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ORIGINAL ARTICLE

Relationships between precipitation, soil water and groundwater at Chongling catchment with the typical vegetation cover in the Taihang mountainous region, China

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Abstract Vegetation cover plays an important role in the process of evaporation and infiltration. To explore the relationships between precipitation, soil water and groundwater in Taihang mountainous region, China, precipitation, soil water and water table were observed from 2004 to 2006, and precipitation, soil water and groundwater were sampled in 2004 and 2005 for oxygen-18 and deuterium analysis at Chongling catchment. The soil water was sampled at three sites covered by grass (*Carex humilis* and *Carex lanceolata*), acacia and arborvitae respectively. Precipitation is mainly concentrated in rainy seasons and has no significant spatial variance in study area. The stable isotopic compositions are enriched in precipitation and soil water due to the evaporation. The analysis of soil water potential and isotopic profiles shows that evaporation of soil water under arborvitae cover is weaker than under grass and acacia, while soil water evaporation under grass and acacia showed no significant difference. Both δ^{18}O profiles and soil water potential dynamics reveal that the soil under acacia allows the most rapid infiltration rate, which may be related to preferential flow. In the process of infiltration after a rainstorm, antecedent water still takes up over 30% of water in the topsoil. The soil water between depths of 0–115 cm under grass has a residence time of about 20 days in the rainy season. Groundwater recharge from precipitation mainly occurs in the rainy season, especially when rainstorms or successive heavy rain events happen.

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Introduction

The Taihang mountainous region is the most important recharge source for the adjacent North China Plain, an area of large population and major crop production suffering from serious water problems, including continuously declining water table and deteriorating water quality (Foster et al. 2004; Li et al. 2008; Mao et al. 2003; Wang et al. 2008; Yang et al. 2002). Investigating the transformations from precipitation to soil water and groundwater, and their relationships with vegetation is hence vital in understanding the water cycle and recharge mechanism of groundwater to the North China Plain.

Deuterium and oxygen-18 isotopes in water undergo fractionation during the processes of evaporation and precipitation due to the differences in bond strength for isotopes. The global meteoric water line (GMWL: $\delta D = 8\delta^{18}O + 10$) was established by Craig (1961), and it provides a useful benchmark against which regional or local waters can be compared. Because isotopically light water molecules evaporate more efficiently than isotopically heavy water molecules, evaporation produces residual water enriched in the heavier isotopes relative to the initial isotopic composition. So the comparison of stable isotope data for soil water and groundwater samples relative to the global or local meteoric water lines can provide information on water cycle processes.

Soil water is the link between precipitation and groundwater, and the dynamics of isotopic composition in soil water are indicative of the processes of precipitation infiltration, evaporation of soil water, and recharge to groundwater. Zimmermann et al. (1967) characterized the effect of evaporation on hydrogen isotope in soil water, concluding that deuterium is enriched near the surface and decreases exponentially with depth.

This theory has been broadly used to determine the infiltration profile and rate of evaporation in arid and semi-arid regions (Abu-awwad 2001; Aragu et al. 1995; Khanzada et al. 1998; Mellander et al. 2004; Schachtschneider and February 2007). However, in humid and semi-humid areas, this exponential decrease is generally interrupted by precipitations. Hence, the combination of the evaporation effect and the isotopic composition of cumulative precipitation events determine the isotope profile in the soil. After isotopically enriched or depleted precipitation, there will be isotope peaks in the soil profile (Zimmermann et al. 1966) and thus seasonal fluctuations are easily observed. This isotope information is ultimately transferred to groundwater once soil water infiltrates to the saturated zone. Based on the isotopic compositions measured in precipitation, soil water and groundwater, infiltration rates can be calculated under certain conditions (Thoma et al. 1987), and groundwater recharge can be studied (Cartwright et al. 2006; Goni 2006).

Infiltration of precipitation is a complicated process affected by the characteristics of precipitation, soil texture and structure, topography and vegetation. Two types of infiltration are summarized as piston flow and preferential flow. In piston flow, water from later precipitation events forces older soil water to flow downward, whereas in preferential flow, water from the most recent precipitation event can be channeled through permeable pathways including cracks, plant roots, earthworm burrows, etc., to surpass older soil water (Markus et al. 2004). The two different infiltration types produce different soil water isotope profile types, which can be used to determine the infiltration type (Gazis and Feng 2004).

Vegetation cover plays an important role in the process of evaporation and infiltration. Structural vegetation characteristics such as leaf area index (Pitman et al. 1999; Shih and Rahi 1983), surface roughness and surface albedo (Riou et al. 1988) exert a significant control on evaporation. Under the cover of vegetation, the accumulation of organic matter and the presence of cracks and fissures created by the roots influence infiltration (Dunne et al. 1991; Mcginty et al. 1979). Stable isotopes have been used to study the influence of vegetation on evaporation and infiltration by many researchers (Brodersen et al. 2000; Hou et al. 2008; Hsieh et al. 1998; Li et al. 2007; Yepez et al. 2005).

This study was undertaken to apply stable isotopes (oxygen-18 and deuterium) to investigate the relationships between precipitation, soil water and groundwater under the typical vegetation cover in Taihang mountainous region, China.

Site description

This study was carried out in the Chongling catchment, Hebei Province, China (115°21′E, 39°23′N), located in northern Taihang mountainous region. Chongling catchment (area of 6 km^2) lies in the upper catchment of Baiyang Lake, the largest lake in the China North Plain, with the altitude between 85 and 300 m. The study area is about 200 km west of the Bohai Sea of China, and its climate is greatly influenced by East Asian monsoon. The northwest monsoon leads to the dry season (from September to May) by drawing cool, dry air from the Asian Continent, and the southeast monsoon leads to rainy season (from June to August) by bringing warm moist air from the Pacific Ocean. The area has an average annual air temperature of 11.6°C, and the maximum and minimum temperature is observed in July and January with extreme values of 40 and −23.4°C. The annual precipitation ranges from 217.0 to 1,004.3 mm, with an average of 641.2 mm. The average annual evaporation, according to Φ20 cm pan data, is 1,906 mm. Soil in the area is mainly sandy loam and loess, which has accumulated in valleys up to depths of 1–2 m. The vegetation coverage is variable (Fig. 1),

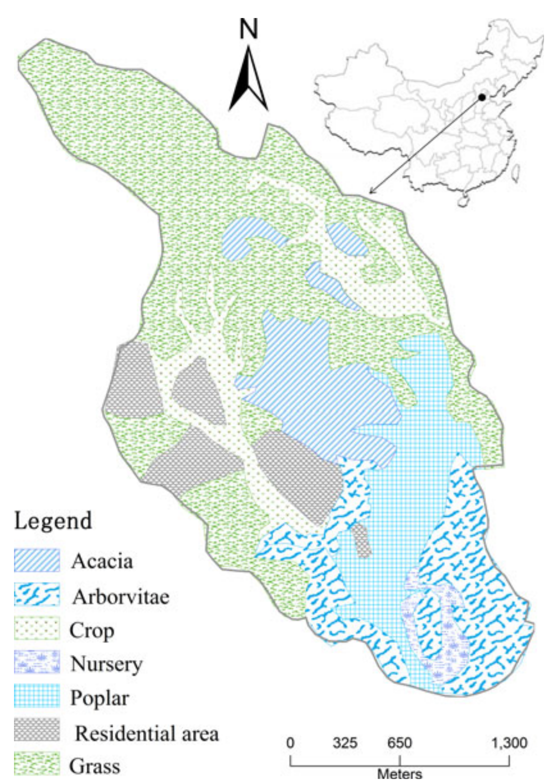

Fig. 1 Vegetation covers of Chongling catchment

including woody plants (Acacia, Arborvitae, poplar), shrubs (*Vitex negundovar*, *Ziziphus jujube var.spinosa*), and herbage (*Carex humilis*, *Carex lanceolata*, *Bothriochloa ischaemum*).

Method

Three typical vegetation types from the Taihang mountainous region are chosen in this study: grass, acacia and arborvitae, which can be taken as representatives of herbage, conifer and broadleaf vegetation respectively. Experimental site A is predominately covered by grass (*C. humilis* and *C. lanceolata*), site B by acacia and site C by arborvitae. The soil texture in the three sites is sandy loam, except for the top 10–20 cm at site C, which is silt loam soil (Table 1). The soil profiles are 0.8–2 m thick, with suction lysimeters placed at fixed depths of 10, 20, 30, 50, 70, 90 and 115 cm, although site C went to 70 cm only, due to the relatively thin soil horizon. The suction lysimeters were constructed out of Teflon pipe and a porous ceramic cup, and were installed at the bottom of 5 cm diameter holes excavated with a hand-operated bucket auger, backfilled with the excavated material. Soil water was collected by applying a vacuum of about −0.8 MPa to the suction lysimeter. Using this method, 10–500 ml of water samples can be taken with little effect on oxygen-18 and deuterium composition. Soil water potential was measured by tensiometer set at the same depths as suction lysimeters. The data were recorded manually every day with precision of 1 mmHg. The water table was measured every 10 days (5 days in the rainy season) at four observation wells (G1–G4), and groundwater was sampled in G1 and G2 wells over the same time intervals.

An auto weather station (DAVIS Weather Station, RJ1412HPL) was used to record the weather conditions, including air pressure and temperature, wind speed and wind direction. Precipitation was measured by SL3 Tipping-Bucket Rainfall Sensors (accuracy of 0.1 mm) and recorded by HOBO event logger (Onset Computer Corporation, USA) at five sites in the catchment (P1–P5). The precipitation samples were collected in 500 ml vials through a 200 mm diameter funnel, in which a ping-pong ball was placed to avoid evaporation. The rainfall samples were gathered into two 50 ml polyethylene air-tight vials after a rain event.

Table 1 Soil water sampling sites

Site	Vegetation	Soil	Sampling depth (cm)
A	Grass	Sandy loam	10, 20, 30, 50, 70, 90, 115
B	Acacia	Sandy loam	10, 20, 30, 50, 70, 90, 115
C	Arborvitae	Silt loam soil → sandy loam at depth	10, 20, 30, 50, 70

The water samples were analyzed at the Environmental Isotope Laboratory of Institute of Geographic Sciences and Natural Resources Research, the Chinese Academy of Sciences. δ^{18}O and δD have been measured using a Finnigan MAT253 mass spectrometer, using the TC/EA method. Results were expressed as parts per thousand deviations from the Vienna Standard Mean Ocean Water (V-SMOW) as follows (Gonfiantini 1978).

$$\delta_{\text{sample}} = \frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \times 1{,}000\ (‰)$$

where R is the ration of D/H or ^{18}O/^{16}O in sampled water (R_{sample}) or Vienna Standard Mean Ocean Water, V-SMOW (R_{VSMOW}). Precisions of ±0.3 and ±2‰ were obtained for δ^{18}O and δD in standard water sample, respectively.

Results

Precipitation and its isotopic composition

The precipitation was recorded by P1 in 2004 and by P1–P5 in 2005 and 2006. In order to study the spatial variances of precipitation in study area, the monthly precipitation recorded by P1–P5 from April to October in 2005 and 2006 is compared in Table 2. The variation coefficient of monthly precipitation on the five sites is <0.2, indicating there is no distinct spatial difference across the study area. Average precipitation for the five sites is hence used in this study.

Table 2 Monthly precipitation recorded by P1–P5 (mm) in 2005 and 2006

	P1	P2	P3	P4	P5	Mean	Cv
2005							
Apr.	22.0	22.1	19.4	21.0	20.2	20.9	0.06
May	74.7	73.6	74.5	73.7	75.1	74.3	0.01
June	83.2	79.0	78.7	73.6	79.4	78.8	0.15
July	128.6	123.0	135.6	124.5	127.6	127.9	0.19
Aug.	152.5	147.6	152.9	147.2	148.3	149.7	0.05
Sept.	31.3	31.8	30.2	32.4	30.4	31.2	0.03
Oct.	5.8	5.4	5.2	5.8	5.5	5.5	0.02
2006							
Apr.	9.8	9.8	9.8	10.7	9.6	9.9	0.02
May	69.9	65.5	68.8	69.3	68.4	68.4	0.04
June	98.3	93.4	89.2	97.6	89.9	93.7	0.19
July	101.4	95.4	104.4	95.4	101.3	99.6	0.16
Aug.	88.8	86.8	78.4	84.1	84.1	84.4	0.18
Sept.	16.8	16.3	17.4	15.3	15.8	16.3	0.04
Oct.	3.1	3.1	3.0	2.6	2.5	2.9	0.03

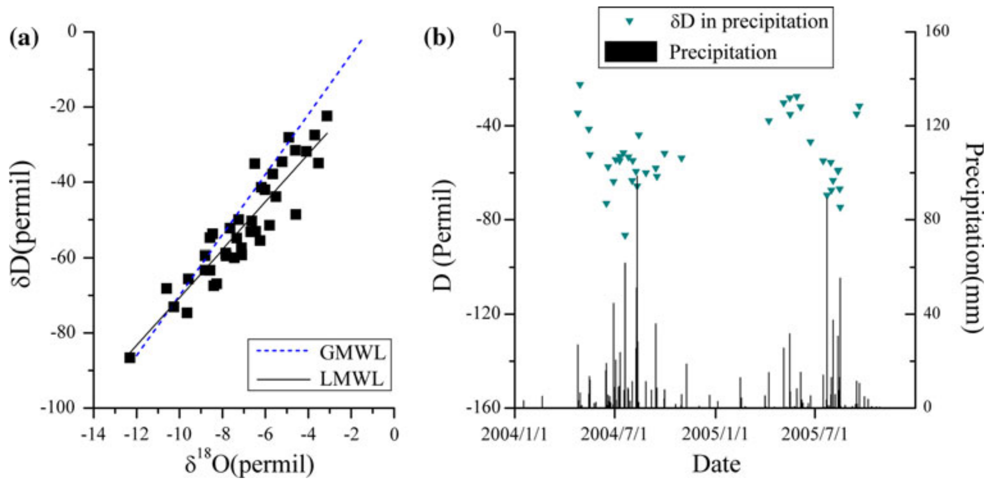

Fig. 2 Isotopes in precipitation. **a** The relationship between δD and δ^{18}O, and **b** the season variation of δD in 2004 and 2005

The average annual precipitation in Chongling catchment is 641.2 mm (1959–2006). In 2004 precipitation was 717.1 mm, indicating a wet year, while in 2005 and 2006 the precipitation was 485.7 and 374.4 mm respectively, dry years. During the 174 rainy days recorded in 2004–2006, light rain (0.1–9.9 mm) accounted for 74.1% of all rainy days, moderate rain (10–24.9 mm) for 16.1%, heavy rain (25–49.9 mm) for 6.9%, and rainstorms (>50 mm) for 2.9%. The distributions of rain days and rainfall intensity were greatly different between seasons. In the rainy season (June–August), the number of rain days accounted for 51% of the whole year, and all of the rainstorm days and 83.3% of heavy rain days occurred in the rainy season. In 2004–2006, precipitation in the rainy seasons accounted for 72.8, 66.9 and 72.7% of annual precipitation, respectively.

According to the measured values of deuterium and oxygen-18 stable isotopes in 43 sets of rainfall samples in April to October of 2004 and April to September of 2005, δ^{18}O values of precipitation ranged from -12.31 to -3.12‰, with a weighted mean value of -7.82‰ and standard deviation of 1.97‰, while deuterium ranged from -86.64 to -22.40‰, with a weighted mean value of -58.02‰ and standard deviation of 14.51‰. The local meteoric water line (LMWL) is: $\delta D = 6.72\delta^{18}O - 5.61$ (Fig. 2a). Both its slope and intercept are lower than that of the GMWL (8 and 10; Craig 1961), indicating evaporation effect during the process of precipitation. The δ^{18}O value of precipitation between June and August is significantly lower ($P < 0.001$) than that of other months (Fig. 2b). Lighter isotopic values were observed during heavy rain events (e.g. July 20, 2004) and after long duration rains (e.g. August 16, 2005).

Soil water potential and isotopic composition in soil water

Soil water potential, a measure of holding strength of the soil matrix for water, reflects the soil water content. Table 3 shows the monthly mean soil water potential under grass, acacia and arborvitae. An ANOVA analysis of the monthly mean soil water potential under the three vegetation cover shows that the evapotranspiration under arborvitae was weaker than that under grass and acacia in the wet year 2004, while in the dry year 2005, the evapotranspiration under the three vegetation cover had no significant difference (Wang et al. 2009). And in July and August of 2005, when the precipitation is abundant, the mean soil water potential under arborvitae is -6.8 and

Table 3 Monthly mean soil water potential under three vegetation covers (kPa)

	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Mean
2004									
Grass	–15	–18.1	–18.2	–28.9	–9.3	–11.4	–23.9	–22.9	–18.5
Acacia	–17.8	–23.4	–15.9	–20.3	–8.3	–17.2	–29.8	–25.9	–19.8
Arborvitae	–6.9	–12.1	–6.7	–20.8	–3.9	–4.6	–9.0	–9.1	–9.1
2005									
Grass		–17.3	–25	–31.9	–33.4	–14.7	–26.3	–27.1	–25.1
Acacia		–20.7	–26.1	–28.8	–22.3	–12.7	–23.5	–28.6	–23.2
Arborvitae		–21.8	–24.6	–24.9	–26.2	–6.8	–14.5	–29.0	–21.1

−14.5 kPa, also much higher than that under grass and acacia (−14.7 and −26.3 kPa under grass, −12.7 and −23.5 kPa under acacia). It can be concluded that when the precipitation is abundant, the evapotranspiration under arborvitae was weaker than that under grass and acacia.

Soil water was collected by suction lysimeters after precipitation, although soil water in some depths could not be collected due to low soil water content. 132 soil water samples were collected from June to August in 2004 and 2005. The δ^{18}O value of soil water ranged from −10.47 to −3.20‰, with mean value of −7.16‰ and standard deviation of 1.38‰, while deuterium ranged from −79.61 to −34.77‰, with a mean value of −57.07‰ and standard deviation of 9.57‰.

All stable isotopes of soil water fall on or slightly to the right side of the LMWL (Fig. 3), indicating soil water originates from precipitation. An evaporation trend line is observed, with the equation: $\delta D = 4.12\delta^{18}O - 21.54$, $r^2 = 0.599$. The mean δ^{18}O value in the top 30 cm of the soil profile is higher than that below 30 cm, which indicates evaporation has a stronger effect in the topsoil (Table 4). The topsoil water tends to have more varied isotopic composition than deeper soil layers, for example, δ^{18}O at 10 cm ranges from −10.47 to −4.75‰, with standard deviation of 1.78‰, while at 50 cm the range is from −9.73 to −4.43‰, with standard deviation of 1.49‰, and at 115 cm the range is from −8.79 to −6.12‰, with standard deviation of 0.84‰. Topsoil water is more varied probably because it is influenced by precipitation and evaporation effects soon after precipitation events. Mixing and homogenization with depth result in the lower range in standard deviation values.

Water table and isotopic composition in groundwater

Four wells are chosen to observe the changes in water table (Fig. 4). G2 and G4 are located in the upper reaches of Chongling catchment, G3 in the middle reaches, and G1 in the lower reaches. From the upper to lower reaches, water table decreases in order from G4, G2, G3, and G1 (Fig. 5), reflecting the groundwater flow path. In general, the dynamics of water table of all the wells obey an annual trend: rising in rainy season, and then declining gradually during the following dry season. Precipitation plays an important role in the dynamics. In the rainy season of 2004, a wet year, the water table rose sharply, but in the rainy season of the dry years 2005 and 2006, the rise was not distinct. Changes in water table in the four wells also show differences due to their different locations in the catchment. In the rainy season, the rise of water table becomes lesser in magnitude from the upper reaches to lower reaches. For

Fig. 3 The relationship between δD and δ^{18}O in soil profile under three vegetation cover and in groundwater of well G1 and G2

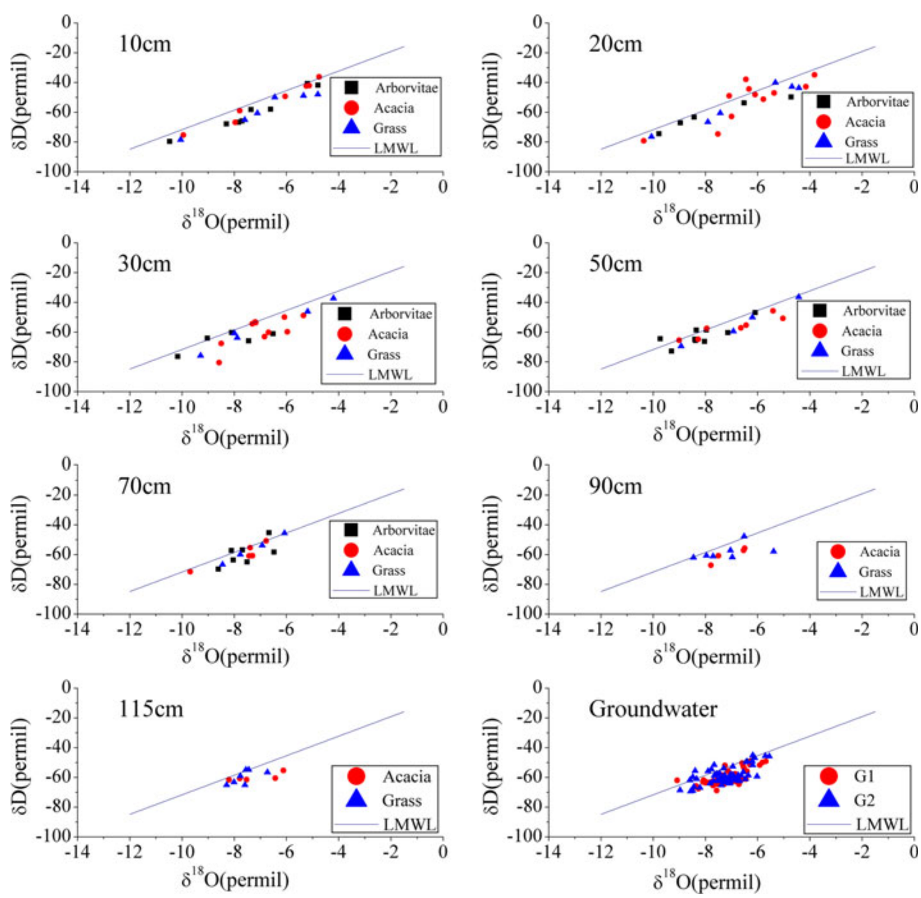

Table 4 General characteristics of isotopic compositions in precipitation, soil water and groundwater (weighted mean values for precipitation, arithmetic mean values for soil water and groundwater)

Types	Depth (cm)	Sample number	$\delta^{18}O$ (‰)				δD (‰)			
			Max.	Min.	Mean	σ	Max.	Min.	Mean	σ
Precipitation		43	–3.12	–12.31	–7.82	1.97	–22.40	–86.64	–58.02	14.51
Soil water	10	23	–4.75	–10.47	–6.99	1.78	–36.11	–79.61	–55.18	12.85
	20	24	–3.82	–10.36	–6.74	1.93	–34.77	–79.13	–54.43	13.64
	30	22	–3.20	–10.29	–6.98	1.88	–37.06	–76.38	–56.28	10.85
	50	22	–4.43	–9.73	–7.43	1.49	–36.39	–72.82	–58.51	8.99
	70	17	–6.08	–9.69	–7.56	0.91	–45.33	–71.40	–58.80	7.65
	90	13	–5.39	–8.46	–7.13	0.87	–47.69	–67.05	–58.94	4.88
	115	11	–6.12	–8.79	–7.61	0.84	–54.77	–69.18	–60.33	4.56
	Total	132	–3.20	–10.47	–7.16	1.38	–34.77	–79.61	–57.07	9.57
Groundwater		137	–5.56	–9.08	–7.24	0.67	–45.11	–69.31	–59.92	4.99

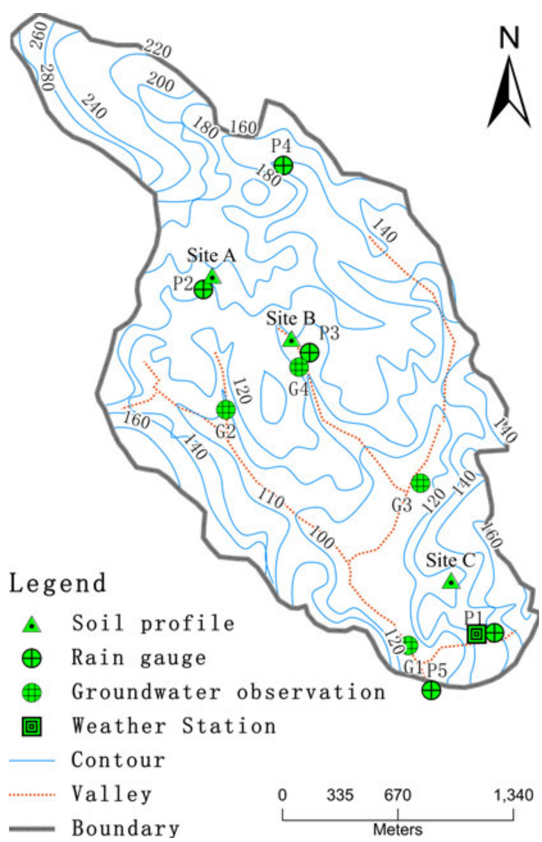

Fig. 4 Distribution of observation instruments

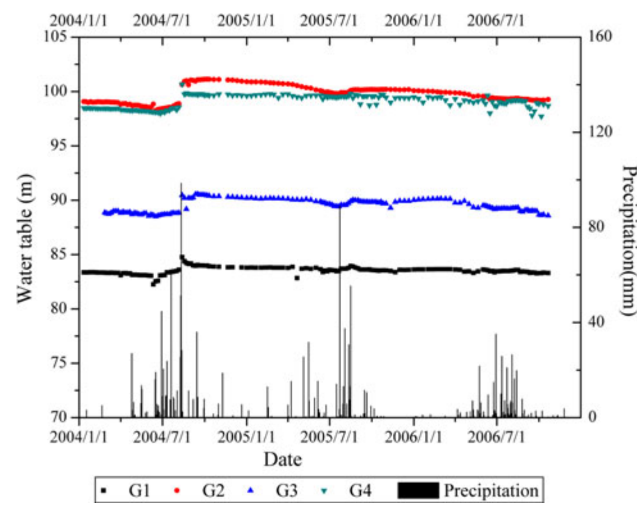

Fig. 5 Dynamics of water table of well G1, G2, G3 and G4 from 2004 to 2006

example, after the 203.5 mm precipitation event in August 8–12, 2004, the water table of G4 rose by 2.36 m, G2 by 1.80 m, G3 by 1.64 m, and G1 by 1.29 m. In 2006, the water table of G4 declined by 0.80 m, G2 by 0.81 m, G3 by 1.14 m, and G1 by 0.32 m, so the groundwater in the lower reaches has the smallest decline. Short-term declines in water table are also observed, such as the 1.04 m decline of G1 on April 21, 2005, and the 1.64 m decline of G4 on June 6, 2006, which may be due to local pumping.

137 sets of groundwater were sampled from G1 and G2 in 2004 and 2005. $\delta^{18}O$ values of groundwater ranged from −9.08 to −5.56‰, with mean value of −7.24‰ and standard deviation of 0.67‰, while deuterium ranged from −69.31 to −45.11‰, with mean value of −59.92‰ and standard deviation of 4.99‰. Groundwater hence had a smaller range of isotopic values compared to precipitation and soil water. Again, $\delta^{18}O$–$\delta^{2}H$ compositions plot on the LMWL or slightly to the right side of the line.

Discussion

Evaporation in soil water under the typical vegetation

Due to the effect of evaporation, isotopes in soil water are enriched, causing departure to the right-side of LMWL (Fig. 3). Besides evaporation, the isotope composition in

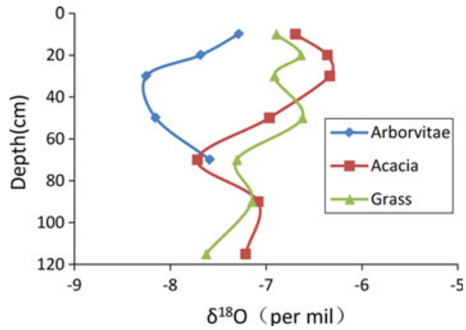

Fig. 6 Variation of average δ^{18}O along soil profile under arborvitae, acacia and grass

soil water is also influenced by precipitation, meaning the isotopic profiles in soil water do not decrease smoothly as predicted by Zimmermann et al. (1967). However, the overall trend still exists, with isotopes enriched in the topsoil compared to deeper layers (Fig. 6). δ^{18}O of soil water under grass decreases from −6.90‰ at 10 cm to −7.31‰ at 70 cm; δ^{18}O of soil water under acacia decreases from −6.70‰ at 10 cm to −7.72‰ at 70 cm; and δ^{18}O of soil water under arborvitae decreases from −7.28‰ at 10 cm to −8.25‰ at 70 cm.

Figure 3 shows that the range of isotopic values in soil water decreases with depth, due to the effect of evaporation and infiltration of precipitation. The isotopic compositions of groundwater are close to those of soil water at 70 cm depth, suggesting evaporation mainly occurs in the top 50 cm. An ANOVA analysis of δ^{18}O of the soil water in top 50 cm shows that δ^{18}O of soil water under arborvitae is significantly lighter than that under grass and acacia ($P = 0.001, 0.033$), and δ^{18}O of soil water under grass and acacia show no significant difference ($P = 0.420$). Because the three soil profiles receive recharge from same precipitation, the δ^{18}O difference of soil water must result from different evaporation intensity. It can hence be concluded that the evaporation of soil water under arborvitae is weaker than that under grass and acacia, while the evaporation of soil water under grass and acacia has no significant difference. The similar conclusion is drawn from the previous study of the dynamics of soil water potential under the three typical vegetation covers in the study area (Wang et al. 2009). The surface properties of soil are greatly altered by vegetation cover; both the shortwave albedo and long wave emissivity of the first layer of soil are affected (Horton et al. 1996). The difference in energy distribution of the soil and ground temperatures under different vegetation cover leads to the different degrees of soil water evaporation.

Evidence for preferential flow

Infiltration of precipitation and subsequent downward percolation is a complex process affected by soil texture, structure, wetness, water potential, slope and vegetation cover. The precipitation event on July 20, 2004 (61.8 mm) had a depleted isotopic composition (δ^{18}O = −10.69‰), and is thus a good tracer to study the infiltration progress. Soil water after the precipitation event was sampled from the three soil profiles under grass, acacia and arborvitae. Some soil water was also collected before the precipitation event, on July 18. The soil water potential was recorded before and after the event, on July 20 and 21.

Figure 7 shows that the shape of δ^{18}O profiles of soil water under acacia is different from grass and arborvitae after the precipitation event. The minimal δ^{18}O value of soil water under grass and arborvitae occurs at 50 cm (−8.39, −9.78%), while under acacia it occurs at 70 cm (−9.69‰), with a maximal value at 50 cm (−6.03‰). According to the piston flow theory, new water pushes the old water down in the process of infiltration. Because the July 20 precipitation had a depleted δ^{18}O of −10.69%, soil water in top layers should have lighter δ^{18}O than the deeper layers if piston flow occurs. Under grass and arborvitae, the soil water in the top 50 cm did have lighter δ^{18}O than in deeper layers, which accorded with the piston flow theory, although in the top 50 cm, the δ^{18}O value decreased gradually with depth, which can be explained by mixing between precipitation and antecedent soil water isotopically enriched by evaporation. However, under acacia, the soil water had the lightest δ^{18}O, similar to the precipitation event at 70 cm, while δ^{18}O decreased gradually in the top 50 cm. That is to say, soil water at 70 cm appeared to receive more recharge from the event than the soil at 50 cm depth. This indicates that preferential flow occurs in soil under acacia. Macropores in the soil created by roots may allow precipitation to penetrate quickly to deep layers under acacia.

Figure 7 also shows changes in soil water potential after the July 20 event in the three soil profiles. One day after the event, the soil water content had greatly increased at a depth of 90 cm under grass, 115 cm under acacia, and 70 cm under arborvitae. This indicates that the heavy precipitation had an influence to these different depths in the different sites, and particularly, that the soil under acacia had the fastest infiltration rate. This is again consistent with preferential flowing through the soil under acacia.

Mixing effect and residence time in soil water

δ^{18}O of precipitation on July 20, 2004 had a depleted value of −10.69‰, while δ^{18}O of soil water sampled at 10 cm under grass, acacia and arborvitae on July 21 was −8.23, −8.55 and −8.43‰, respectively. The difference in δ^{18}O between precipitation and soil water cannot be accounted for by evaporation, considering the short interval between

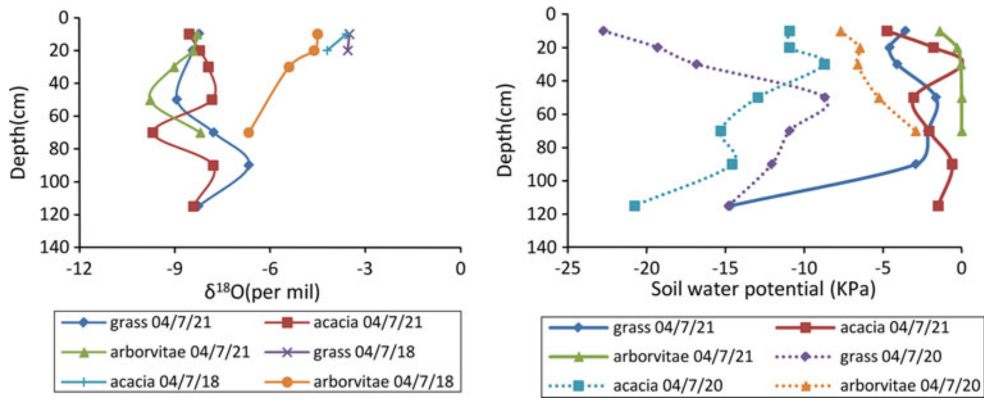

Fig. 7 $\delta^{18}O$ and soil water potential profile before and after July 20 precipitation event

precipitation and measurement. Rather, the difference can be explained by mixing of rainfall with antecedent soil water, already isotopically enriched by evaporation. The soil water after precipitation can be seen as a mixture of precipitation ("the new water") and the antecedent soil water ("the old water"). By comparing the $\delta^{18}O$ value of soil water before and after precipitation with that of precipitation, a crude estimate of the percentage of the old water remaining in the soil after precipitation can be made using the balance of isotopic mass.

If the effect of evaporation on isotopic composition during the period July 18–21 is considered negligible, then the $\delta^{18}O$ value of soil water sampled on July 18 can be seen as the pre-precipitation value and that sampled on July 21 as the 18th post-precipitation value. The $\delta^{18}O$ value of soil water at 10 cm on July 18 was −3.5‰, −3.6 and −4.5‰, under grass, acacia and arborvitae respectively. Based on isotopic mixture, the percentage of 'old water' making up the soil water after precipitation was 34.2, 30.2 and 38.6% under grass, acacia and arborvitae respectively. Hence it can be estimated that the antecedent or old water still makes up >30% of total soil water after a heavy rainstorm. Gazis and Feng (2004) compared the $\delta^{18}O$ of precipitation and soil water from profiles at six sites near Hanover, USA, and found that shallow soil water after precipitation (44 mm) contained more than 20% of old water. Also, he found that despite evidence for mixing, abrupt changes in soil water $\delta^{18}O$ with depth indicated that partial piston-flow occurred. That is, while some old water remains in the soil, the new water successively displaces a proportion of existing soil water by pushing it downward. If this is the case, the $\delta^{18}O$ profile of soil water should be broadly consistent with the precipitation time series prior to sampling. According to the $\delta^{18}O$ profile under grass on July 21 (Fig. 6), the $\delta^{18}O$ of soil water in the top 50 cm appeared to be affected by precipitation from the rainstorm on July 20. The $\delta^{18}O$ of soil water at 90 cm (−6.66‰) corresponded with precipitation between July 3–11 (48.6 mm, −6.60‰); and the $\delta^{18}O$ of soil water at 115 cm (−8.25‰) corresponded with precipitation on June 29 (44.7 mm, −8.45‰). Hence, soil water to a depth of 0–115 cm may have a residence time of about 20 days in the rainy season.

Seasonal isotopes variations in groundwater

As shown in Fig. 8 and Table 4, the ranges of $\delta^{18}O$ and δD values in groundwater are smaller than those in precipitation. The standard deviation of $\delta^{18}O$ decreases from 1.97‰ in precipitation to 0.67‰ in groundwater, and the standard deviation of δD decreases from 14.51‰ in precipitation to 4.99‰ in groundwater. The coefficient of variation of $\delta^{18}O$ and δD of groundwater is 37 and 33% of the values in precipitation, respectively. The seasonal variations observed in precipitation are smoothed or attenuated in groundwater. Eichinger et al. (1984) noted that the variation of $\delta^{18}O$ of soil water at a depth of 9 m had been reduced to <10% of precipitation. Darling and Bath (1988) found that the seasonal variation of δD in soil water at a depth of about 5 m had been attenuated to <5% of precipitation. Clark and Fritz (1997) related this attenuation effect in groundwater to the mixture of water among differential flow paths, including the porous matrix, open fissures and other fast pathways.

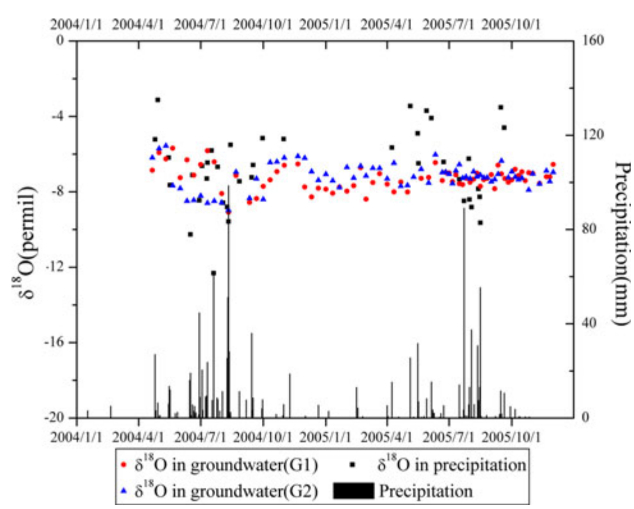

Fig. 8 $\delta^{18}O$ in precipitation and groundwater

Thought the isotopic composition of groundwater has a narrow range, it changes remarkably after a rainstorm with a highly depleted isotopic composition. For example, after the precipitation event on July 20, 2004 (61.8 mm, $\delta^{18}O = -10.69‰$, $\delta D = -86.64‰$), the $\delta^{18}O$ value in groundwater from G1 and G2 decreased by 1.69 and 1.08‰ respectively between July 21–30, while δD decreased by 7.21 and 9.69‰. This indicates that rainstorms can recharge the groundwater quickly and directly, which is also consistent with fast changes of water table after such storms. The fact that the variances in the isotopic composition of groundwater in 2004 is larger than that of 2005 (standard deviation of $\delta^{18}O$ in 2004 and 2005 was 1.01 and 0.42 respectively; standard deviation of δD in 2004 and 2005 was 7.15 and 2.33 respectively), also indicates the groundwater received more recharge from precipitation in 2004 than in 2005.

Conclusions

Precipitation, soil water and groundwater Chongling catchment were measured for oxygen-18 and deuterium composition in the Taihang mountainous region in northern China in a range of different vegetation types. Precipitation is mainly concentrated in the rainy season, and has no significant spatial variance in study area. The slope and intercept of the LMWL are both lower than that of GMWL, indicating an evaporation effect of precipitation. The isotopic compositions are more depleted in the rainy season (June to August) than in other months. The isotopic composition is enriched in soil water due to the evaporation, while the range of isotopic composition decreases with depth.

Comparing the $\delta^{18}O$ values in soil water, it is found that the evaporation mainly occurs in the top 50 cm soil water, and evaporation of soil water under arborvitae is weaker than under grass and acacia, while evaporation intensity of soil water under grass and acacia showed no significant difference. The $\delta^{18}O$ profile after an isotopically depleted rainstorm indicates that preferential flow occurs in the soil under acacia. Both the $\delta^{18}O$ profile and soil water potential dynamics reveal that the soil under acacia has the fastest infiltration rate, which may be related to the preferential flow.

Soil water after precipitation can be seen as a mixture of precipitation ("new water") and antecedent soil water ("old water"). Based on isotope balance, old water composes over 30% of total soil water after a rainstorm. It appears that precipitation mixes with existing soil water to some degree and also pushes soil water downwards via piston flow. This is indicated by a broad correlation between $\delta^{18}O$ values in the precipitation time series and in the soil water vs depth profile. Soil water at a depth of 0–115 cm under grass has a residence time of about 20 days in the rainy season.

Groundwater recharge from precipitation mainly occurs in the rainy season, especially when rainstorms or successive heavy rain events happen. The dynamics of water table becomes lesser in magnitude from the upper reaches to lower reaches.

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