H ratio
			Theoretical	Measured	
W-06	45.37	0.99	39.6	36.6	1:37
W-07	45.08	3.94	157.6	38.3	1:10
W-08	15.12	1.57	62.8	38.3	1:24
W-09	42.37	1.90	76.0	37.8	1:20
W-10	112.47	2.71	108.4	70.7	1:26
W-11	71.62	2.23	89.2	38.5	1:17
W-12	115.16	2.17	86.8	61.5	1:28

The variations in monthly average water levels and monthly precipitation in each sector are shown in Fig. 6 (see Fig. 9a for the locations of selected observation wells in this discussion). As shown in the figures, the groundwater levels of all four sectors show a seasonal pattern of fluctuation. This mainly results from the effects of rainfall (Lee and Lee 2000). Highest levels of groundwaters normally occur throughout the island during September to October at the end of the monsoon season and lowest during February to March. As previously described, over 60% of the precipitation occurs in the summer season (June and August). A lag of 1 month is observed between high groundwater levels and peak precipitation.

The groundwater levels and amplitude of fluctuation in each sector, however, are different to one another depending on the type of groundwater occurrence. The lowest

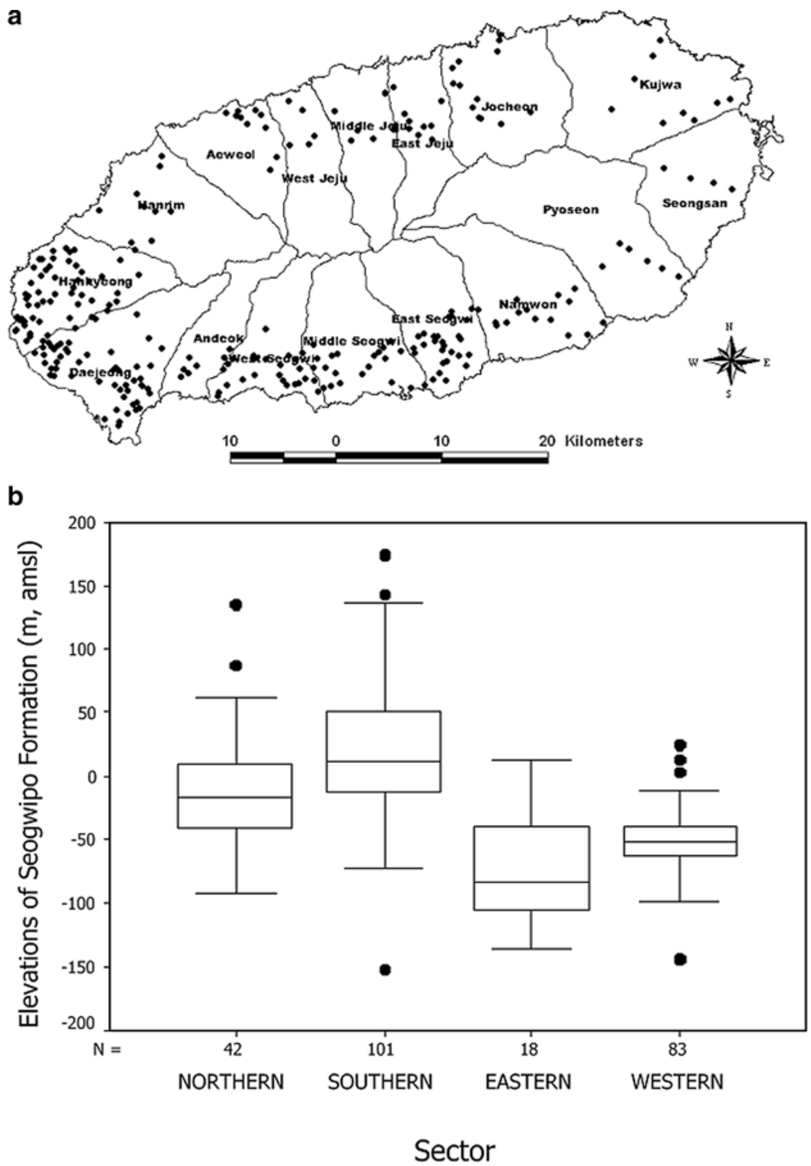

Fig. 7 Location of the wells with geological logs of the Seogwipo Formation (**a**) and box plot of the elevations where the formation occurs (**b**)

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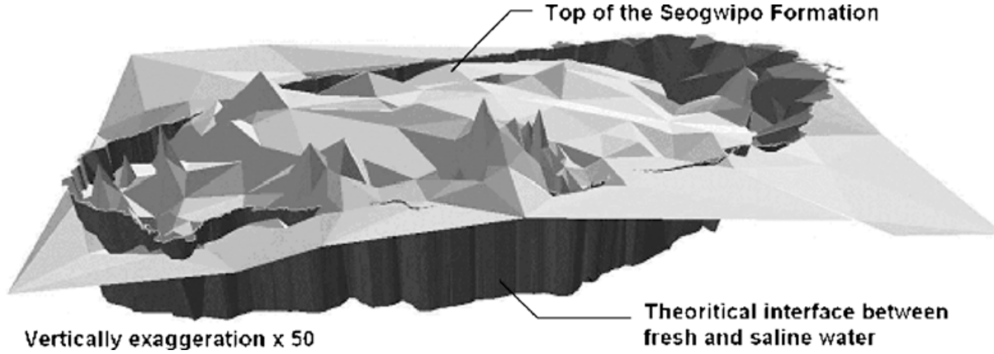

Fig. 8 Three-dimensional view of the distribution of the Seogwipo Formation

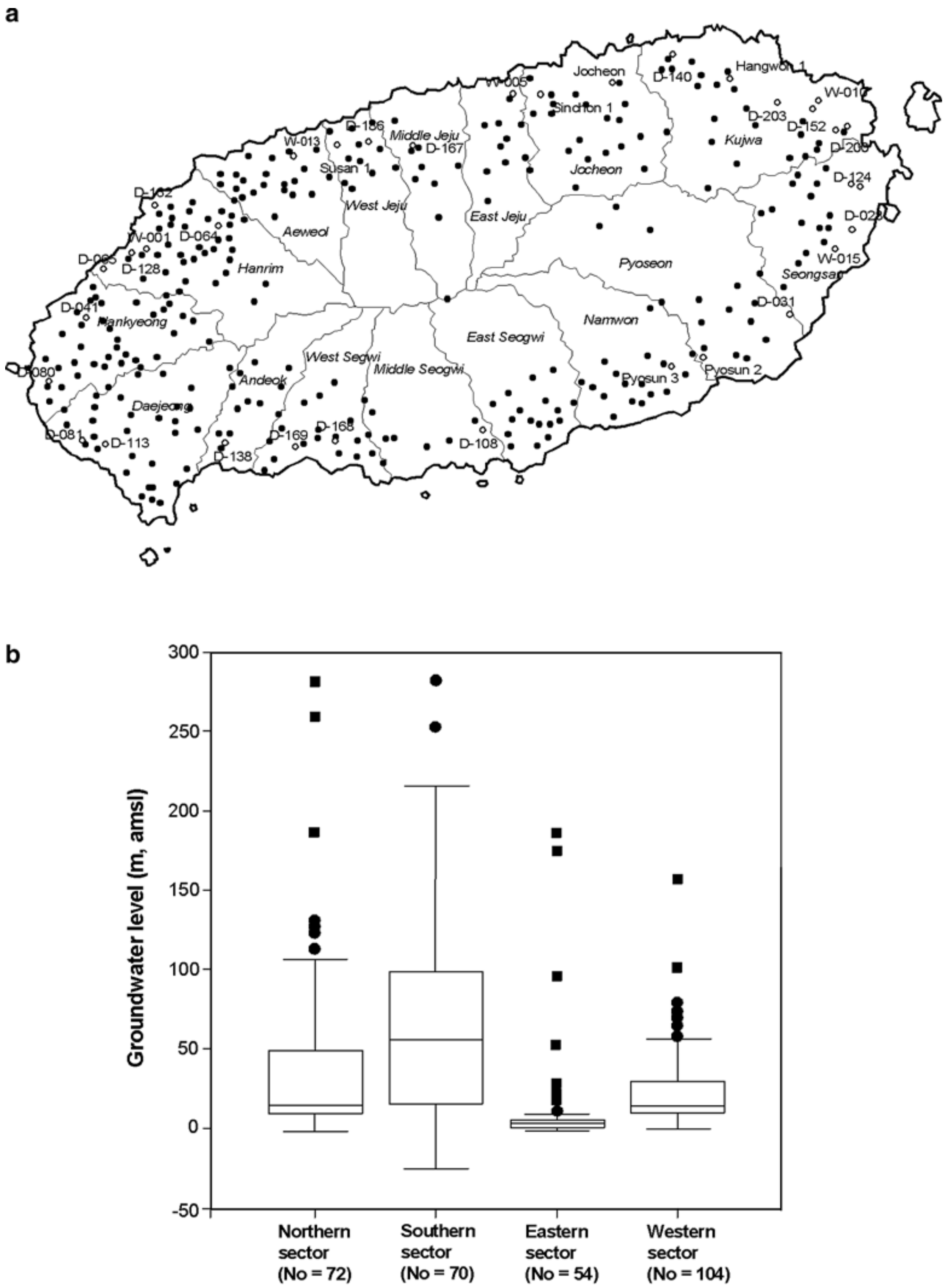

Fig. 9 Location of the wells for measuring water levels (**a**) and box plot of the groundwater levels (**b**)

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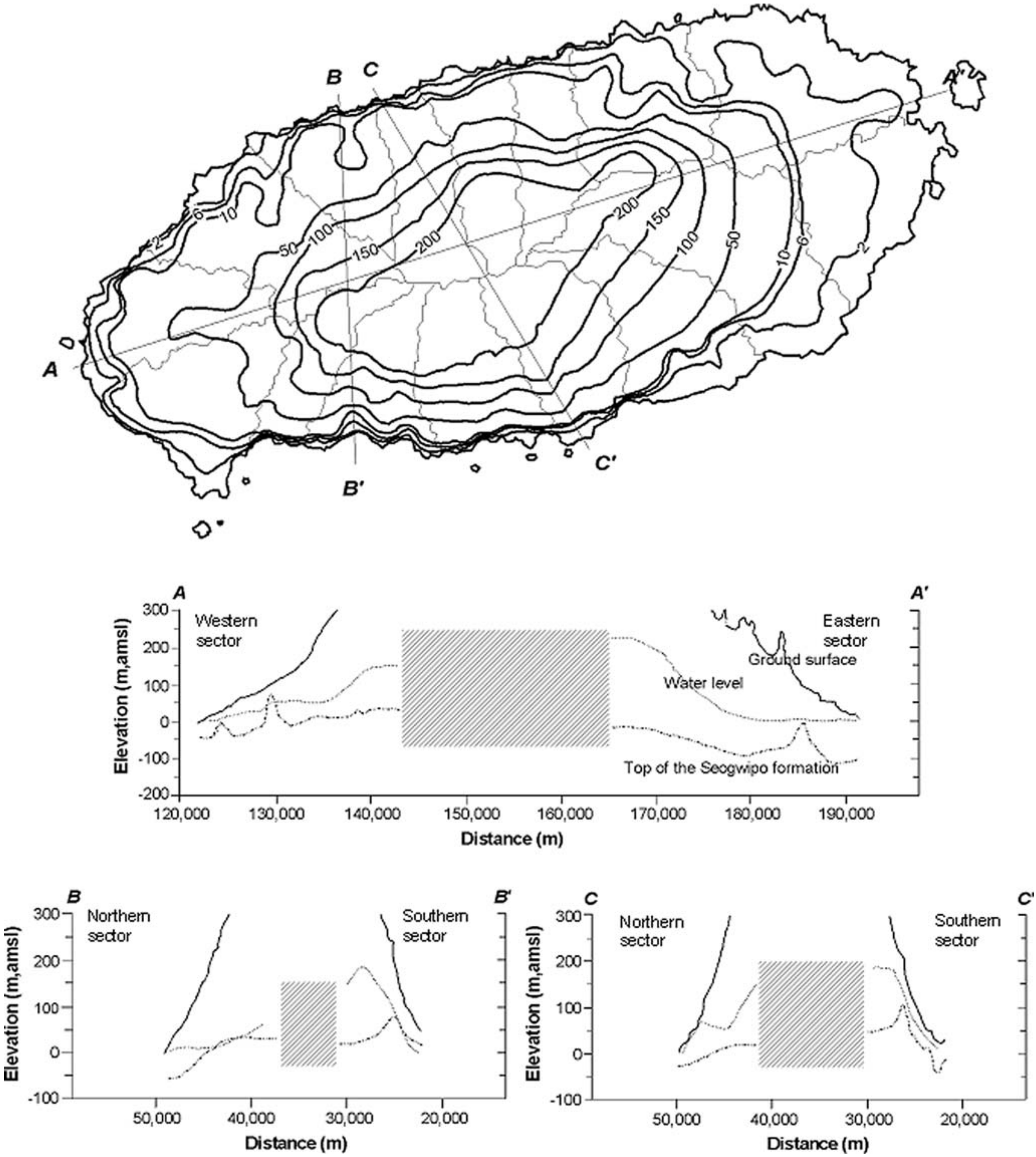

Fig. 10 Water-table map (*top*) and relationship among ground surface, water level and top of the Seogwipo Formation

groundwater levels and smallest fluctuation amplitude occur in the eastern sector where a basal lens is widely distributed. On the contrary, except for D-167 in the northern sector, the highest groundwater levels and largest fluctuation amplitude occur in the southern sector where high level groundwater is mainly distributed. The amplitude of the groundwater level fluctuation is related to the subsurface location of the poorly permeable Seogwipo Formation. When the formation is located at shallow depth, the thickness of the aquifer is smaller, which results in a reduction of aquifer transmissivity. Generally, the groundwater level fluctuates most in the area where the transmissivity is reduced compared with the surrounding areas. In the northern and western sectors where parabasal groundwaters are

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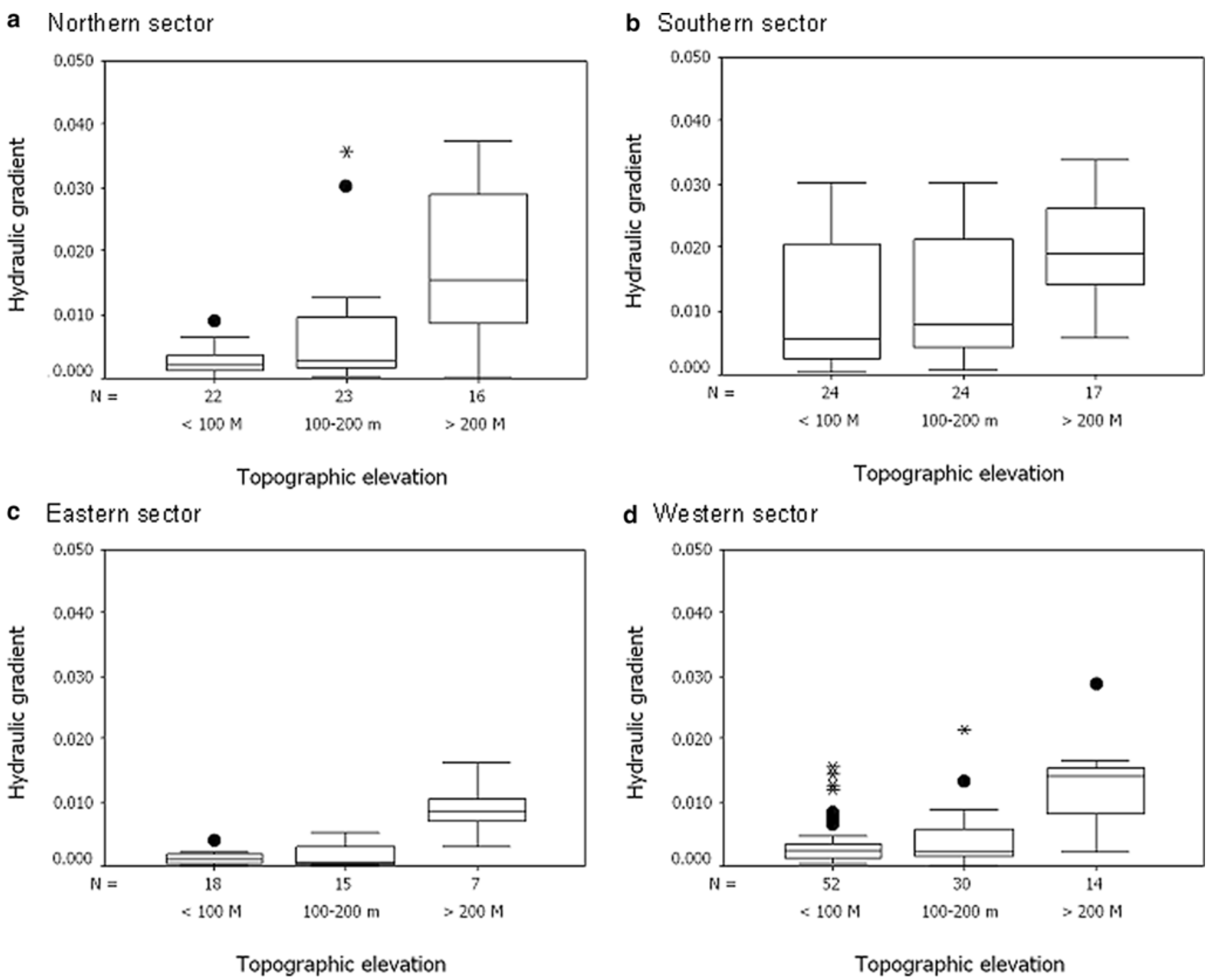

Fig. 11 Box plots showing statistical analysis results for hydraulic gradients in each sector

mainly distributed, groundwater levels and fluctuation amplitude are somewhat higher and larger than those of the eastern sector, respectively.

Distribution of groundwater occurrence types

Relationship between Seogwipo Formation and groundwater levels

There is a positive correlation between the groundwater level and the depth of the subsurface distribution of the Seogwipo Formation (Koh 1997; Koh and Yoon 1997). Consequently, the types of groundwater occurrences on Jeju Island are largely controlled by the spatial distribution of the Seogwipo Formation that is a relatively impermeable layer (Hahn et al. 1994; Koh 1997; Koh and Yoon 1997; KOWACO 2003). Also, hydraulic gradients of groundwater vary according to groundwater occurrence type (Izuka and Gingerich 1998; Cruz and Silva 2001). Therefore, the boundaries among the groundwater occurrence types were delineated based on the distribution of the Seogwipo Formation, and the hydraulic gradients of groundwaters.

To analyze the spatial distribution of the Seogwipo Formation, 244 geological well logs reaching or penetrating the formation were examined (Fig. 7a). The Seogwipo Formation occurs widely over the island at elevations between −152 m to 175 m below or above mean sea level (Fig. 7b). As shown in Fig. 7b, the Seogwipo Formation occurs at high altitude in the southern and northern sectors while in the eastern sector it occurs mostly below mean sea level. The three-dimensional view of the distribution of the Seogwipo Formation also supports this interpretation (Fig. 8).

Water levels of 300 groundwater wells were measured during 20th August to 27th September 2002 (Fig. 9). Groundwater levels on the island are located in the range between −26 and 282 m below or above mean sea level. In general, groundwater levels in the northern and southern sectors are higher than those in the eastern and western sectors, which is the same trend for the elevations of the Seogwipo Formation. But the groundwater levels in the northern and southern sectors show a wider range compared to those

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in the eastern and western sectors. Medians of the groundwater levels are 12.61, 56.25, 3.13, and 11.35 m for the northern, southern, eastern, and western sectors, respectively. As expected, the more the distance from the coast, the higher the groundwater level (see Fig. 6).

Figure 10 shows a water-table map based on the water level data measured in 2002 and a relationship among ground surface, water level and top of the Seogwipo Formation. The groundwater body of the island shows a relatively high level and steep hydraulic gradient in the southern and northern sectors while a low groundwater level and highly gentle hydraulic gradient is seen in the eastern sector. In the southern sector, intermediate groundwater levels and hydraulic gradient are shown. Water levels are also highly positive and linearly correlate with the topographic elevations. Furthermore, highly positive linear correlations between the groundwater levels and the top of the Seogwipo Formation were observed, especially in the southern and northern sectors (r^2=0.83−0.95; Koh and Yoon 1997).

Delineation of groundwater occurrence type distribution

The inland boundary of basal groundwater is delineated based on the spatial distribution of the Seogwipo Formation and the hydraulic gradient. For analysis of the hydraulic gradient, a water level contour map was first produced and then hydraulic gradients were analyzed using the ARC/Info program (ESRI, Inc.). Based on the analyzed hydraulic gradient (Fig. 11), a changing trend in the gradi-

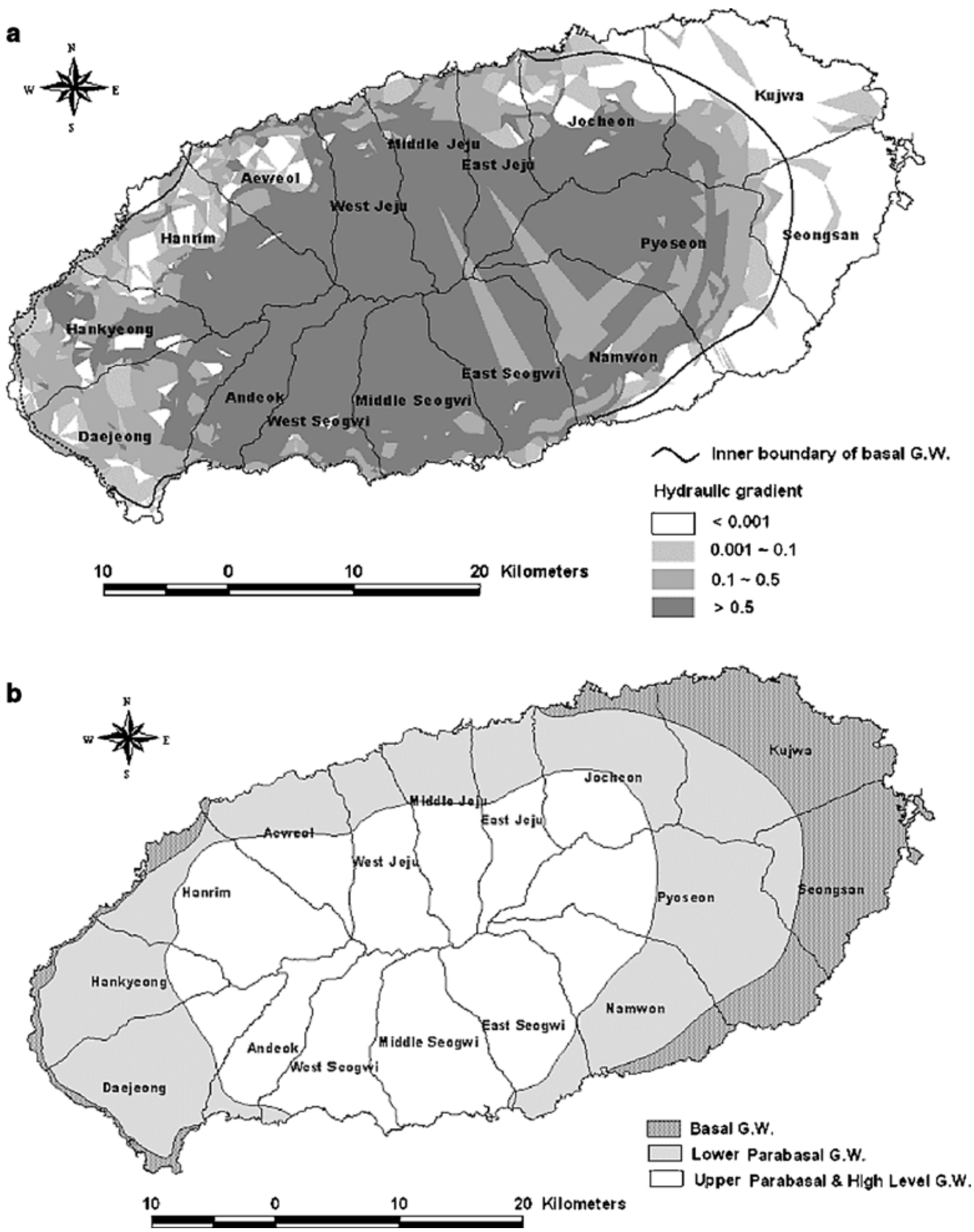

Fig. 12 Maps showing distribution of hydraulic gradient and the inland boundary of basal groundwater (**a**) and delineated groundwater occurrence boundary on Jeju Island (**b**)

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ents was identified and inflection points were extracted for 22 lateral lines using the profile algorithm in the Arc View. In the coastal area of the eastern sector, the size of unit TIN (Triangulated Irregular Networks) was large because the amount of groundwater level monitoring data was relatively small and the hydraulic gradients sharply changed at 0.001 mainly due to the effects of the Seogwipo Formation.

The basal groundwater has gentle hydraulic gradients (e.g., Izuka and Gingerich 1998; Cruz and Silva 2001) because it forms mainly due to a difference in physical characteristics (i.e., density) compared with seawater while parabasal groundwater, which is located above the low permeability rocks, the Seogwipo Formation, has relatively steep hydraulic gradients following the formation slope (see Fig. 4). Therefore, points of sudden or substantial changes in the hydraulic gradients may be regarded as the boundary between the parabasal and the basal groundwaters. Furthermore, the boundary between upper and lower parabasal groundwaters is delineated by connecting the points where the elevation of the Seogwipo Formation is equal to mean sea level (see also Fig. 4).

Figure 12 shows the distribution of the hydraulic gradient and inland boundary or extent of the basal groundwater and the map showing the ground occurrences on Jeju Island. As shown in the figure, the hydraulic gradients are high over 0.1 inland while the values are low in coastal regions. Especially in the eastern sector, the hydraulic gradient is relatively very low (<0.001). As also shown in the figure, the basal groundwater emerges extensively along the coast of the eastern sector but narrowly along the coast of the western sector. The lower parabasal groundwater appears extensively over most of the island except for the southern sector where it occurs very locally in the coastal area.

Conclusions

This study evaluated occurrence and features of groundwater resources in Jeju Island. The island has been dependent almost solely on groundwater for water supply. The groundwater bodies on Jeju Island are classified into three types: high level, basal and parabasal groundwaters. In this study, the distribution of each groundwater occurrence type was examined based on the spatial distribution of the Seogwipo Formation, groundwater levels and hydraulic gradients. It shows that the basal groundwater emerges extensively along the coast of the eastern sector and narrowly along the coast of the western sector while the parabasal groundwater appears extensively over the island except for the southern sector. However, the boundaries of basal and parabasal groundwater in the eastern sector are somewhat obscure owing to the lack of data for the distribution of the Seogwipo Formation. To delineate the boundaries among groundwater occurrence types more precisely, further investigation for the distribution of the Seogwipo Formation in the eastern sector of the island is essential.

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