

Determining the seasonality of groundwater recharge using water isotopes: a case study from the upper North Han River basin, Korea

Kwang-Sik Lee · Yongje Kim

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Abstract The stable isotopes of oxygen and hydrogen were used to determine the seasonal contributions of precipitation to groundwater recharge at a forested catchment area in the upper North Han River basin, Korea. A comparison of the stable isotopic signatures of groundwater and precipitation indicates that the precipitations which occurred during both the dry and rainy seasons are the important source of groundwater recharge in this region. A stable isotopic signature shown in the stream waters at the upstream reaches is similar to that of groundwaters, indicating that stream waters are mostly fed by groundwater discharge. Reservoir waters in the downstream flood control dams have lower deuterium excess values or *d*-values compared with those of the upstream waters, indicating a secondary evaporative enrichment. These results can provide a basis for the effective management of groundwater and stream water resources in the North Han River basin.

Keywords Groundwater recharge · Water isotopes · Precipitation · Stream water · North Han River basin

K.-S. Lee (✉)
Environmental Tracer Team,
Korea Basic Science Institute,
Eoeun-dong 52, Yusung-gu,
Daejeon 305-333, South Korea
e-mail: kslee@kbsi.re.kr

Y. Kim
Korea Institute of Geoscience and Mineral Resources,
Daejeon 305-350, South Korea

Introduction

Environmental isotopes and chemical tracers have been routinely used as valuable tools for investigating recharge processes and groundwater flow mechanisms in hydrologic systems. Specially, oxygen (^{18}O) and hydrogen (^2H) isotopes of waters are ideal conservative tracers of water sources because they are parts of the water molecule itself. The water isotopes are, therefore, widely used to trace hydrologic cycles and to constrain water budget in various terrestrial environments (Clark and Fritz 1997).

Determining the seasonality of groundwater recharge in any region is important for effective management of groundwater resources. Comparison of the oxygen and hydrogen isotopic compositions of precipitation and groundwater provides an excellent tool for evaluating recharge mechanism and for estimating the amount of recharge in tropical and temperate regions where the strong seasonal bias in the isotopic composition of precipitation is observed (Clark and Fritz 1997; Jones et al. 2000; Jones and Banner 2003).

According to previous studies in many temperate regions (Wenner et al. 1991; Clark and Fritz 1997; Dennis et al. 1997; Winograd et al. 1998), the recharge rates appear to be the highest during early spring when snow starts to melt, the soils are saturated, and vegetations are dormant. However, the recharge is minimal during summer when most of the short duration and high-intensity rainfall is lost through direct surface runoff and/or is returned to the atmosphere because of high temperatures and high-transpiration rates (Clark and Fritz 1997).

Several recent studies documented that the precipitation in Northeast Asia showed a distinct seasonal

variation in deuterium excess values or *d*-values, originally defined by Dansgaard (1964) with higher values in winter ($d > 15\text{‰}$) and lower values in summer ($d < 10\text{‰}$) (Araguás-Araguás et al. 1998; Lee and Lee 1999; Taniguchi et al. 2000; Asano et al. 2002; Lee et al. 2003). Such a distinct stable isotopic signal can potentially provide a means for evaluating the relative contribution of rainy- and dry-season precipitations to groundwater recharge in Northeast Asia.

Lee et al. (1999) applied the oxygen and hydrogen isotope technique to groundwater systems of a volcanic island in South Korea for evaluating the contribution of seasonal precipitation to groundwater recharge. They found that the precipitation over the whole year on the island contributed to groundwater recharge in proportion to the precipitation amount, which is unlike many temperate climates (Wenner et al. 1991; Clark and Fritz 1997; Dennis et al. 1997; Winograd et al. 1998), and they attributed this finding to the peculiar hydrogeological characteristics of the volcanic island, which facilitate rapid infiltration of precipitation into the ground.

To further examine such seasonality of groundwater recharge in other parts of the Korean Peninsula where the hydrogeological settings are different with the Jeju volcanic island, the stable isotopic studies of groundwater and stream water were carried out in a forested catchment area in the upper reaches of the North Han River basin, Korea.

The study area

The Korean Peninsula is located in the northeastern part of the East Asian continent, between 33 and 43°N latitude and 124 and 132°E longitude (Fig. 1a). About 70% of the peninsula is mountainous with these regions concentrated mainly to the north and east. The south and west parts of the peninsula contain most of the arable plain.

The Korean Peninsula has a temperate climate with four distinct seasons: hot and humid summer; cold and dry winter; and mild and pleasant spring and fall. Air masses reaching the peninsula vary substantially with seasons. In winter, winds commonly originate in the north–northwest with air-mass characteristics, reflecting northern continental conditions. In contrast, winds commonly come from south–southeast during the summer with air-mass characteristics, reflecting North Pacific maritime conditions (Kwon 1985).

This study was conducted along the upper reaches of the North Han River (Fig. 1b). The river originates at altitudes of more than 1,300 m above the sea level in the Taebaek Mountains, which run subparallel to the eastern coast of South Korea. The river flows E, traversing

the mid-western parts of the Korean Peninsula before reaching the Yellow Sea. The Taebaek Mountains separate South Korea into two geographic regions: east and west. The mountains fall steeply to the eastern coasts, but descend gradually into broad coastal plains along the western coasts of the peninsula (Fig. 1a). The geology of the study area consists mainly of Precambrian granitic gneisses and Jurassic granites (Chough et al. 2000). Soils are poorly developed because of steep topography of mountainous regions in the study area.

Monthly average temperatures recorded over a 30-year period from 1971 to 2000 in Chuncheon show a typical cyclic variation between -4.5°C in January and 24.5°C in August with an annual mean temperature of 15.5°C (Korea Meteorological Administration, www.kma.go.kr). The 30-year annual precipitation amount is 1,267 mm. High temperature and humidity from the northern Pacific air masses usually results in a monsoonal rainy season lasting from June to September. This period accounts for about 71% of the total precipitation.

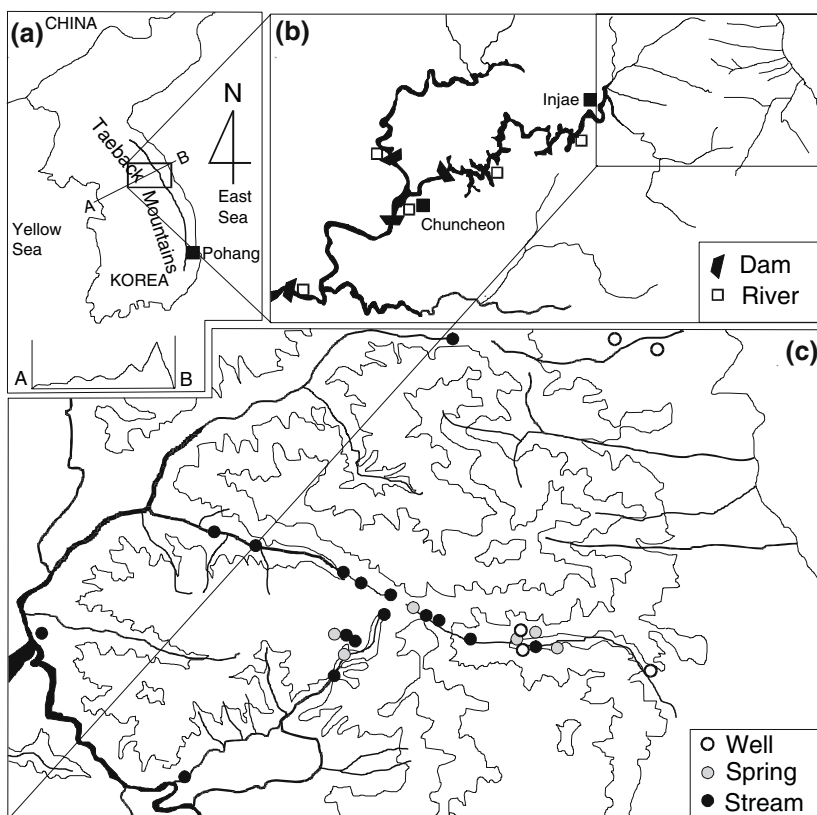
The North Han River is fed by both precipitation and groundwater discharge throughout the year. During the summer monsoon (June through September), surface run-off from local precipitation dominates the river discharge. During the rest of the year, however, water discharge to rivers is mainly sustained by the effluent seepage of groundwater. There are several flood control dams on the river, which can affect the flow of the river considerably (Fig. 1b).

During winter (November through February), the study area receives ~80% of its precipitation in the form of snow because of low-air temperature. Usually, snow begins to accumulate in November and continues through March. Thus, the mountainous regions of the study area are commonly covered by snowpack during winter. The snowpack begins to melt in early spring and the river discharge is considerably increased in spring season (river discharge data from Han River Flood Control Office, website: www.hrfco.or.kr).

Sampling and analytical methods

Water samples from streams, rivers, springs, and wells were collected for oxygen and hydrogen isotopic analyses between June 1999 and February 2000. The sampling was carried out during both wet and dry periods. The sampling locations are shown in Fig. 1b. Each water sample for rainfalls and snows was collected in Injae. River waters were taken from the reservoir surface of four flood control dams in the North Han River: Cheongpyeong, Euam, Chuncheon, and Soyanggang dams (Fig. 1b). Of these, the Soyanggang

Fig. 1 Maps showing the Korean Peninsula (a), the dams and sampling locations of reservoir waters (b),³ and drainage, topography and sampling locations of the North Han River basin (c)



dam is the largest in size with a total reservoir capacity of about 3 billion m³.

The water samples for oxygen isotopic analyses were prepared by conventional H₂O–CO₂ equilibration (Epstein and Mayeda 1953). About 2 ml of each water sample was equilibrated with CO₂ gas at 25 ± 0.1°C. The CO₂ gas was then extracted and cryogenically purified in a vacuum line. For deuterium analysis, metallic zinc was used to produce hydrogen gas (Coleman et al. 1982).

The oxygen and hydrogen isotopic compositions of the samples were determined with a VG Prism II stable isotope ratio mass spectrometer at Korea Basic Science Institute. The analytical reproducibility is ±0.1‰ for δ¹⁸O and ±1‰ for δD. All oxygen and hydrogen isotopic analyses are reported in the conventional δ-notation relative to the V-SMOW standard in which δ = (R/R_{V-SMOW} - 1) 1,000 and R and R_{V-SMOW} represent either the ¹⁸O/¹⁶O or the D/H ratio of the sample and standard, respectively.

Results and discussion

Stable isotopic composition of precipitation

The oxygen and hydrogen isotopic compositions of precipitation provide important information on

atmospheric circulation and climate change (Yurtsever and Gat 1981). In particular, the deuterium excess value (or *d*-value), originally defined by Dansgaard (1964) as equal to $d = \delta D - 8\delta^{18}O$, is generally regarded as the most useful parameter for characterizing the vapor origin of water (Gat and Carmi 1970). The low *d*-values of precipitation reflect slow evaporation at its source region due to high humidity, whereas the high *d*-values reflect fast evaporation at its source region due to low humidity (Clark and Fritz 1997).

When discussing the oxygen and hydrogen isotopic data of precipitation, it is important to identify the mechanisms that govern the final isotopic compositions. Generally, the stable isotopic compositions of precipitation decrease with decreasing temperature (the so-called temperature effect) and with increasing rainfall amount (the so-called amount effect). The temperature effect is generally pronounced at the precipitation of high-latitude continental regions, whereas the amount effect is pronounced at the precipitation of tropical regions (Yurtsever and Gat 1981).

Based on the oxygen and hydrogen isotopic data of precipitation published to date in South Korea (Kim and Nakai 1988; IAEA 1992; Lee and Chang 1994; Lee and Lee 1999; Lee et al. 2003), the most isotopically depleted precipitation occurs during the summer rainy season, which produces an amount effect. Such an

amount effect is clearly shown in Fig. 2 in which the oxygen isotopic compositions of summer precipitation, obtained from the Pohang IAEA/WMO station in South Korea during the period 1961–1976, show a negative relation with monthly average precipitation amount. Winter precipitation, however, is isotopically enriched, which is the opposite of the temperature effect found worldwide (Fig. 2; Dansgaard 1964).

Figure 2a reveals that $\delta^{18}\text{O}$ values of precipitation in South Korea do not show the temperature effect.

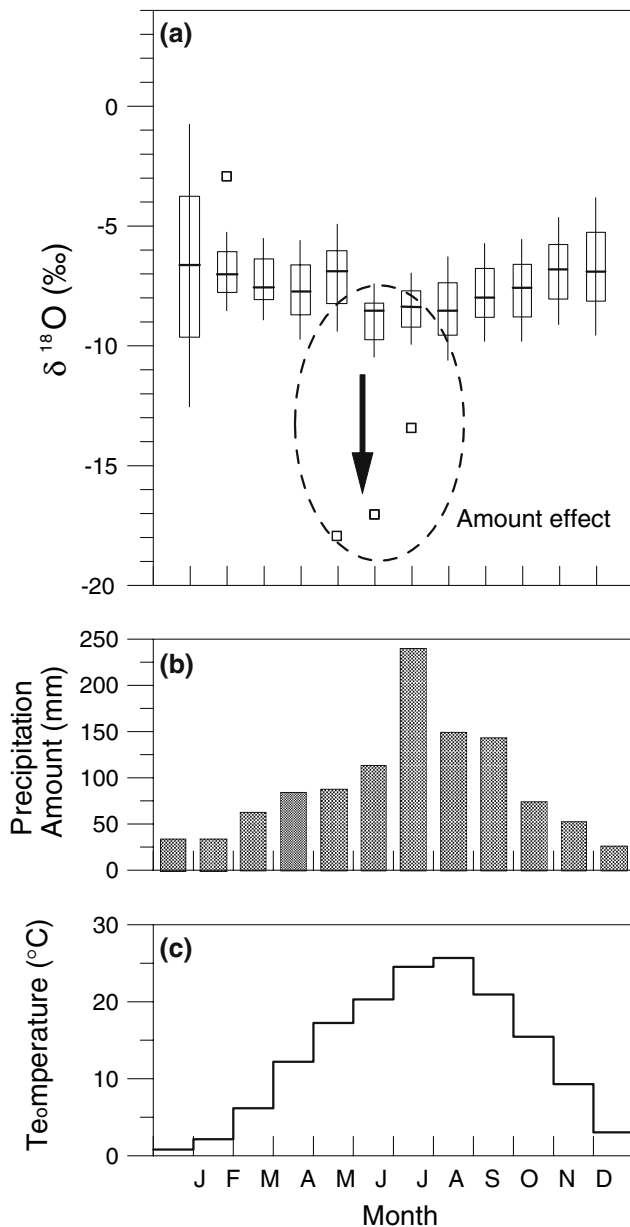


Fig. 2 Box and whisker plot of $\delta^{18}\text{O}$ values (a), precipitation amount (b), and monthly average air temperature (c) obtained from the IAEA/WMO Pohang station, which was operated from 1961 to 1976

However, according to Lee et al. (2003), the deuterium excess values ($d = \delta\text{D} - 8\delta^{18}\text{O}$) show a distinct seasonal variation in South Korea: low d -value in summer (mean of $\sim +10\text{‰}$) and high d -value in winter (mean of $\sim +20\text{‰}$). Such a seasonal variation in d -values appears to be closely related to the difference in air masses affecting the Korean Peninsula during different seasons: cold, dry continental Siberian air masses in winter and hot, humid maritime North Pacific air masses in summer. The water samples obtained from winter precipitation (mostly snow samples) in the study area show the most enriched isotopic compositions (Fig. 3). The isotopic enrichment of winter precipitation could reflect the modification of isotopic composition of Siberian air masses during air–sea interaction over the relatively warm the Yellow Sea and the East Sea (Waseda and Nakai 1983; Lee et al. 2003). This is the reason that the winter precipitations are more enriched than the summer rains from the North Pacific, which would be more isotopically evolved due to a longer trajectory and more rainout at sea.

Thus, based on the isotope data of precipitation in South Korea (Kim and Nakai 1988; Lee and Chang 1994; Lee and Lee 1999; Lee et al. 2003) along with data obtained from this study, two different regression lines can be obtained for the different seasons: $\delta\text{D} = (7.93 \pm 0.25)\delta^{18}\text{O} + (8.11 \pm 1.89)$, ($r^2 = 0.987$,

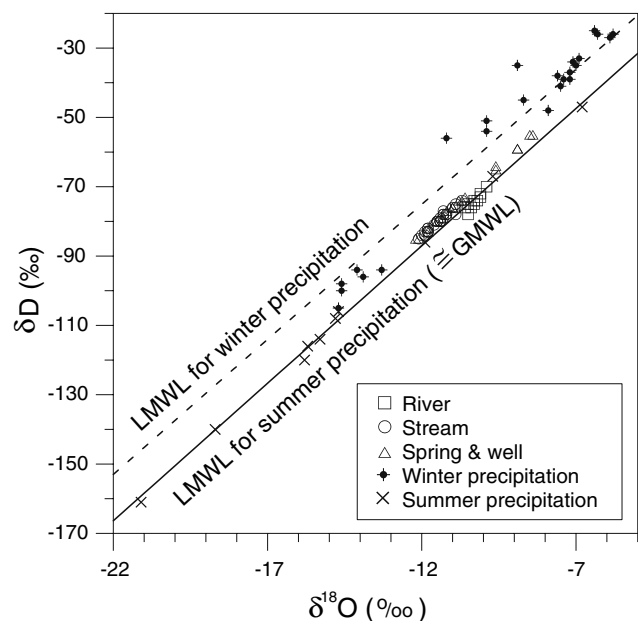


Fig. 3 Plot of δD versus $\delta^{18}\text{O}$ for several types of water samples collected for the study. GMWL and LMWL represent the global meteoric water line of Craig (1961) and the local meteoric water line, respectively. Groundwaters plot between LMWLs for winter and summer precipitations, indicating the contribution of both season precipitations to groundwater recharge

$n = 124$) for summer precipitation (June through September) and $\delta D = (7.79 \pm 0.37)\delta^{18}O + (18.39 \pm 2.65)$, ($r^2 = 0.925$, $n = 175$) for winter precipitation (November through February) (Fig. 3). Most of the spring and fall precipitation samples plot between these two lines (Lee et al. 2003). Both the slope and the y -intercept of the summer precipitation regression are virtually identical to those of the global meteoric water line (GMWL) of Craig (1961). In the case of winter precipitation, the slope is nearly the same as that of the GMWL, but the y -intercept of 18.39 is much higher than that of the GMWL of 10 (Fig. 3).

Such distinct isotopic characteristics of precipitation in South Korea could, therefore, be effectively used in quantifying the seasonal contributions of precipitation to groundwater recharge and in investigating groundwater recharge mechanism through the unsaturated zones.

Stable isotopic compositions of groundwaters and its implications on seasonal groundwater recharge

The stable isotopic compositions of groundwater samples collected from wells and springs are presented in Table 1. The oxygen and hydrogen isotopic compositions of groundwaters range from -12.2 to -8.4‰ and from -85 to -55‰ , respectively. These data are within the range of the isotopic compositions of precipitation sampled during the study period. They also plot between the LMWLs of summer and winter precipitations (Fig. 3), indicating that they were recharged during both seasons. There was little difference in isotopic values of groundwaters between wet and dry seasons.

As shown in Fig. 3, all groundwater samples typically plot to the left of the LMWL of summer rains, indicating that the recharge waters infiltrate after precipitation or melting without significant loss by evaporation. A regression line drawn through all these data except for one sample St-1 collected in summer (because this sample was weakly affected by surface evaporation) is: $\delta D = 8.06\delta^{18}O + 12.87$ ($n = 21$, $r^2 = 0.998$), which is subparallel to both the summer and winter LMWLs. The displacement of the isotopic composition of groundwater toward the winter LMWL can be determined from the d -values listed in Table 1. The d -values of groundwater range from $+11.4$ to $+13.0\text{‰}$ with a mean of $+12.2 (\pm 0.5)\text{‰}$, which is slightly displaced toward the LMWL for summer precipitation (Fig. 3). Considering that the sampling covers both wet and dry periods, the d -values of groundwaters are nearly constant. Such a remarkable temporal stability of d -values indicates that the groundwater storage is

significantly large and well mixed, and the groundwater age is relatively old in the study area.

The weighted average d -value collected from the Pohang IAEA/WMO station, which was operated from 1963 to 1976, is $+7.3\text{‰}$ ($n = 37$) for summer rains, and is $+17.3\text{‰}$ ($n = 33$) for winter precipitation. By using these endmember d -values, the relative contributions of rainy and dry season precipitations to the groundwater recharge in the upper part of the North Han River basin were calculated by a mass-balance equation: $d_{\text{groundwater}} = Xd_{\text{rainy season}} + (1-X)d_{\text{dry season}}$, where X and $(1-X)$ are the fraction of rainy season and dry season precipitations, respectively.

Based on their d -values, the groundwaters consist of $\sim 49\%$ dry season precipitation and 51% rainy season precipitation, representing the similar importance of both seasons as a source of groundwater recharge in the study area. This result could be confirmed by the absence of a discernible altitude effect in spring waters that are recharged from precipitation (Fig. 4). Considering that an altitude effect is not generally observed in snow (Cunningham et al. 1998; Winograd et al. 1998), if snow is the major source of recharge in any region, then spring waters of the region will not show a good altitude effect. This implies that the recharge season is volumetrically more important than the recharge altitude in determining the isotopic composition of groundwater in the study area.

Similar observations were made in many other temperate regions (Wenner et al. 1991; Clark and Fritz 1997; Dennis et al. 1997; Winograd et al. 1998). According to these studies, the recharge rates appear to be the highest during early spring when snow starts to melt, the soils are saturated, and vegetation is dormant. This implies that the contribution of precipitation to groundwater recharge is strongly dependent upon the hydrogeological characteristics of the study area, including bedrock geology, soil cover, soil thickness, climate, and vegetation.

Stable isotopic composition of stream and river waters

Water samples were collected from different parts of the upstream tributaries of the North Han River (Fig. 1b, c) and their isotopic data are presented in Table 1. The oxygen and hydrogen isotopic compositions of streams range from -12.1 to -10.7‰ and from -85 to -74‰ , respectively. A regression line drawn through these data is: $\delta D = 8.06\delta^{18}O + 11.81$ ($n = 26$, $r^2 = 0.968$), which is almost identical to that for groundwater. This close correspondence of the two regressions may suggest that the streams in the

Table 1 Oxygen and hydrogen isotopic compositions of water samples collected for this study

Sample number	Altitude (m)	June 1999			February 2000		
		$\delta^{18}\text{O}$	δD	d^a	$\delta^{18}\text{O}$	δD	d^a
Rivers							
R-1	20	-10.3	-75	7.4	-10.1	-73	7.8
R-2	40	-10.5	-78	6.0	-10.6	-76	8.8
R-3	60	-10.5	-75	9.0	-10.4	-76	7.2
R-4	90	-10.2	-74	7.6	-9.9	-70	9.2
R-5	160	-10.1	-72	8.8	-10.3	-74	8.4
Streams							
St-1	180	-10.9	-78	9.2	-11.2	-78	11.6
St-2	350	-11.8	-83	11.4	-11.5	-80	12.0
St-3	480	-11.8	-83	11.4	-11.4	-80	11.2
St-4	720	-11.9	-84	11.2			
St-5	810	-12.0	-84	12.0	-11.6	-81	11.8
St-6	910	-12.1	-85	11.8	-11.9	-83	12.2
St-7	660	-11.8	-83	11.4			
St-8	580	-11.4	-80	11.2			
St-9	860	-11.8	-82	12.4			
St-10	450	-11.2	-78	11.6	-10.7	-74	11.6
St-11	620	-11.3	-79	11.4	-11.3	-77	13.4
St-12	600	-11.8	-82	12.4	-11.4	-80	11.2
St-13	400	-11.5	-80	12.0	-10.9	-76	11.2
St-14	370	-11.3	-78	12.4	-11.4	-79	12.2
St-16	250	-11.3	-78	12.4	-10.9	-75	12.2
St-17	540	-11.0	-76	12.0			
Springs							
Sp-1	620	-11.0	-76	12.0	-11.5	-80	12.0
Sp-2	380	-11.8	-83	11.4	-11.6	-80	12.8
Sp-4	450	-10.6	-73	11.8			
Sp-6	380	-11.2	-77	12.6	-11.3	-79	11.4
Sp-8	390	-10.8	-74	12.4	-10.7	-74	11.6
Sp-9	680	-11.6	-80	12.8	-11.8	-82	12.4
Wells							
W-1		-9.6	-65	11.8	-9.6	-64	12.8
W-2		-8.9	-59	12.2	-8.9	-59	12.2
W-3		-8.4	-55	12.2	-8.5	-55	13.0
W-5		-11.1	-76	12.8	-11.0	-76	12.0
W-6		-12.2	-85	12.6	-12.1	-85	11.8

^a $d = \delta\text{D} - 8\delta^{18}\text{O}$
(Dansgaard 1964)

upstream area are mainly sustained by the groundwater discharge. This can be partly verified by the fact that the spring waters have the same average d -values as the groundwaters. However, this does not prove that the groundwaters are recharging the streams, as the reverse could be the case. Therefore, additional studies such as hydrograph separation using chemical and isotopic tracers are needed to support this point.

The slope of the regression line (8.06) of the stream waters is the same as that of GMWL (8.0), indicating that little or no evaporation occurs in these high-altitude streams. This is probably due to the fast flow induced by the steep gradients in the Seolak Mountains (Fig. 1a).

River waters obtained from four reservoirs such as Cheongpyeong, Euam, Chuncheon, and Soygang dams have much lower d -values relative to groundwaters and upstream waters collected during the same sampling period. Such low d -values appear to be

produced by evaporative enrichment of river waters at the dams.

Until now, there are no available data for residence times of these reservoirs. Thus, studies on the residence times of the waters are required to better understand the hydrogeology and isotopic evolution of the North Han River waters.

Summary

In the Northeast Asia, there is a stronger isotopic depletion in summer rains than in winter precipitation, and this isotopic signal provides a basis for the interpretation of the seasonality of groundwater and stream water recharge. In this study, such isotopic signatures were used to determine the seasonal contributions of precipitation to a groundwater system in a heavily forested area in the North Han River, Korea.

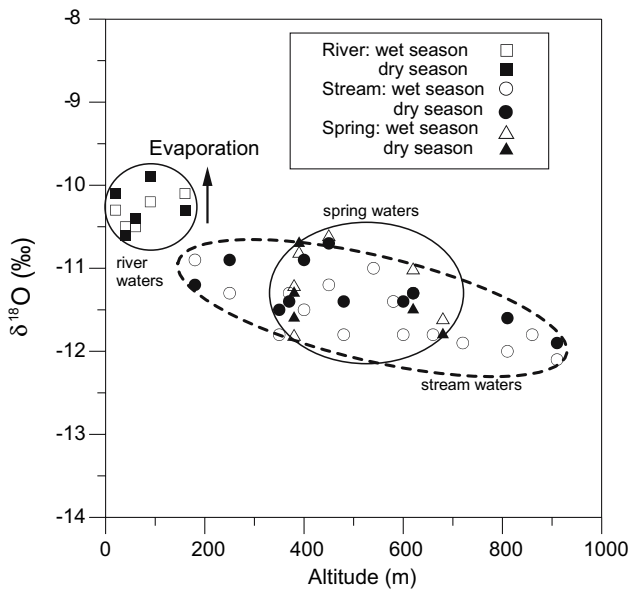


Fig. 4 $\delta^{18}\text{O}$ values of spring and stream waters, and their sampling altitudes

A comparison of deuterium excess values or *d*-values of groundwater and of precipitation collected during the period of June 1999–February 2001 indicates that the monsoonal summer rains, which contribute ~71% of the annual precipitation, provide only half fraction of the groundwater recharge. Instead, dry season precipitation accounting for the rest fraction of the groundwater recharge is also another major source of the groundwater recharge. The same isotopic pattern appears for stream waters in the study area, which plot along the same regression line as groundwater. This may indicate that stream waters are mainly fed by groundwater discharge. The deuterium excess values for river waters in the flood control dams are relatively lower than those of stream water, indicating evaporation.

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