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ORIGINAL ARTICLE

Characterizing groundwater recharge using oxygen and hydrogen isotopes: a case study in a temperate forested region, South Korea

Mukesh Kumar Gautam[1,2] · Kwang-Sik Lee[1] · Byeong-Yeol Song[1,3]

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Abstract
In the cool temperate region of South Korea, oxygen and hydrogen isotopes of groundwater, lake water, and precipitation were studied to determine the season of groundwater recharge. All the groundwater samples, irrespective of season, on $\delta^{18}O$–δ^2H scale plotted along the summer precipitation, suggesting summer precipitation largely modulates recharge. The deuterium excess values of groundwater (*d*-excess) show clear seasonal difference, higher in winter (> 18‰) and lower in summer (< 10‰). And its resemblance to the summer precipitation *d*-excess value further suggests dominant role of summer precipitation in groundwater recharge. Based on the mass balance equation, with end-member *d*-excess values of seasonal precipitation and groundwater as input variables, groundwater is composed of 66% summer and 34% winter precipitation. Despite the study area being heavily forested, summer rainfall contribution higher than winter suggests that evapotranspiration effect is minimal in the region; may be due to thin sand–gravel-based porous soil overlying highly weathered granitic rock system.

Keywords Oxygen isotope · Hydrogen isotope · Deuterium excess · Groundwater · Cool temperate ecosystem · South Korea

Introduction

Oxygen ($\delta^{18}O$) and hydrogen (δ^2H) isotopes of water are the natural integrator of water cycling processes in an ecosystem (Clark and Fritz 1997; Gautam and Lee 2016). Understanding of the fractionation of δ^2H and $\delta^{18}O$ and their subsequent spatial and temporal variabilities during routing in various terrestrial components, and the empirically estimated *d*-excess values ($d = \delta^2H - 8 \times \delta^{18}O$) have helped to understand the relationship among different water reservoirs, like precipitation, soil water, and groundwater (Andreo et al. 2004; Daansgard 1964; Jasechko et al. 2014; Lee et al. 1999; Lee and Kim 2007; Gautam et al. 2017a, b; Sánchez-Murillo et al. 2017).

In many regions of the world where groundwater makes bulk of the water supply, extraction of groundwater overrides replenishment rates. The subsequent increase in the unsustainable water utilization could then cause significant social impacts and affect the agricultural sustainability in a region. For example, in some regions of South Korea, groundwater fulfills all required demand for the drinking water and most of the demand for irrigation (Lee et al. 1999, 2014). For this reason, maintaining a perpetual supply of potable water in such area is a major challenge and is highlighted, with urgency, in the framework for Integrated Water Resource Management (IWRM) for Korea. Despite there being dwindling groundwater reservoirs, there are only a limited number of studies that provide information about the magnitude of groundwater recharge and its relationship with the precipitation on regional scale. Consequently, there is a need to investigate the season of groundwater recharge for

✉ Mukesh Kumar Gautam
mukeshcric@gmail.com

✉ Kwang-Sik Lee
kslee@kbsi.re.kr

Byeong-Yeol Song
songby23@gmail.com

1 Division of Earth and Environmental Sciences, Korea Basic Science Institute, Ochang, Chungbuk 363-883, Republic of Korea

2 Department of Natural Sciences, Baruch College, City University of New York, New York, NY 10010, USA

3 Chemical Analysis Division, National Forensic Service, Wonju 220-170, Republic of Korea

the effective management of the groundwater reservoir in a region (Lee and Kim 2007).

Generally, strong seasonal δ^{18}O and δ^{2}H isotopic differences between summer and winter precipitation are observed in both temperate and tropical regions (Lee et al. 2003; Rozanski et al. 1993; Wu et al. 2015). And the comparison of seasonal differences in the water isotope of precipitation with that of the groundwater can provide insight about the groundwater recharge and season of recharge (Jasechko et al. 2014; Wenner et al. 1991; Yeh et al. 2011). In Northeast Asia, summer rains are isotopically different from winter rains (Lee and Kim 2007; Tan et al. 2016; Wu et al. 2015). Similar to other isotopic studies in the Northeastern Asia, we also have observed significant difference in the deuterium excess values between summer and winter precipitation in the study region (Gautam et al. 2017a, b). Such seasonal differences in the isotopic values can be helpful in interpreting the season of groundwater recharge.

In this study, we have attempted to quantify the relative contribution of summer and winter precipitation in groundwater recharge. Our assumption is, since soil of the study region is poorly graded gravel–sand mixture overlain by highly weathered granitic rocks, and the study region receives bulk of the total precipitation in summer season, probably summer precipitation is playing a major role in groundwater recharge. This study has stemmed from another work (Gautam et al. 2017a, b) in which δ^{18}O and δ^{2}H isotopic composition of precipitation and throughfall was investigated in the same study region, South Korea. We observed distinct *d*-excess values (deuterium excess values Daansgard 1964) between summer precipitation and winter precipitation; the winter *d*-values (> 18‰) were higher than the summer *d*-values (< 10‰). This difference could potentially help in evaluating the relative importance of summer recharge against winter recharge of groundwater.

Materials and methods

Study site

The study was carried out in the cool temperate region of Ochang, Chengwon-gun, South Korea (33° 43′N latitude and 127° 26′E longitude) (Fig. 1). The altitude of the study area ranged between 85 and 248 m above mean sea level. The study region is a sub-urban–rural interface where the valley is dominated by agriculture and hilly areas are dominated by forests. The annual mean temperature during the study period was 12 °C, with the lowest temperatures being recorded in January (− 20.2 °C) and the highest in August (37.9 °C). The annual rainfall in the study area during the investigation period was 1448 mm, which was distributed into 1079 mm summer rainfall, and 202 mm winter rainfall, the bulk of which was in the form of snow. These values are identical to the long-term mean average values for the region (Korea Meteorological Administration, www.kma.go.kr). During winter, snow starts accumulating in the region in mid-December, but the lag phase between deposition and melting is small (less than 24 h to 10 days).

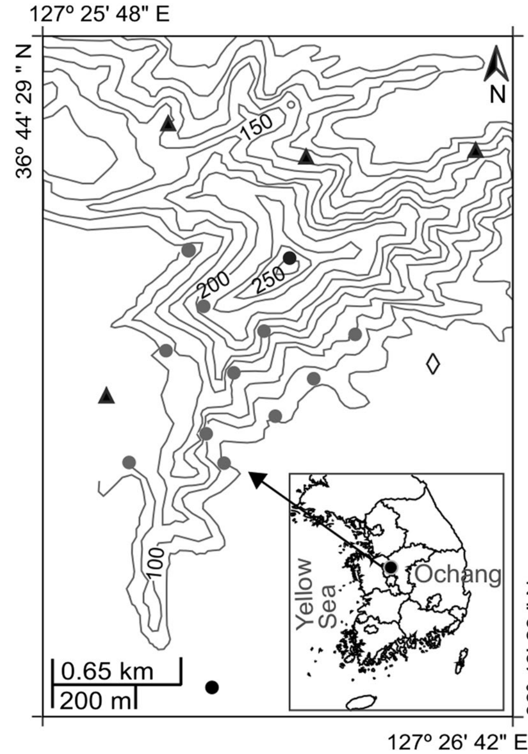

Fig. 1 Map of Korean peninsula (inset) showing the study region and the sampling locations. Closed circles are precipitation sampling locations, triangles are groundwater sampling locations, and closed rectangle represents lake

Sampling and analysis

The groundwater samples were collected every month from four bore wells located in vicinity of the Mt. Mokryeong catchment. Most bore wells in the region are in the alluvium and in the weathered zones of granitic rocks. According to the drilling data and bore well inventory, depth of water table ranges 10–20 m (Kim and Hamm 1999). Since, soil is skeletal and coarse textured (Gautam et al. 2017a, b), study region has a very higher hydraulic conductivity and hence high net recharge rate. The hydraulic conductivity of soil in the studied region is about 10–20 m/d (Chung et al. 2010). Based on the Tritium contents, suggested age of groundwater recharge is 5–10 year (Choi et al. 2010). Additionally, monthly samples were also collected from a lake (2 ha) which receives surface inflows from the surrounding forested catchment. Precipitation samples were collected from

April 23, 2012, to February 04, 2013. Polyethylene funnels of 21 cm rim diameter (Nalgene™) were used to channel rainfall into 10 L fluorinated, high-density polyethylene containers (Nalgene™). Since, the study region is forested, precipitation includes both rainfall and throughfall samples. Collected samples were brought to the laboratory and filtered using 0.45 µm pore size filter papers (Advantec® mixed cellulose membrane 47 mm size). Filtrates were collected in 1 L polystyrene filterwares (Nalgene™) and subsequently stored in a refrigerator at 2 °C until isotopic analyses.

The composition of oxygen and hydrogen isotopes in the collected water samples was measured on the GV Instruments IsoPrime, and the Micromass Optima, UK isotope ratio mass spectrometer at Korea Basic Science Institute. Prior to instrumental analysis, for oxygen isotopic analysis, about 2 mL of each sample was equilibrated with tank CO_2 gas at 25 °C. The CO_2 gas was subsequently extracted and cryogenically purified. For deuterium analysis, metallic chromium was used to produce hydrogen gas using an automatic online sample preparation system (GV Instruments, Euro PyrOH, UK). The stable isotopic compositions were expressed in δ notation relative to Vienna Standard Mean Ocean Water (VSMOW) for oxygen and hydrogen isotopes:

$$\delta(‰) = \left(\frac{R_{\text{Sample}}}{R_{\text{Standard}}} - 1\right) \times 1000$$

where R = D/H or $^{18}O/^{16}O$. The analytical reproducibility for each standard and sample was ± 0.1‰ for $\delta^{18}O$ and ± 0.5‰ for $\delta^{2}H$. During the sample analysis, the laboratory standards for each isotope were run after every nine samples.

Data analysis

The relationship of $\delta^{2}H$ versus $\delta^{18}O$ of all the waters, and the local meteoric water line (LMWL) were obtained using linear regression analyses. The LMWL was then compared with the global meteoric water line (GMWL) of Craig (1961) that shows the global relationship between $\delta^{2}H$ and $\delta^{18}O$ of different waters. If the slope is lower than 8, we can suggest the role of evaporation. We have calculated the deuterium excess value (*d*-value) (after Daansgard 1964) to identify the processes that contribute to variations in the isotopic composition (Gat 2010; Lee et al. 2003). To estimate the relative contribution of summer and winter season precipitation to groundwater recharge, distinct *d*-excess values of summer and winter precipitation are used as two end members for respective seasons in the mass balance equation described by Lee and Kim (2007) as,

$$d_{\text{Groundwater}} = Xd_{\text{Summer}} + (1 - X)d_{\text{Winter}}$$

where *d*-excess is deuterium excess values, X is the fraction of summer precipitation, and $(1 - X)$ is the fraction of winter precipitation. For this calculation, we have binned the precipitation values broadly into summer which also includes rainfall received in spring and autumn (1246 mm), and winter (202 mm). The estimation of groundwater recharge percentage was calculated three ways: using *d*-excess values of only rainfall, using only throughfalls, and the average values of both. Isotopic signatures and *d*-excess values of throughfall for the region are given in Gautam et al. (2017a, b).

Results and discussion

Oxygen and hydrogen isotopic composition

The $\delta^{18}O$ and $\delta^{2}H$ values of the groundwater range from − 8.84 to − 7.62‰ (mean − 8.47‰ ± 0.30) and − 64.7 to −56.7‰ (mean −61.5 ± 2.1), respectively (Fig. 2). Additionally, the $\delta^{18}O$ and $\delta^{2}H$ values of the lake water range from − 9.35 to − 5.44‰ (mean − 7.84‰ ± 1.2) and − 69.2 to − 46.0‰ (mean − 59.2 ± 7.8), respectively (Table 1). Detailed description of the precipitation is given in Gautam et al. (2017a, b). Seasonally, the mean summer precipitation (− 8.28‰) is enriched in $\delta^{18}O$ in comparison with the mean winter precipitation (− 9.66‰) (Fig. 3). Generally, isotope composition of precipitation varies depending on the temperature effect or the (rainfall–) amount effect (Clark and Fritz 1997). Our results agree with the latter, since we noticed precipitation becomes isotopically depleted with the increase in the amount of precipitation in the rainy season (Gautam et al. 2017a, b), whereas there was no pattern of enrichment and depletion in the winter precipitation. Such an effect was also seen in the previous studies from South Korea where the most isotopically depleted precipitation was recorded in the rainiest time of summer (Kim and Nakai 1988; Lee et al. 2003). However, such difference is not noticeable in the $\delta^{2}H$ isotopic composition seasonally.

Groundwater had a very constant isotopic composition among all the sampled bore wells. Also, no significant seasonal differences exist in its $\delta^{18}O$ and $\delta^{2}H$ isotopic composition (Table 1). This consistency suggests the groundwater reservoir represents a single well-mixed water mass beneath the Mokryeong forested catchment. The average isotopic composition of groundwater ($\delta^{18}O$: − 8.48‰; $\delta^{2}H$: − 61.6‰) is comparable with the average isotopic composition of precipitation ($\delta^{18}O$: − 8.86‰; $\delta^{2}H$: − 58.5‰). Superficially, such a resemblance in isotopic composition suggests no seasonal biasness to the groundwater recharge (Clark and Fritz 1997). However, when we partitioned precipitation broadly into summer (April–October) and winter (November–March), $\delta^{18}O$ is 1.38‰ enriched in summer precipitation relative to winter precipitation.

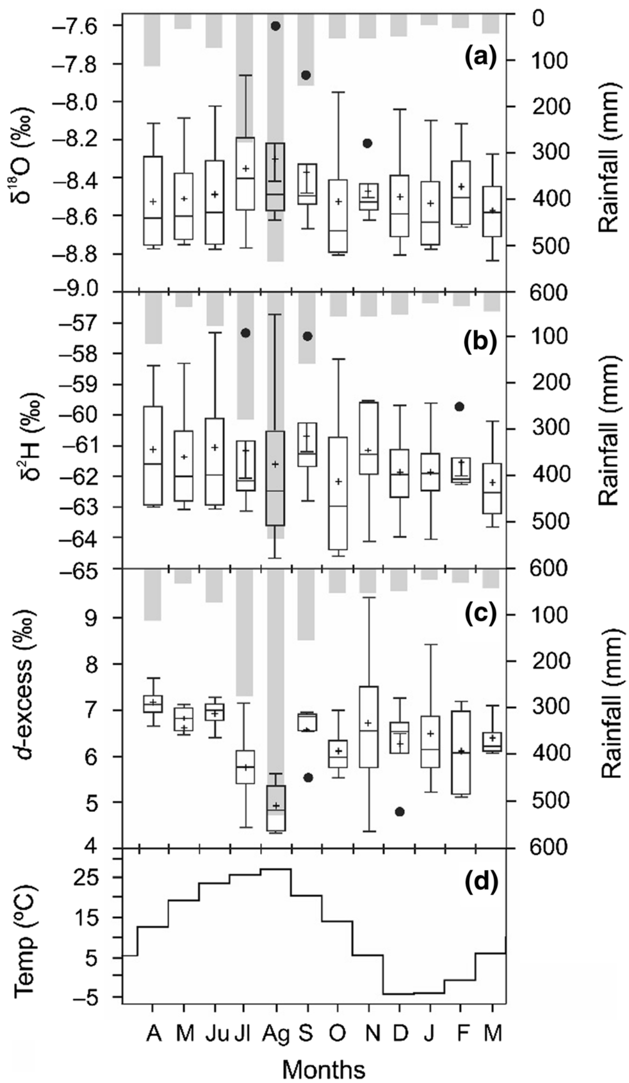

Fig. 2 Box and whisker plot of monthly pattern of oxygen (**a**) and deuterium (**b**) isotopic composition, and *d*-excess values (**c**) of groundwater. Horizontal lines within boxes indicate median of the values; the plus sign corresponds to the means; the lower and upper limits of the box are the first and third quartiles, respectively, and the lower and upper ends of the whiskers are minimum and maximum values for each event. Circles below and above the whiskers are outliers

$\delta^{18}O$–δ^2H plot and local meteoric water line (LMWL)

The affinity of groundwater samples to LMWL's of summer and winter precipitation, due to the difference in the evaporative enrichment, can further constrain recharge season. The $\delta^{18}O$ and δ^2H values of all the samples were plotted, and local and global meteoric water lines were forced through them (Fig. 4). The $\delta^{18}O$–δ^2H plot for the groundwater was positioned toward right of the GMWL (Fig. 4a). Irrespective of the season, groundwater samples from all the borewells plot close to the LMWL of summer precipitation (Fig. 4c). Such displacement of groundwater samples to the right of the LMWL and the GMWL is in agreement with the results reported by Choi et al. (2010) in the region close to the study site presented here. The positioning of the groundwater samples toward the right of the summer precipitation LMWL indicates the effect of evaporation and/or evapotranspiration during different stages of infiltration to the groundwater (Clark and Fritz 1997; Lee et al. 2003). This further suggests that summer precipitation is important for groundwater recharge in this region. The best-fit line for all the groundwater samples resulted in $\delta^2H = 6.27\ (\pm\ 0.44) \times \delta^{18}O + 8.41\ (\pm\ 3.74)$ ($r = 0.90$). The mean $\delta^{18}O$ value of groundwater is 0.62‰ lower than the weighted annual average of precipitation recorded in the study area during the study period. A slope ≤ 6 that we noticed in this study is less than the slope of 8 of the GMWL. This suggests that water may be subjected to evaporative loss, mixing with the antecedent water while infiltrating through the soil and/or the kinetic effect of water vapor diffusion (Gat 2010; Kendall and Doctor 2011).

Deuterium excess (*d*-) values

The seasonally discriminated *d*-excess value, which was defined by Daansgard (1964), has the potential to characterize the groundwater recharge by summer and winter precipitation. Recharging water that experiences evaporative loss generally has low *d*-excess values relative to GMWL and LMWL. This happens due to greater kinetic isotope fractionation of oxygen isotopes than hydrogen isotopes (Clark and Fritz 1997; Choi et al. 2010). In the absence of evaporative loss, *d*-excess values exceed that of GMWL and LMWL. The *d*-excess values of groundwater for the sampling period are in the range of 4.28–9.39‰ (Fig. 2c). Irrespective of season, *d*-excess values of the groundwater never exceed the *d*-excess values of GMWL (10‰) or LMWL (9.6‰) (Gautam et al. 2017a, b), indicating evaporative isotopic enrichment (Choi et al. 2010). Whereas, average *d*-excess values of summer and winter precipitation are distinct, lower in summer (≈ 8‰) and higher in winter (18.6‰) precipitation (Fig. 3c), as observed by previous studies in the Northeastern Asian region (Lee et al. 1999, 2003). This is attributed to the seasonal differences in the air masses that affect this region (Lee and Kim 2007). And groundwater *d*-excess values (4.28–9.39‰) fall within the summer precipitation *d*-excess range (4.67–15.3‰). Generally, in winter evaporative losses are negligible; hence, *d*-excess value is higher in winter (> 15‰) compared to summer (< 10‰) when evaporative losses are at a maximum (Lee and Kim 2007). This suggests that groundwater in the study area experiences evaporative losses prior to recharge. Furthermore, average *d*-excess values for summer (6.11‰ ± 0.49) and winter (6.45‰ ± 0.63) samples are identical. Such a seasonal constancy in *d*-excess values probably indicates

Table 1 Seasonal and annual range and average $\delta^{18}O$ (‰), $\delta^{2}H$ (‰), and *d*-excess values (‰) of lake water

	$\delta^{18}O$ (‰)			$\delta^{2}H$ (‰)			*d*-excess		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
GW									
Summer	− 8.80	− 7.62	− 8.43 (± 0.31)	− 64.7	− 57.2	− 61.3 (± 2.22)	4.29	7.21	6.11 (± 0.49)
Winter	− 8.84	− 8.04	− 8.51 (± 0.16)	− 64.1	− 58.4	− 61.7 (± 1.19)	4.28	9.39	6.45 (± 0.63)
Annual	− 8.57	− 8.30	− 8.46 (± 0.07)	− 61.1	− 62.2	− 61.4 (± 0.54)	4.28	9.39	6.28 (± 0.45)
Lake									
Summer	− 9.35	− 5.44	− 7.45 (± 1.55)	− 69.2	− 45.9	− 56.8 (± 9.79)	2.49	5.79	2.82 (± 3.08)
Winter	− 8.91	− 8.24	− 8.48 (± 0.27)	− 67.1	− 60.1	− 63.4 (± 2.52)	3.60	5.75	4.44 (± 0.88)
Annual	− 9.35	− 5.44	− 7.85 (± 1.20)	− 69.2	− 45.9	− 59.2 (± 7.80)	2.49	5.79	3.59 (± 2.28)

Values in the parenthesis are standard deviations

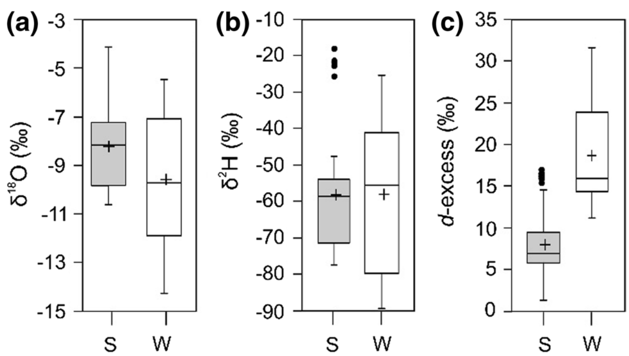

Fig. 3 $\delta^{18}O$ (‰), $\delta^{2}H$ (‰), and *d*-excess (‰) summer and winter precipitation boxplot for the study area. Horizontal lines within boxes indicate median of the values; the plus sign corresponds to the means; the lower and upper limits of the box are the first and third quartiles, respectively, and the lower and upper ends of the whiskers are minimum and maximum values for each event. Circles below and above the whiskers are outliers. These values include both the rainfall and throughfall samples

that groundwater recharge predominantly is governed by summer precipitation, and its storage is significantly large and well mixed. This observation is in contrast with other studies, which suggested that recharge in summer is small because of the high evaporation from soil and transpiration from vegetation in contrast with winter which is manifested with diminished evaporation, and transpiration since vegetation enters dormant stage (Wenner et al. 1991; Winograd et al. 1998; Clark and Fritz 1997). Recently, Jasechko et al. (2014) also suggested that in temperate climates groundwater recharge is higher in winter than in summer. However, one aspect that is important to underline in this context is that the process of infiltration in a particular region is significantly impacted by the physical properties of soil, especially when soils are thick and fine textured which impede the movement of water downward in the soil. For example, Wenner et al. (1991) observed contrasting results on thick Piedmont soils with well-developed clay-rich B-horizon

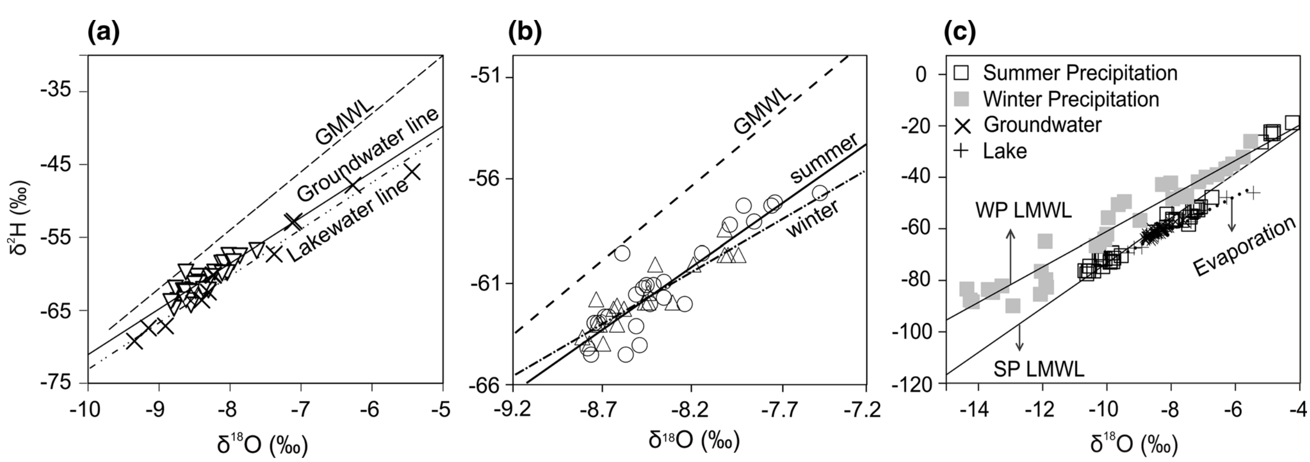

Fig. 4 **a** Covariation plot of $\delta^{2}H$ (‰) and $\delta^{18}O$ (‰) of groundwater and lake water with **b** seasonal breakup of all the groundwater samples into summer (○) and winter (Δ) rainfall, and **c** groundwater and lake water samples plot with respect to summer (SP) and winter (WP) precipitation. GMWL is Craig (1961) global meteoric water line defined by $\delta^{2}H = 8 \times \delta^{18}O + 10$

(~ 50%); winter rainfall dominantly influenced groundwater recharge because in thick clay-rich soil infiltration was slow and region was dominated by dense forests, and these settings allowed more time for evapotranspiration in summer.

Mass balance equation and seasonal groundwater recharge

The isotopic distinction observed between seasons has significant implication for current and future groundwater management in the region. It has been reported that in South Korea, especially in rural areas, groundwater is an important freshwater resource (87%) for their irrigational (49%) and domestic (46%) use throughout the year (MLTMA 2012). Therefore, understanding groundwater recharge is important for devising effective management plans. It is critically important for areas, like the region discussed in this study, where precipitation is predominant source of groundwater recharge. Studies have suggested that in such areas, the groundwater system has not yet reached a state of dynamic equilibrium and decades of excessive seasonal pumping have impacted the level of groundwater (Lee et al. 2014, 2017). We used mass balance equation described by Lee and Kim (2007) to estimate the proportional recharge contribution by summer and winter precipitation. The average end-member *d*-excess value for summer precipitation used in the mass balance equation was 8.0‰ and that of winter was 18.6‰. Precipitation here is the average values of both rainfall and throughfalls collected from the region. The result of mass balance equation indicates that 66% of summer precipitation and 34% of winter precipitation contribute to the groundwater recharge. Thus, a substantial amount of summer precipitation recharges the groundwater reservoir in the study region. According to a previous study by Lee and Kim (2007) in the South Korean north temperate region in the catchment of Northern Han river, both summer precipitation and winter precipitation were equally important in groundwater recharge, with winter (49%) recharge proportion almost equal to summer recharge (51%). In our study, however, the estimated proportion of recharge is different from the proportion of summer and winter precipitation. Although comparison of our study results with their results is of little significance since their study was done in different regions having different environmental settings. Despite our study region being forested, the dominance of summer recharge is noteworthy. Our study site was overlain by thin soil layer, which is poorly graded sand–gravel mixture and a porous decomposed rock system; hence, region is highly permeable. Such a setting probably facilitates rapid infiltration of precipitation to deeper layers away from the most active rooting zone (0–50 cm) of the tress. As well as thick litter layers with high storage capacity always exist from past fall season over soil layer that substantially decrease the surface runoff loss (Keith et al. 2010; Neris et al. 2013). Thus, Mokryeong Mountain despite being forested, summer precipitation seems to the major source of groundwater recharge because the soil is coarse textured and may be allowing bulk of the water to move fast and away from rooting zone to deeper layers due to its high soil hydraulic conductivity (Kozak et al. 2005), restricting the water loss tied to evapotranspiration. Therefore, plotting of groundwater samples toward the right of summer precipitation (Fig. 4c) and the similarity of groundwater *d*-excess values with the summer precipitation accentuate that the contribution of summer precipitation to groundwater recharge is major. However, it is noteworthy that percentage of winter precipitation was low relative to summer precipitation, despite that its contribution to groundwater recharge was more than 30%. This proportion is nearly the same as the proportion of winter precipitation to groundwater recharge observed in other regions of South Korea (Lee et al. 1999). Several interrelated factors may be responsible for this, such as, expect a few, generally light sporadic snowfall with short time lag between snowfall, its melting and subsequent disappearance were observed in the study region. And this is due to intermittent wet precipitation of low intensity following snowfall events, intervening long gaps between two events, and intense incident solar radiation afterward. All of these factors combined with the coarse textured soil are then probably responsible for groundwater recharge in winter.

Our precipitation samples contain water from both rainfall and throughfall events. However, we have previously reported the alteration of H and O isotopes as rainfall traverses through tree canopies as throughfall (Gautam et al. 2017a, b). Overall, the $\delta^{18}O$ and $\delta^{2}H$ values of throughfall were about 0.35–0.59 and 0.85–1.95‰ higher than rainfall, and these differences between the two forms of waters are substantially larger than 0.10 and 0.50‰ analytical uncertainty for $\delta^{18}O$ and $\delta^{2}H$, respectively. An important aspect of such changes in the forested landscapes is whether such alterations are significant enough to be considered in groundwater recharge in a region dominated by forests. Xu et al. (2014) showed that a 0.5‰ difference in $\delta^{18}O$ can produce > 15% bias in the contribution to groundwater. We, therefore, separated *d*-excess values of throughfall and rainfall, and computed recharge proportion separately for the two different precipitation types. With throughfall only, the proportion is 69 and 31% for summer (with *d*-excess value of 7.7‰) and winter (with *d*-excess value of 18.3‰), respectively, whereas with rainfall only, it is 61% (with *d*-excess value of 8.7‰) and 39% (with *d*-excess value of 19.5‰), respectively. The differences due to throughfall and rainfall *d*-excess values are small in this study compared to the extent of bias suggested by Xu et al. (2014). However, there may be underestimation in calculation, since we used rainfall seasonal proportion in mass balance rather than throughfall because continuous long-term values of throughfall budget are not available for the region. And it is well known that tree canopies intercept a great amount of incident precipitation, which subsequently evaporates, both during and after the precipitation event.

In the case of lake water, significant seasonal changes exist between the samples collected in summer and winter (Table 1). $\delta^{18}O$–$\delta^{2}H$ line forced through samples resulted in $\delta^2H = 6.41\ (\pm\ 0.33) \times \delta^{18}O + 8.87\ (\pm\ 2.63)$ (adj $r = 0.99$). Slopes and intercepts of the seasonal regression lines differed from each other, with a lower slope in summer—$\delta^2H = 6.24\ (\pm\ 0.45) \times \delta^{18}O + 10.30\ (\pm\ 3.44)$ (adj $r = 0.98$) compared to winter—$\delta^2H = 8.93\ (\pm\ 1.73) \times \delta^{18}O + 12.40\ (\pm\ 14.66)$ (adj $r = 0.94$). The lake water samples, which represent a terminal water body, show $\delta^{18}O$ and δD values along the summer LMWL trajectory initially, and later extending out away from the summer water LMWL (Fig. 4c), suggesting evaporative losses. The slope of the lake water is steeper than that of evaporating water from an open water reservoir close to 5. This shows that the mixing of the lake water with the rainfall runoff, which is in the lower drainage relief supplied by the forested catchment surface runoff. The slope higher than 8 in the winter is apparent of negligible evaporative losses in this season. Typically, terminal lakes are more likely, than other type of surface water reservoir, to suffer evaporative modification. Since, residence time of water is longer in terminal lakes because of the absence of outflow, which allow more time for contact and exchange with the atmosphere.

Conclusion

The groundwater recharge and its seasonality are critical for the sustainability of groundwater and water balance of any region. In South Korea, groundwater is an important freshwater resource, particularly in the rural regions which derive groundwater for their irrigational need, especially in dry seasons. The reliance, particularly of agriculture and industry, on groundwater has increased manifold in recent years, and in many areas where groundwater makes bulk of the water supply, extraction of groundwater overrides the replenishment rates. Accordingly, effective management of groundwater cannot be achieved unless the season of groundwater recharge is determined. It is a general assumption that in temperate regions that receive winter precipitation as snowfall, a greater proportion of snowmelt recharges groundwater, and the groundwater isotopic values would be biased toward the winter precipitation. Despite very small difference in the isotopic values of groundwater between summer and winter seasons (0.08‰ $\delta^{18}O$ and 0.39‰ δ^2H), which also suggests seasonal biases to recharge are slight, all the groundwater samples plotted close to the summer LMWL and the average *d*-excess values of summer precipitation overlap with that of groundwater *d*-excess values. This indicates that summer precipitation is important in groundwater recharge even in temperate regions which receives bulk of precipitation in summer and where infiltration occurs rapidly though a sand–gravel soil admixture and the underlying permeable bedrock system.

Our study is a short-term study and short-term studies are important, and as a prelude to longer term, these studies can provide key initial insights about relationship between precipitation and groundwater. Since groundwater recharge is weather dependent and temporal changes in the amount of precipitation (seasonal and annual), especially during drought years, can produce variations in the contributions to groundwater, it is important that the results of short-term studies should be related with the long-term study results. It is suggested that in the future a long-term study should be attempted to better model the seasonal recharge contributions. Such long-term research is, therefore, required to reinforce understanding about a generalized relationship between seasonal precipitation and groundwater recharge and to check whether there is unanimity between the results of short-term recharge and long-term recharge or not. The correspondence between the two sets of results can be used as a framework around which optimal groundwater management can be planned. Furthermore, similar to most of the stable isotope studies, we did not perform water balance studies for the region. Adding the component of water balance in stable isotopes studies of waters can reinforce the understanding about the groundwater recharge dynamics.

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