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Isotopic characterization and mass balance reveals groundwater recharge pattern in Chaliyar river basin, Kerala, India

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Study region: The Chaliyar river basin, Kerala State, India.
Study focus: Detailed understanding about spatio-temporal variation in the interaction and exchange of water between surface and sub-surface reservoirs is important for effective watershed management. Spatio-temporal variations in the oxygen isotopic composition ($\delta^{18}O$) were used to understand the interaction between groundwater and river water, and to estimate the groundwater recharge from river water in the Chaliyar river basin.
New hydrological insights for the region: Based on the spatio-temporal variation in $\delta^{18}O$ values of river and groundwater and fluctuation in ground water levels, following important inferences are made: (1) estimated river water contribution to post-monsoon groundwater recharge is ~16% in the lowland coastal area of the Chaliyar river basin and 29% in midland region; (2) north-east winter monsoon rains contribute to the groundwater of Chaliyar river basin only in an insignificant manner, and with a delayed response; (3) unlike river water samples which exhibit both seasonal and spatial variation of more than 3‰, the groundwater samples vary only marginally (~1‰) between the seasons and across the physiographic zones; (4) groundwater samples exhibit inverse altitude gradient in $\delta^{18}O$ values in the highland zone, in all the three seasons. This may be due to flow of the isotopically depleted groundwater down the gradient and evaporation of residual water in the upper reaches of the basin.

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1. Introduction

The water balance of a river basin is governed by precipitation, evapotranspiration, and overland and subsurface flows into and out of the basin, which may be highly variable in space and time (Winter, 1989; Van der Kamp and Hayashi, 2009). Groundwater recharge mainly occurs through infiltration of rainwater as well as surface water. On the other hand, groundwater can also play an important role in sustaining stream flow (Sear et al., 1999). Therefore, detailed understanding about spatio-temporal variation in the interaction and exchange of water between surface and sub-surface reservoirs is necessary for effective watershed management.

Stable isotopes of oxygen (^{16}O and ^{18}O) and hydrogen (^{1}H and ^{2}H or D) forming water molecules are inert and conservative in mixing relationship and hence used worldwide as a tracer to understand various hydrological processes including groundwater–surface water interaction and recharge characteristics (Gat, 2010; Criss, 1999; Kendall and Mc Donnell, 1998; Clark and Fritz, 1997). There are also several Indian studies in which stable isotopes have been used to understand various hydrological processes (Deshpande et al., 2003; Deshpande and Gupta, 2012; Deshpande et al., 2013; Achyuthan et al., 2013; Gupta et al., 2005; Sukhija et al., 2002; Saravana Kumar et al., 2010; Nachiappan et al., 1995; Nachiappan, 2000; Datta, 1999; Datta and Tyagi, 1995; Datta et al., 1994a,b; Navada and Rao, 1991; Gupta, 1983).

The isotopic composition of ground water is controlled by relative contribution from local rainfall, rivers and other surface water bodies. Rivers usually originate in high altitude regions where precipitation is isotopically depleted compared to that in the plains. Therefore, rivers are usually isotopically depleted compared to groundwater and local precipitation in the plains. In contrast, surface water bodies in plains are isotopically enriched in heavier isotopes due to continuous evaporation. Simultaneous monitoring of temporal variation in isotopic composition of groundwater and surface water can provide useful insights about spatio-temporally varying recharge characteristics and can help to estimate the recharge contribution of rain and river water to groundwater or vice versa. The isotopic difference between groundwater and other hydrological components (precipitation, river, lake, etc.) has been used to estimate the ground water recharge using simple mass balance (Yeh et al., 2009; Langhoff et al., 2006; Mathieu and Bariac, 1996; Payne, 1988). There are also a few Indian studies in which stable isotopes have been used to quantitatively estimate the groundwater recharge. For example, in the state of Karnataka, storm water contribution to ground water recharge was estimated to be ~19–27% (Shivanna et al., 1994). In Pushkar Canal Command area in the state of Andhra Pradesh, contribution of canal water to groundwater at Ellamilli and Kodavali locations was estimated to be, respectively, 41% and 13%; and contribution of precipitation to groundwater at these two locations was estimated to be 59% and 87% (Vijayakumar et al., 2011).

In this study, observed spatiotemporal variations in stable oxygen isotopic composition of groundwater and river water in the Chaliyar basin have been used to estimate the seasonally varying contribution of river water to groundwater recharge. In addition, regionally varying pattern of interaction between river water and groundwater, and the role of recycled vapour in local precipitation has been highlighted (Mukherjee et al., 2015).

2. Study area

The Chaliyar river basin is the third largest river basin in the state of Kerala in south India (Fig. 1). Chaliyar river originates from the Ilambalari hills in Gudalur taluk of Nilgiris district in Tamil Nadu, at an elevation of 2066 m above mean sea level. This interstate river has a total drainage area of 2923 km^2 of which 2535 km^2 lie in Kerala State and rest 388 km^2 in Tamil Nadu. The river has a length of about 170 km. In the lower reaches the river is also known as Beyporepuzha. The main river is contributed by the important tributaries Chaliyarpuzha, Punnapuzha, Maruthapuzha, Karimpuzha, Kanchirapuzha, Kuthirapuzha, Iruvenhipuzha and Cherupuzha (PWD, 1974). The drainage map of the Chaliyar river basin with sampling location is shown in Fig. 1.

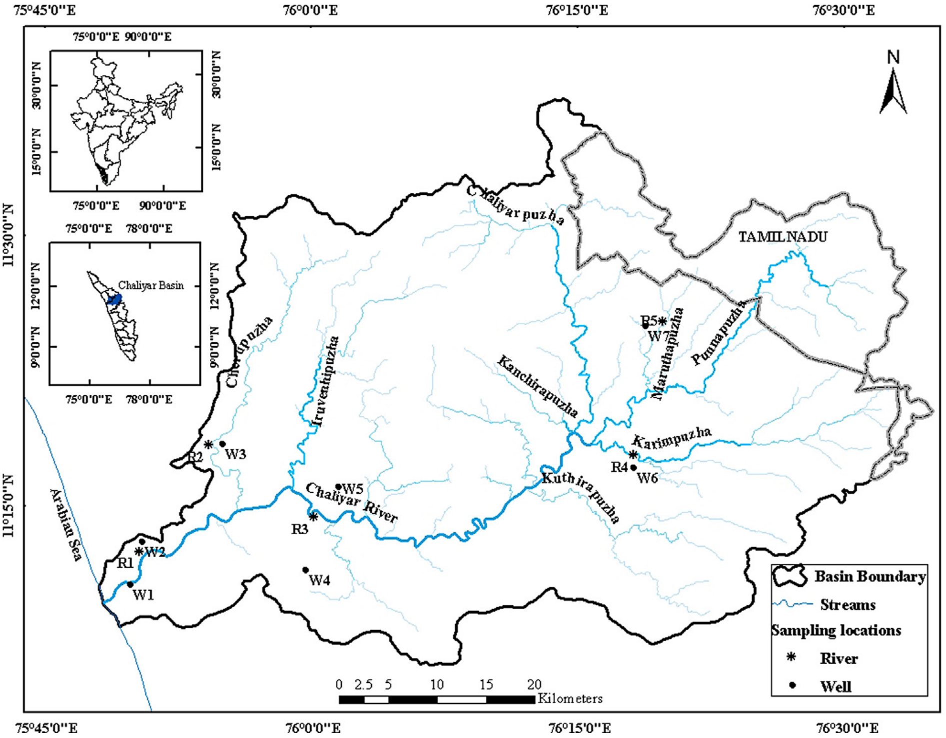

Fig. 1. Groundwater (W) and river water (R) sampling locations shown in the drainage map of the Chaliyar river basin.

2.1. Physiography and soils

The Chaliyar river basin can be broadly classified into three physiographic zones as given below (PWD, 1974): (1) the highland region in the eastern boundary of the state, situated 75 m above the mean sea level; (2) the midland region lying between 7.5 and 75 m above mean sea level; and (3) the lowland region lying below 7.5 m above mean sea level.

The five different types of soils which occur in this river basin are coastal alluvium, riverine alluvium, lateritic soil, brown hydromorphic soil and forest loam. Coastal alluvium is predominantly of marine origin, with some fluvial sediment along the coast. Riverine alluvium is seen along the river valleys, cutting across the extensive laterite soils. The lateritic soil is the predominant soil type in the basin and it occurs in the midland and highland regions. The laterite soil is a weathered product derived under humid tropic conditions. The brown hydromorphic soil is the second predominant soil type found in this basin. This occurs mostly in the valleys between undulating topography in the midland and in the low lying areas in the coastal strip. This soil is formed as a result of transportation of materials from adjoining hill slopes and deposition by the river. The forest loam is developed in the hilly and forest areas. The upper layer of soil is highly enriched with organic matter derived from the decomposed leaves. Due to organic matter, the soil is dark reddish brown to black in colour (CGWB, 2009).

2.2. Rainfall and climate

The two monsoons, namely, south-west (SW) monsoon in summer and north-east (NE) monsoon in winter, are the deciding factors in the climate of the basin. The SW monsoon begins in June and ends in September contributing to about 60% of the annual rainfall. The NE monsoon is experienced in the month of October–November contributing to about 25% of the total annual rainfall, January–May are

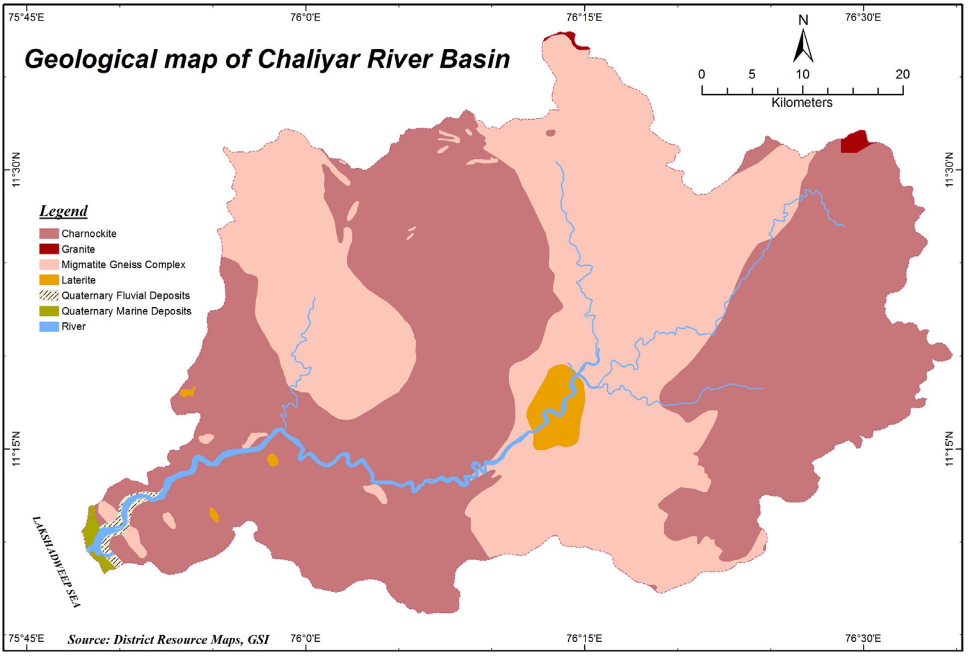

Fig. 2. Map of the study area showing important geological features.

the dry months of the year, about 15% of the total rainfall is received during this period. The coastal belt is humid and damp and relative humidity decreases towards the eastern parts of the basin. The climate of the basin is generally moderate. The maximum temperature ranges from approximately 22 to 33 °C and the minimum temperature ranges from approximately 22 to 26 °C. The average annual maximum temperature is 30.9 °C and minimum is 23.7 °C. The temperature starts rising from January reaching the peak in April. It decreases during monsoon months (Ambili, 2010).

2.3. Geology and geomorphology

Geologically the Chaliyar river basin is characterized by charnockites, metapelites, schists, gneisses and quartz reefs of Pre-Cambrian age (Hariharan, 2001; Ambili, 2010), laterites of Pleistocene age and alluvial formations of Recent to sub Recent age. Laterites formed due to tropical weathering of crystalline rocks occur as residual formation, capping over the older rocks. Laterites are found as both primary (in situ) as well as secondary (transported) material. They are exposed as irregular patches with varying thickness from one geomorphic unit to the other. The recent alluvial formation includes coastal sand, river alluvium and valley fill. These are composed of fine to medium grained sand. The important geological features in the study area are shown in Fig. 2.

Geomorphologically, the Chaliyar drainage basin includes parts of distinct provinces like the Wayanad plateau and the Nilgiri hills at higher altitude, the Nilambur valley forming the slopes of the foot hills and low lands adjoining the main trunk of the Chaliyar river. The lowest reaches of the Chaliyar main channel shows a sudden change in the geomorphology beyond 110 km from the source in the downstream direction. The channel takes a sharp bend at 110 km and beyond this the river shows meanders at consistent intervals. The main stream Chaliyar is a 7th order stream and the drainage network analysis shows that the pattern is dendritic combined with rectangular. The latter is the more characteristic for the area close to the confluence of Punnapuzha with Chaliyar river (Hariharan, 2001; Ambili, 2010).

Table 1
$\delta^{18}O$ (‰) of river water (R) and groundwater (W).

Sample ID	Pre-monsoon $\delta^{18}O$ (‰)	Monsoon $\delta^{18}O$ (‰)	Post-monsoon $\delta^{18}O$ (‰)
Lowland			
River (R-1)	−1.2	−4.5	−1.8
G W (W-1)	−4.9	−5.1	−4.5
G W (W-2)	−4.9	−4.9	−4.3
Midland			
River (R-2)	−2.7	−4.4	−3.7
River (R-3)	−3.0	−4.9	−3.1
G W (W-3)	−4.2	−5.1	−4.0
G W (W-4)	−4.6	−5.0	−4.3
G W (W-5)	−4.9	−5.1	−4.4
Highland			
River (R-4)	−3.9	−5.3	−3.9
River (R-5)	−4.4	−5.1	−4.2
G W (W-6)	−4.3	−5.2	−4.0
G W (W-7)	−3.9	−4.5	−3.7

3. Methodology

River water samples from five locations (R1 to R5 in Fig. 1), and groundwater samples from seven locations (W1 to W7 in Fig. 1) were collected periodically for isotope monitoring. The sampling locations were selected to represent the three physiographic zones, namely, lowland, midland and highland. Water samples were collected during March 2011, August 2011 and January 2012 representing, pre-monsoon, monsoon and post-monsoon seasons, respectively. The water level fluctuations in the observation wells were monitored bimonthly. Water samples were analysed for stable oxygen isotopic composition ($\delta^{18}O$). Measurement of $^{18}O/^{16}O$ ratio was done by CO_2 equilibration method, using Isotope Ratio Mass Spectrometer (IRMS) at the Isotope Hydrology Division of Centre for Water Resources Development and Management (CWRDM), Kozhikode using continuous flow measurement techniques. The isotopic composition of equilibrated CO_2 gas reflects the $^{18}O/^{16}O$ ratio of the water sample and the data acquisition system directly provides the isotopic composition of water samples. The isotopic composition of water is usually expressed in δ notation in terms of per mil (‰) with reference to an international standard [$\delta^{18}O$ or $\delta D = (R_{sample}/R_{standard} - 1) \times 1000$], where R denotes the abundance ratio of heavy to light isotope [i.e., $^{18}O/^{16}O$ or ^{2}H (or D)/^{1}H] in the sample or standard. In the case of water, the international standard refers to Vienna-Standard Mean Ocean Water (V-SMOW) (Craig, 1961; Gonfiantini, 1978). The overall external precision obtained from repeated analyses of multiple aliquots of secondary laboratory standard was ±0.18‰ for $\delta^{18}O$.

4. Results and discussion

4.1. Isotopic characteristics of groundwater and river water

The measured values of $\delta^{18}O$ for river water and ground water samples collected from three physiographic zones and during three different seasons, namely, pre-monsoon, monsoon and post-monsoon are given in Table 1. The observed spatio-temporal variations in isotopic composition of groundwater and river water samples are graphically shown, respectively, in Fig. 3a and b, which reveal the following important points.

(1) Chaliyar river water samples in all physiographic zones show more prominent seasonal and spatial variations compared to corresponding groundwater samples.
(2) Isotopic difference between river water and groundwater samples is minimum during monsoon season and maximum during pre-monsoon season.

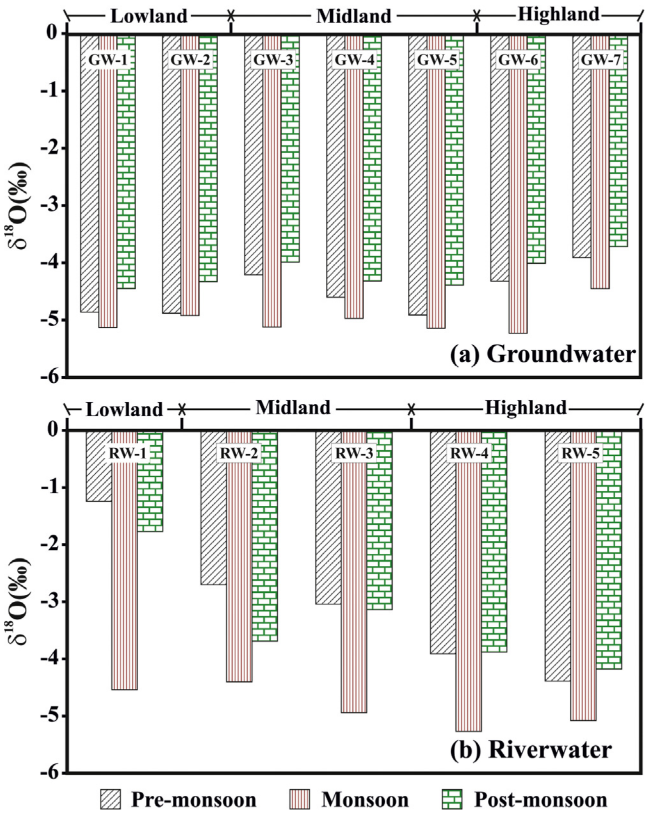

Fig. 3. Variation in the $\delta^{18}O$ values of (a) groundwater and (b) river water samples from Chaliyar river basin collected during pre-monsoon (March), monsoon (August) and post-monsoon (January) from three physiographic zones, namely, lowland, midland and highland.

(3) Isotopic depletion with increasing altitude is observed in river water samples during pre-monsoon months, with $\delta^{18}O$ values decreasing from −1.2‰ in lowland zone to −4.4‰ in highland zone. Isotopic depletion in rain occurs primarily because heavier isotopes are rained out in the lower altitudes and lighter isotopes are preferentially deposited in the higher altitude. In addition to this altitude effect, the observed isotopic depletion in river water with increasing altitude during pre-monsoon season may also be due to dwindling flow in the river during pre-monsoon, increased evaporation and mixing of evaporated river water with sea water penetrating in the mouth of the river in the lower altitude. This isotopic depletion observed in river water samples during pre-monsoon season diminishes in monsoon season during which $\delta^{18}O$ values of river Chaliyar in the lowland (−4.5‰) zone are very close to that in the highland (−5.3‰). This pattern of isotopic depletion in river water with increasing altitude is observable once again in the post-monsoon season, with $\delta^{18}O$ values decreasing from −1.8‰ in lowland to −4.2‰ in highland.

(4) Unlike river water samples which exhibit both seasonal and spatial isotopic variation of more than 3‰ in $\delta^{18}O$, the groundwater samples vary only a little between the seasons (∼1.2‰) and across the physiographic zones (∼1.5‰).

(5) Groundwater samples strangely exhibit an inverse altitude gradient, with the most enriched $\delta^{18}O$ values in the highland zone, in all the three seasons. This may be due to flowing of the isotopically depleted groundwater down the gradient and evaporation of residual groundwater in the upper reaches of the basin.

(6) In case of groundwater samples, there is an isotopic enrichment in post-monsoon season (January), compared to monsoon season (August) which is unexpected for this region. This is because, the NE winter monsoon rainfall in this region during Nov-Dec is known to be isotopically depleted (range: −5.9‰ to −8.6‰) compared to SW summer monsoon rainfall during June–September (range: −1.3‰ to −5.6‰) (Warrier et al., 2010). Therefore, the observed isotopic enrichment in January (instead of expected depletion) suggests that NE winter monsoon rainfall does not replenish groundwater quick enough (within 1–2 months) to manifest isotopic depletion in groundwater in post-monsoon season (January).

(7) Instead of expected isotopic depletion in the post-monsoon (January), the same is observed a few months later, i.e., in the pre-monsoon season (March), with lower δ^{18}O in groundwater from all the three physiographic zones compared to the values in January. This indicates that it takes longer (maximum 3–4 months) for precipitation during NE winter monsoon to replenish the groundwater in Chaliyar basin. This delayed effect of NE winter rains could be due to the fact that rainfall during NE winter monsoon is only ∼25% of the annual rainfall in Chaliyar basin and it takes longer for isotope effect to manifest in groundwater. However, this inference can be tested only after long-term isotopic monitoring.

(8) Isotopic depletion in March (pre-monsoon) compared to preceding post-monsoon (January), which is observed in groundwater, is not observed in river water (except in RW-5), possibly due to evaporative enrichment. This suggests that even during the relatively cooler months of November–December to March, there is considerable evaporation from the river water.

(9) In general the river water samples are enriched in ^{18}O compared to corresponding groundwater samples regardless of physiographic zones or season of sampling. This indicates not only the more intense evaporation from river water compared to groundwater, but also that the Chaliyar river does not cause significant groundwater recharge in the lean flow season, or else the groundwater would also have shown considerable isotopic enrichment, similar to that of river water.

(10) River water samples collected from the lowland coastal area have considerably enriched δ^{18}O value in pre-monsoon (−1.2‰) and post-monsoon (−1.8‰) compared to monsoon which suggests the mixing of evaporated river water towards its terminal end with sea water penetrating in the river in these seasons. But in monsoon season, the δ^{18}O of river in the lowland coastal area is low (−4.5‰) and similar to the δ^{18}O values (−4.4‰ to −5.3‰) of other samples away from the coast, indicating the effect of dilution by incoming fresh water, derived from higher altitude regions where precipitation is known to be isotopically depleted to progressive rainout of heavier isotopes.

4.2. Groundwater recharge from river

The total groundwater recharge in Chaliyar river basin is contributed by two major constituent components, namely, rainwater and river water. A two component (groundwater and river water) mixing model has been used in this study to estimate the river water fraction in groundwater recharge. As mentioned earlier, there is a distinct difference between δ^{18}O values of groundwater and river water samples, particularly during pre-monsoon and post-monsoon seasons (Table 1 and Fig. 3).

The fraction of river water in ground water was quantitatively estimated from the following isotope mass balance equation; from this percentage recharge contribution of river water was calculated. As per the isotope mass balance equation:

$$\delta_1 M_1 + \delta_2 M_2 = \delta_{\mathrm{AM}}$$

$$M_1 + M_2 = 1$$

where δ_1 represents δ^{18}O of the pre-monsoon groundwater end-member (without any river contribution) and δ_2 represents the δ^{18}O of river water. δ_{AM} is the δ^{18}O of admixture, comprising pre-monsoon groundwater and river water. M_1 and M_2 are the fractions of pre-monsoon groundwater and river water in the admixture, respectively.

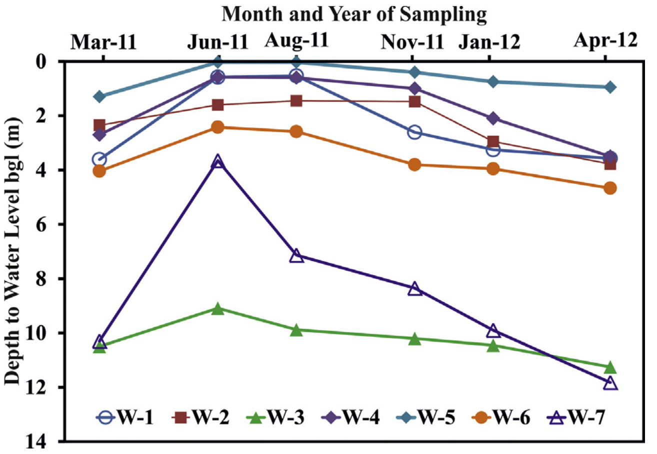

Fig. 4. Temporal fluctuations in the ground water levels in the sampled wells.

From the above equations the percentage of river water mixed with groundwater can be evaluated from the following equation:

$$\text{River water contribution}\quad(\%) = \left[\frac{(\delta_{AM} - \delta_1)}{(\delta_2 - \delta_1)}\right] \times 100$$

In the above calculations, ground water in the post-monsoon season (isotopic composition δ_{AM}) is considered to be a mixture of the pre-monsoon groundwater (isotopic composition δ_1) present in the aquifer prior to the monsoon and the infiltrating post-monsoon river water (isotopic composition δ_2). Using the average values of pre-monsoon groundwater and post-monsoon river water for the three physiographic zones as the end-members, the river water contribution to ground water in each zones has been estimated. The $\delta^{18}O$ values of the end-members used in the above mass balance equations and the estimated river water contribution to groundwater recharge have been given in Table 2. The three columns in Table 2 which contain end-member values have been identified with respective labels, namely, δ_1, δ_2, and δ_{AM}. The $\delta^{18}O$ values of pre-monsoon groundwater end-members (δ_1) for lowland, midland and highland zones are, respectively, −4.9‰, −4.6‰, and −4.1‰. The $\delta^{18}O$ values of the post-monsoon river water end members (δ_2), for lowland, midland and highland zones are, respectively, −1.8‰, −3.4‰, and −4.0‰. Using the above approach, the river water contribution to post-monsoon groundwater (e.g., at Farook and Olavanna stations) in the coastal area of the Chaliyar river basin is estimated at ~16%. The groundwater in the midland region (Thavannor, Areakkode and Chathamangalam) is estimated to receive ~29% of river water contribution. This approach, however, is not applicable in the highland zone because the average post-monsoon groundwater $\delta^{18}O$ value (−3.9‰) is higher than the average $\delta^{18}O$ values for pre-monsoon groundwater (−4.1‰) and the post-monsoon river (−4.0‰). This suggests that in the highland zone, with steep slope, the groundwater is not recharged by river water which quickly flows down the gradient. Instead, it seems that groundwater in the highland is probably recharged by the rainwater which has undergone significant evaporation during canopy interception and also while flowing through tortuous surface and sub-surface path in mountainous terrain.

4.3. Groundwater–rainwater interaction

The temporal variations in the ground water levels in the sampled wells (W-1 to W-7) from different physiographic zones in the Chaliyar river basin are shown in Fig. 4. The highest ground water levels in all the wells are observed during SW summer monsoon season (June, 2011 and August, 2011) suggesting that maximum groundwater recharge occurs from SW monsoon rains. It is also seen that

Table 2
Percentage contribution of river water in ground water recharge in different physiographic zones.

Zone	Groundwater $\delta^{18}O$ (‰)					River water $\delta^{18}O$ (‰)				
	Station name	Pre-monsoon	Avg. pre-monsoon (δ_1)	Post-monsoon	Avg. post-monsoon (δ_{AM})	Location	Pre-monsoon	Post-monsoon	Avg. post-monsoon (δ_2)	% Contribution of river to groundwater recharge
L	Farook (W-1)	−4.9	−4.9	−4.45	−4.4	River (R-1)	−1.2	−1.8	−1.8	16
	Olavanna (W-2)	−4.9		−4.33						
M	Chathamangalam (W-3)	−4.2	−4.6	−4.0	−4.2	River (R-2)	−2.7	−3.7	−3.4	29
	Thavannoor (W-4)	−4.6		−4.3		River (R-3)	−3.0	−3.1		
	Areakkode (W-5)	−4.9		−4.4						
H	Karulai (W-6)	−4.3	−4.1	−4.0	−3.9	River (R-4)	−3.9	−3.9	−4.0	–
	Marutha (W-7)	−3.9		−3.7		River (R-5)	−4.4	−4.2		

Physiographic zones: L, lowland; M, midland; H, highland; W, groundwater; R, river water; δ_1, pre-monsoon groundwater end-member; δ_2, post-monsoon river end-member; and δ_{AM}, post-monsoon groundwater being admixture of the two end-members.

after August-2011, groundwater levels in all the wells continue to decline progressively. The continuation of this declining trend even during and after the NE winter monsoon season (i.e., in November, 2011 and January, 2012) suggests that NE winter rains do not contribute to the groundwater in any significant manner, excepting in W-2 where water level increases slightly during August, 2011 to November, 2011. The inference from water level fluctuation, that NE winter rains do not contribute to the groundwater, in a way corroborates the earlier inference that Chaliyar river does not cause significant groundwater recharge in the lean flow season. This is perhaps due to the fact that NE winter rains amounts to only 25% of annual rainfall in the region.

The maximum water level fluctuation is observed in well number W-7 in which water level increases suddenly from $\sim$10 m below ground level (bgl) in March, 2011 to $\sim$4 m bgl in the beginning of the SW monsoon season (June, 2011). Also the water level in this well decreases suddenly to $\sim$7 m in August, 2011 which suggests that the well is located in the recharge zone of the basin from where rainwater is infiltrating and quickly drained down the slope to feed the aquifers in the lower reaches of the basin.

5. Summary and conclusions

Spatio-temporal variations in the oxygen isotopic composition ($\delta^{18}O$) of groundwater and river water samples, and seasonal variation in groundwater levels have been used to understand the groundwater-river water interaction and to estimate groundwater recharge from river water in the Chaliyar river basin. Some of the important observations and inferences are: (1) River water contribution to post-monsoon groundwater is estimated at $\sim$15% in the lowland coastal areas and 29% in midland region. (2) NE winter rains contribute to the groundwater of Chaliyar river basin only in an insignificant manner and with delayed response. (3) Unlike river water samples which exhibit both seasonal and spatial variation of more than 3‰, the groundwater samples vary only marginally ($\sim$1‰) between the seasons and across the physiographic zones. (4) Groundwater samples exhibit inverse altitude gradient, with the most enriched $\delta^{18}O$ values in the highland zone, in all the three seasons. This observation, together with rapid increase and decrease in groundwater level in upper reaches, suggests rapid downward flow of isotopically depleted groundwater from the upper reaches and groundwater recharge by evaporated residual water. (5) In general, the river water samples are enriched in ^{18}O compared to corresponding groundwater samples regardless of physiographic zones or season of sampling. This indicates not only the more intense evaporation from river water compared to groundwater, but also that the Chaliyar river does not cause significant groundwater recharge in the non-monsoon season, or else the groundwater would also have shown considerable isotopic enrichment, similar to that of river water.

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