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# Hydrological functioning of forested catchments, Central Himalayan Region, India



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## Abstract

**Background:** Central Himalayan forested catchments provide fresh water supply and innumerable ecosystem services to millions of people. Hence, the understanding of linkages between forests and water is very crucial for availability and quality of water at catchment scale. Therefore, the present study aims to understand the hydrological response of two forested catchments (namely, Arnigad and Bansigad) in the Central Himalayan Region.

**Methods:** Three-years' data (March, 2008 to February, 2011) were collected from meteorological and hydrological stations in Arnigad and Bansigad catchments. The present paper describes the mean hydrological response of these forested catchments investigated through detailed field investigation.

**Results:** The annual hyetograph analysis revealed that the rainfall at both the catchments was highly seasonal, and wet-period (June–September) plays a key role in catchment functioning. Exceedance of rainfall threshold of ~ 200 mm (~ 10% of annual rainfall) significantly increased streamflow generation in both catchments. In Arnigad, the stream was perennial with a mean baseflow of ~ 83 mm per month (~ 6% of annual baseflow) whereas, Bansigad had greater seasonality due to lack of streamflow during the pre-wet-period (March–May). Separation of hydrographs in Arnigad and Bansigad catchments i.e. stormflow (6% and 31%, respectively) and baseflow (50% and 32%, respectively) helped to understand the probability of flooding during wet-period and drought during dry-period. The forest ecosystem in Arnigad displayed healthier hydrological functioning in terms of reduced stormflow (82%), and enhanced baseflow (52%), soil moisture (13%), steady infiltration rate (22%) and lag time (~ 15 min) relative to Bansigad. These enhanced values indicated soil capability to store water in the forested catchment (Arnigad) and helped to understand the volume of water (discharge) that was available during dry-period. The lower denudation rate at Arnigad by 41% resulted in decreased suspended sediment (18%) and bed load (75%) compared to Bansigad. Further, the enhanced dissolved solids in the Arnigad stream resulted from the higher organic matter generated in the forest floor.

**Conclusion:** This study shows that rainfall during the wet-period was the main driver of hydrological functioning, whereas, forests provided substantial services by regulating water balance, soil moisture and sediment budget through different mechanisms of forest components at catchment-scale in the Central Himalayan Region.

**Keywords:** Forested catchments, Stormflow, Baseflow, Soil moisture, Sediment transport, Water budget

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## Introduction

Catchments, as environmental systems, are characteristically complex and heterogeneous (Kirchner 2016), consisting of wide range of processes (natural/anthropogenic) which may function simultaneously, affecting spatial and temporal variability of the system (Zabaleta and Antiguada 2013). This is particularly evident for mountain headwater catchments where interactions between geology, geomorphology, vegetation and harsh topography coupled with climatic forcing and multiple water inputs beyond rainfall (spring water, meltwater from snowpack, glaciers and permafrost), makes the hydrological response highly complex (Bolch et al. 2019; Scott et al. 2019). Understanding those processes is crucial in order to manage runoff (qualitatively and quantitatively), particularly when climate or landuse are changing (Naef et al. 2002; Negley and Eshleman 2006; Stewart and Fahey 2010). The change of landuse especially forest loss or forest degradation interrupts the hydrologic cycle, disturbing the food chain and habitat (Thompson et al. 2011; Jones 2013), which in turn leads to serious damage in functioning of the ecosystem (Bond et al. 2008; Blumenfeld et al. 2009; Wei and Zhang 2010; Brandon 2014; Pereira et al. 2014; Poirier and Nguyen 2017).

Substantial advancements have been made in forest hydrological research all over the globe; nevertheless, studies in the Himalayas are in their infancy (Qazi et al. 2020). Many headwater catchments in the Central Himalayan Region (CHR) in India are covered with dense forests (Tiyagi et al. 2014), which provide numerous ecosystem services to millions of people living in this region (Tiwari et al. 2017). However, these services have not gained much attention in national economic decision-making (Pandey 2012). Studies (Qazi et al. 2012; Tiyagi et al. 2014; Chauhan et al. 2017; Qazi et al. 2017; Qazi and Rai 2018) suggest that forests play a significant role in hydrological functioning of catchments in the CHR. Unfortunately, these forests are under severe stress due to dam construction, deforestation, overgrazing, tunneling, and other anthropogenic activities as well as climate change (Chaturvedi et al. 2011; Gopalakrishnan et al. 2011; Tiwari et al. 2017), disrupting hydrological services at local or catchment scale in the CHR. Further, long term field-based data, which is the key for forest and water managers to understand and predict the spatial and temporal variability of hydrology, is also scarce in this region.

The present study aims to contribute to a better understanding of the hydrological functioning of forested catchments in the CHR, India, by comparing dry and wet-period variations of hydrological processes over a 3-year period for two forested catchments: dense oak forest and a degraded oak forest. In the present study, long

term field-based data has been used in order to understand (i) how forests offer services to regulate hydrological processes, specifically streamflow, soil moisture and sediments; (ii) how spatial and temporal variability affects hydrological functioning at catchment-scale in the CHR. The hydrological response of forested watersheds was studied for three consecutive years (March, 2008 to February, 2011) and the paper displays the average hydrological scenario for these catchments. Such understanding is necessary to improve our ability to manage multiple water resources at catchment-scale, and to meet the needs of local people without adversely affecting the environment.

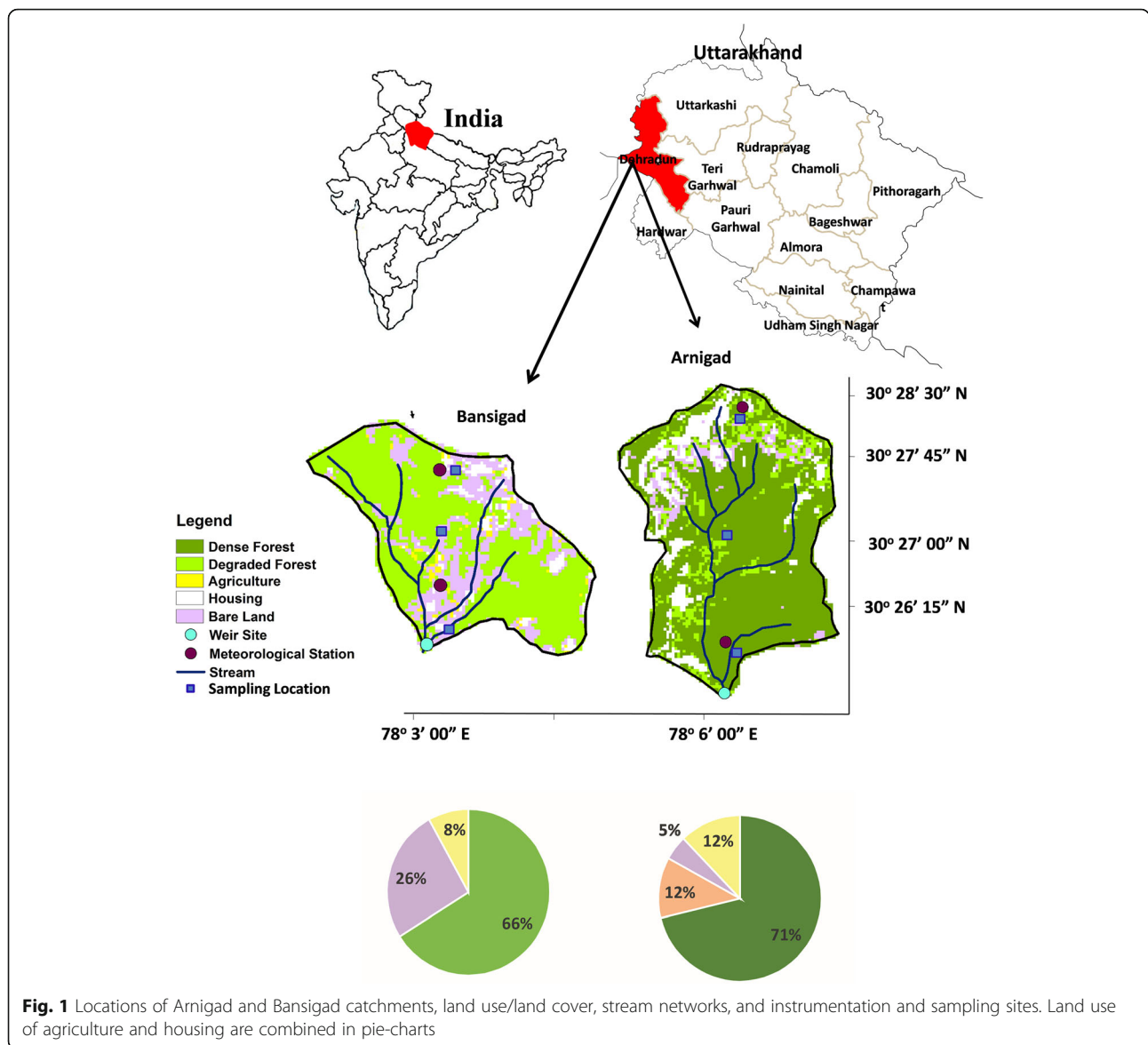
## Description of study area

### Morphometric characteristics of catchments

Two small neighboring headwater catchments, i.e. the dense-forested catchment, Arnigad (285.7 ha; 30°27' N, 78°5.5' E) and the degraded-forested catchment, Bansigad (190.5 ha; 30°27' N, 78°2.5' E) in Mussoorie area, CHR (Fig. 1) were selected for the present study. Both catchments are located near (~1.5 km areal distance) each other, have similar mean slopes (21.86°, Arnigad and 23.61°, Bansigad) and aspects (south-facing). The morphometric characteristics of both the catchments are also almost same (Table 1). Both the catchments are drained by second-order streams at the gauging site. The Arnigad subsidizes to the Rispana River (Ganga River Basin) whereas the Bansigad subsidizes to the Tones River (Yamuna River Basin, a tributary of Ganga River). Both catchments are protected under private ownership and management and no forest cover change was noticed during the study period.

### Characteristics of vegetation

Arnigad and Bansigad catchments are dominated by Oak forest (*Quercus leucotrichofora*), having 237 and 124 ha of forest canopy cover (FCC), respectively (Fig. 1). The image for FCC (Linear Imaging Self Scanning Sensor, LISS-III satellite imagery, resolution 23.5 m) was taken from the Bhuvan website in 2008. Landuse/Land cover maps were developed from LISS-III imagery with the help of software (ERDAS Imagine 9.2). Tree density (TD) was measured by laying out the quadrates. Six representative sites (three in each watershed) were selected and five quadrates (10 m × 10 m) were laid down at each site. TD was higher in Arnigad catchment ( $487 \pm 210$  trees-ha<sup>-1</sup>) as compared to Bansigad catchment ( $380 \pm 194$  trees-ha<sup>-1</sup>). Diameter at breast height (DBH) was measured at each quadrate (at 1.73 m height) by using a tape measure. Average DBH was also larger at Arnigad ( $30.57 \pm 8$  cm) as compared to Bansigad ( $16 \pm 7$  cm). At Bansigad, out of 15 quadrates selected at three sites, the species composition was found to be 64% Oak, 17%



Cupressus, and 19% others (which includes Bhimal, Parang, Kail, Khadki, Terbara, Jungli Nashpati), whereas at Arnigad, the species composition was 98% Oak and 2% others. The percentage differences of FCC, TD and DBH were calculated as  $((A-B) \cdot B^{-1} \times 100)$ , where 'A' and 'B' represents Arnigad and Bansigad, respectively. It was found that FCC (91%), TD (28%) and DBH (98%) were higher at Arnigad as compared to Bansigad.

**Climatology of the region**

The climate of the study area was considered to be Cfa (Warm Oceanic climate/Humid subtropical climate) according to the Köppen-Geiger climate classification. Mean annual rainfall was 2243 mm (1869–2010), most of which (80%) occurred during summer months (June to September) while 20% occurred during the winter

months (Sharma et al. 2012). Maximum annual temperature was 28 °C and was observed in May, while minimum annual temperature was 6 °C and was observed in January (Sharma et al. 2012).

**Methodology**

**Rainfall measurements**

In order to measure rainfall, two types of rain gauges were used: a tipping bucket rain gauge (Rainwise, USA; 325 cm<sup>2</sup> orifice, 0.25 mm per tip) and manual rain gauge (RK Engineering, India; 2000 cm<sup>2</sup> orifice). The data from the tipping bucket rain gauges were cross-checked with the manual rain gauges (1-day temporal resolution) installed at the same measurement site. Both types of rain gauges were installed at two elevations (at ~ 1700 m and ~ 1900 m a.s.l.) in each catchment. There was no

**Table 1** Methodology adopted and result of morphometric characteristics of Arnigad and Bansigad catchment

Sr. No.	Parameters (Symbols), Units	Formula/Software used	Arnigad	Bansigad	Reference
1	Elevation (Z), m	Arc GIS	1650–2230	1620–2170	
2	Perimeter (Pe), km	Arc GIS	7.54	6.31	
3	Slope (S), degree		21.86*	23.61*	
4	Stream Order (U)	Arc GIS	Hierarchical Rank		Strahler 1957
5	Stream Number (Nu)	Arc GIS	7	7	
6	Stream length (Lu), km	Arc GIS	6*	5*	Horton 1945
7	Mean stream length (Lsm), km	$Lsm = Lu/Nu$	1*	1	Strahler 1964
8	Basin Length (Lb), km	Arc GIS	2.50	1.55	
9	Drainage density (Dd), km·km <sup>-2</sup>	$Dd = Lu/A$	2.10	2.53	Horton 1932
10	Texture ratio (T), km <sup>-1</sup>	$T = Nu/Pe$	0.93	1.12	Horton 1945
11	Length of overland flow (Lg), m	$Lg = \frac{1}{2} * Dd$	1.05	1.26	Horton 1945
12	Drainage Area (A), km <sup>2</sup>	Arc GIS	2.86	1.91	
13	Circularity ratio (Rc)	$Rc = 12.57 * (A/Pe^2)$	0.63	0.60	Miller et al. 1953
14	Elongation ratio (Re)	$Re = 2/Lb * (A/ )^{0.5}$	0.76	1.00	Schumm 1956
15	Form Factor (Ff)	$Ff = A/Lb^2$	0.46	0.79	Horton 1932
16	Constant of channel maintenance (C), km <sup>2</sup> ·km <sup>-1</sup>	$C = 1/Dd$	0.48	0.40	Schumm 1956
17	Drainage Frequency (Fμ), km <sup>-2</sup>	$Fs = Nu/A$	2.45	3.67	Horton 1932
18	Basin relief (R), m	$R = Z - z$	580	550	
19	Relief ratio (Rr)	$Rr = R/Lb$	232	355	Schumm 1956

\*Mean value

significant difference between the rainfall sums measured at the two stations in both the catchments. Apparently, the elevation difference between the two stations was inadequate, while, the slope, aspect and other morphometric characteristics which are vital factors affecting rainfall in CHR (Katiyar and Striffler 1984), were almost similar in both the catchments (Table 1).

**Discharge measurements**

A rectangular weir with a sharp-crested 120° V-notch was constructed for better gauging of low flows at both the catchments (Fig. 2). The width of the weir was 4.8 and 6.6 m at Arnigad and Bansigad, respectively. Water levels were measured using Automatic Water Level Recorder (AWLR) at 15-min intervals and converted



**Fig. 2** View of the type of broad-crested compound weirs used to gauge streamflow at Arnigad and Bansigad

into discharge. AWLR (Virtual make) is an Optical Shaft Encoder based instrument with float and pulley (Range: 0 to 5 m, Resolution: 1 mm and Accuracy:  $\pm 5$  mm). Hydrograph separation was done with the help of physically based filter technique given by Furey and Gupta (2001). Furthermore, baseflow recessions were examined by using the method described by De Zeeuw (1973). The dry period (1st Oct. 2009 to 28th Feb. 2010) was selected for recession period because of clear visibility of the end of direct flow or starting point of baseflow.

#### Soil moisture measurements

In the present study, WATERMARK Sensors were used for the measurement of soil moisture. WATERMARK Sensor (IRROMETER, California) is a granular matrix sensor (Range: 0–200 Centibar). Three sites were selected at both the catchments for measuring the soil potential (Fig. 1) and sensors were installed at 25, 50 and 80 cm depths, at each site. The soil matric potentials from all the sensors were monitored fortnightly throughout the study period. During sensor installation, undisturbed soil samples were collected from all three depths at each site and soil moisture retention curves were developed with the help of pressure plate apparatus for 0.1, 0.33, 0.5, 0.7, 1, 3, 5, 7, 10 and 15 bar pressure. The soil moisture retention curves were used to convert the observed soil matric potential values into equivalent values of volumetric soil moisture content (SM). SM values held at 0.33 bar were considered as field capacity (FC) of catchments (Thompson 1999).

#### Annual water budget

The hydrologic cycle for both catchments was calculated mathematically by the water budget equation (Edwards et al. 2015):

$$Q_t = P - ET \pm \Delta S \pm \Delta G$$

where  $Q_t$  is total streamflow,  $P$  is rainfall,  $ET$  is evapotranspiration,  $\Delta S$  is the change in soil moisture storage (i.e., water present in soil), and  $\Delta G$  is the change in groundwater storage. The corresponding changes in soil moisture ( $\Delta S$ ) and groundwater ( $\Delta G$ ) storage between water years were derived by associated difference in volumes of soil moisture and baseflow at the start and finish of each water year. Combining the  $Q_t$ ,  $P$ ,  $\Delta S$  and  $\Delta G$ , gave apparent annual evapotranspiration losses ( $ET$ ) for the catchments. Average values of three respective water years were used in this study.

#### Sediment measurements

The water samples were collected in 1-l bottles at the gauging sites on the mainstream (Fig. 2). The collected water samples were analyzed by following a grab sample method (International Atomic Energy Agency 2005).

Whatman-72 filter papers were used for the separation of suspended sediments from the water samples. During the wet-period (June–September), the sampling was done three times a day: 8:00 AM, 2:00 PM and 8:00 PM whereas during the dry-period (October–May), sampling frequency was daily (8:00 AM). The suspended sediment concentration ( $\text{mg}\cdot\text{L}^{-1}$ ) was converted into suspended sediment load, suspended sediment load (SSL) ( $\text{t}\cdot\text{km}^{-2}$ ) by using conversion factor, discharge and area of the catchments.

Total dissolved solids were measured using TDS meter. During wet-period, the frequency of TDS measurement was on daily basis, however, during rest of the year the frequency was once every fortnight as there was no significant change in TDS. The concentration of TDS (ppm) was converted into total dissolved load, Total dissolved load (TDL) ( $\text{t}\cdot\text{km}^{-2}$ ) using a conversion factor based on the discharge and area of the catchments.

Bed load (BL) was estimated following Hedrick et al. (2013). The pond like structure (6 m  $\times$  4.8 m for Arnigad and 12 m  $\times$  6.62 m for Bansigad) at gauging sites were constructed so that sediments could accumulate within them. It was assumed that most of the BL material got deposited in these structures. The volumes of BL were derived by measuring various depths/heights of deposited material at these structures. A bulk density of 1.4  $\text{t}\cdot\text{m}^{-3}$  (BBMB, Bhakra Beas Management Board 1997) was used for the conversion of these volumes into mass. The measurement of accumulated BL followed by mechanical cleaning was carried out every month; however, during wet-period, the frequency of measurements followed by cleaning was 5–6 times in a month to avoid flushing of bed material during peak events. Total sediment budget is the sum of SSL, TDL and BL.

In the Himalayan region, high relief and high intensity monsoonal rainfall provides favorable conditions for mass wasting (Korup and Weidinger 2011). Long-term mass wastage or denudation rates were estimated following Gregory and Walling 1973:

$$\text{Rate of denudation} = \frac{\left( \frac{\text{Total load}}{\text{Area} \times \text{Density}} \right)}{1000}$$

Denudation ( $D$ ) rates are expressed in  $\text{mm}\cdot\text{yr}^{-1}$ , which is equivalent to  $\text{m}^3\cdot\text{km}^{-2}\cdot\text{yr}^{-1}$ , total load is in  $\text{tonnes}\cdot\text{yr}^{-1}$ , area is in  $\text{km}^2$  and the average density of rock or soil was considered to be  $2.67 \text{ g}\cdot\text{cm}^{-3}$  (Lupker et al. 2012; Chauhan et al. 2017).

#### Infiltration measurements

Eight infiltration tests were conducted (4 in each catchment) with the help of double-ring infiltrometers in March 2010 when the soil profile had dried out. The inner ring was 30 cm in diameter and 15 cm high, while

the outer ring was 60 cm in diameter and 15 cm high, respectively.

### Soil properties

To evaluate the soil properties, soil samples were collected from predetermined depths of 0–15, 15–30, 30–60, 60–90 and 90–120 cm by using an Auger. All soil samples were collected at six representative sites (three in each catchment) (Fig. 1). The three sites spanned a gradient from ridgeline to catchment outlet (1650–2230 m a.s.l. for Arnigad and 1620–2170 m a.s.l. for Bansigad). The soil samples were analyzed for organic matter (Walkley and Black 1934), texture and porosity (Black 1965).

### Statistical analysis

*T*-tests were performed in order to calculate statistical differences. The percentage differences of all parameters between Arnigad and Bansigad were calculated as  $((A-B) \cdot B^{-1} \times 100)$ , where 'A' and 'B' represents Arnigad and Bansigad, respectively.

### Lag time analysis

In order to understand the response of catchments after rainfall, around 40 hydrographs (during wet-period) were analyzed to determine lag time between rainfall and discharge. The lag time was analyzed by calculating the delay between the maximum rainfall amount and the peak discharge. Out of 40 hydrographs, 3 hydrographs along with corresponding hyetographs were analyzed in detail in

order to calculate the volume of water/discharge ( $\text{m}^3 \cdot \text{s}^{-1}$ ) released from catchments after rainfall events.

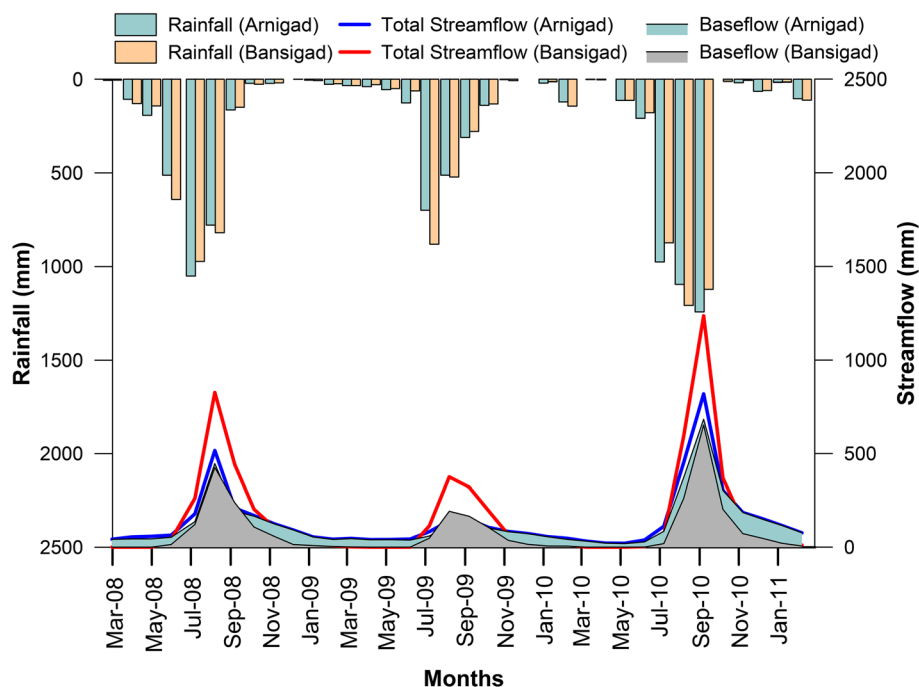
## Results

### Temporal variations of rainfall

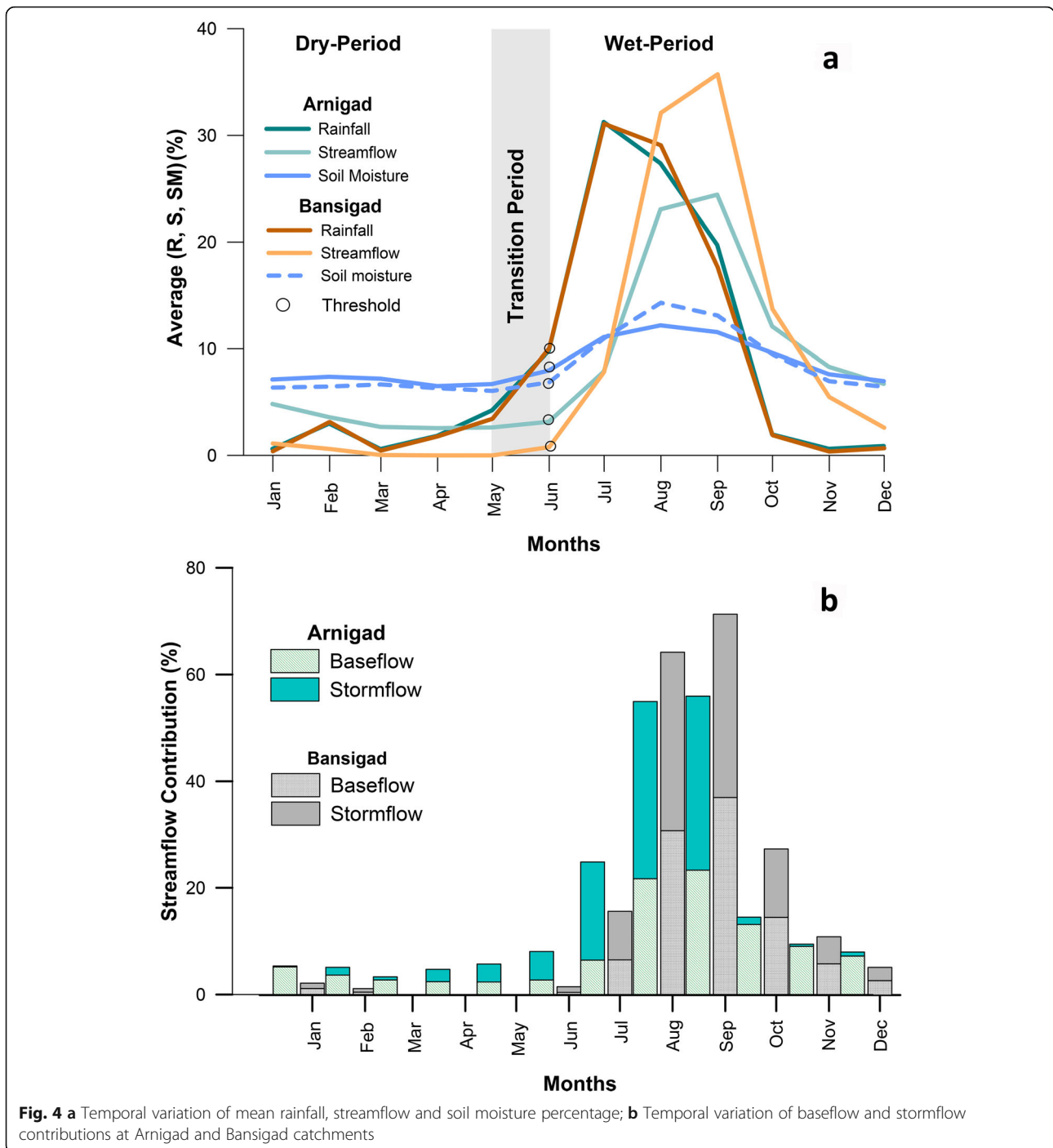
Wet-period (June to September), was the core season when hydrological processes in catchments were the most active; and were inactive during dry-period (October to May). The wet-period played a substantial role in the catchments' functioning by providing ~78% (for each catchment) of the annual rainfall of 2922 mm (Fig. 3). Patterns and amount of monthly rainfall observed (during 3-years) over both the catchments were quite similar and did not differ significantly ( $p < 0.05$ ) from each other. Minimum and maximum values of mean monthly rainfall ranged from 11 to 909 mm in both catchments. Winter rainfall in the form of snow was negligible at either location. May and June were transition months/stage between dry and wet periods. During this transition period, rainfall exceeds thresholds (~10% of annual rainfall) and hyetograph starts rising. July, August and September were the peak months whereas October, the falling limb of the hyetograph (Fig. 4a).

### Streamflow behavior

Temporal variations of  $Q_t$  for both the catchments clearly reflect the seasonal patterns and are in coherence with dry and wet-periods (Fig. 3). Generally, during last week of June,  $Q_t$  of Arnigad and Bansigad reached values of 48 and 14 mm (~3% and 1% of annual flow) and after



**Fig. 3** Temporal variation of rainfall, streamflow and baseflow of Arnigad and Bansigad catchments from March 2008 to February 2011



that  $Q_t$  started rising instantly (Fig. 4a). Bansigad had greater seasonality due to lack of flow during the pre-wet-period (March–May), whereas discharge was maintained year-round in Arnigad stream. Seasonal (wet-period) and annual  $Q_t$  in Arnigad were lower by ~34% and 13%, respectively relative to Bansigad.

Mean stormflow production in the Arnigad was modest with the sum of  $167 \text{ mm}\cdot\text{yr}^{-1}$  (10% of annual  $Q_t$ ), 90% of which occurred during the main wet-

period. Conversely, stormflow was much higher for the degraded catchment amounting to  $914 \text{ mm}\cdot\text{yr}^{-1}$  (49% of annual  $Q_t$ ), with 78% contribution from the wet-period. In addition, stormflows during post-wet-period (October–November) were important at Bansigad, contributing 18% of the annual totals whereas it was just 2% at Arnigad. Annually, stormflow at Arnigad was lower by ~82% as compared to Bansigad.

Mean annual baseflow at Arnigad and Bansigad was 1446 and 949 mm·yr<sup>-1</sup> (90% and 51% of annual flow) whereas seasonal (wet-period) contribution was 784 mm (54%) and 712 mm (75%), respectively. Baseflow was ~52% (annually) higher at Arnigad and became an important contributor for making the stream perennial unlike the ephemeral Bansigad. The contribution of stormflow and baseflow significantly varied from January to December and its temporal variation is presented in Fig. 4b. Recession rates of the baseflow for the Bansigad catchment during the dry-period were much faster, with a reservoir response factor of ~0.028 per day, whereas it was ~0.0083 per day for the densely forested Arnigad (Fig. 5). The exponential recession curve of the outflow from groundwater reservoirs in either catchment (Fig. 5) did not deviate from linear reservoir theory, indicating negligible leakage losses and hence letting direct comparison between the two catchments. The annual water budgets (Fig. 6) for the studied catchments displayed that though there was no significant difference in annual *P*, however, there was significant difference in annual *Q<sub>t</sub>*,  $\Delta S$ ,  $\Delta G$  storage and ET, respectively, between the catchments. On an average, 43% (Arnigad) and 36% (Bansigad) of *P* was lost as ET, which means only 55% and 64% of *P* respectively was available as *Q<sub>t</sub>* at Arnigad and Bansigad catchments (Fig. 6).

**Soil moisture behavior**

Temporal behavior of SM at different depths is presented in Fig. 7a. Mean annual volumetric SM at Arnigad and Bansigad was higher (41% and 39%) during wet-period, however it was lower (28% and 24%) during dry-period. This showed that Arnigad was having 4% (wet-period) and 16% (dry-period) higher SM as compared to Bansigad,

respectively. At annual scale (at Arnigad) mean SM was lower by 4% at upper surface and higher by 13% and 31% at deeper layers as compared to Bansigad (Fig. 7b). At Arnigad, SM at 80-cm depth held more SM than at 50 cm.

**Infiltration rate**

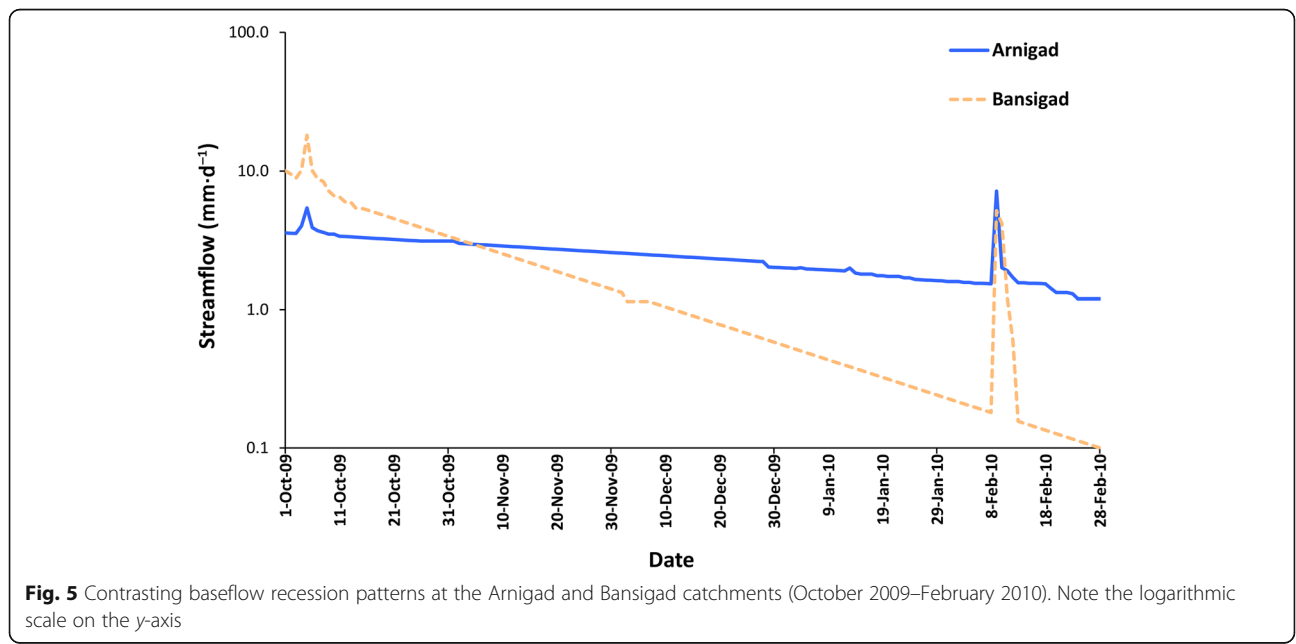
Variations of initial and steady infiltration rates in Bansigad were smaller (50–64 cm·hr.<sup>-1</sup> and 13–32 cm·hr.<sup>-1</sup> respectively) as compared to Arnigad (20–134 cm·hr.<sup>-1</sup> and 8–30 cm·hr.<sup>-1</sup> respectively). Initial infiltration rate was lower by 29%, while steady infiltration rate was higher by 21% at Arnigad relative to Bansigad (Table 2).

**Characteristics of soil**

Soil texture analysis gave higher amount of silt and clay (13% and 23%) fractions at Arnigad as compared to Bansigad. Organic matter (OM) and porosity were also higher (by 35% and 8% respectively) at Arnigad as compared to Bansigad. The results revealed that soil texture was better in the forested catchment (Arnigad) as compared to degraded forest (Bansigad) catchment. Figure 8 shows the variation of soil properties with depth.

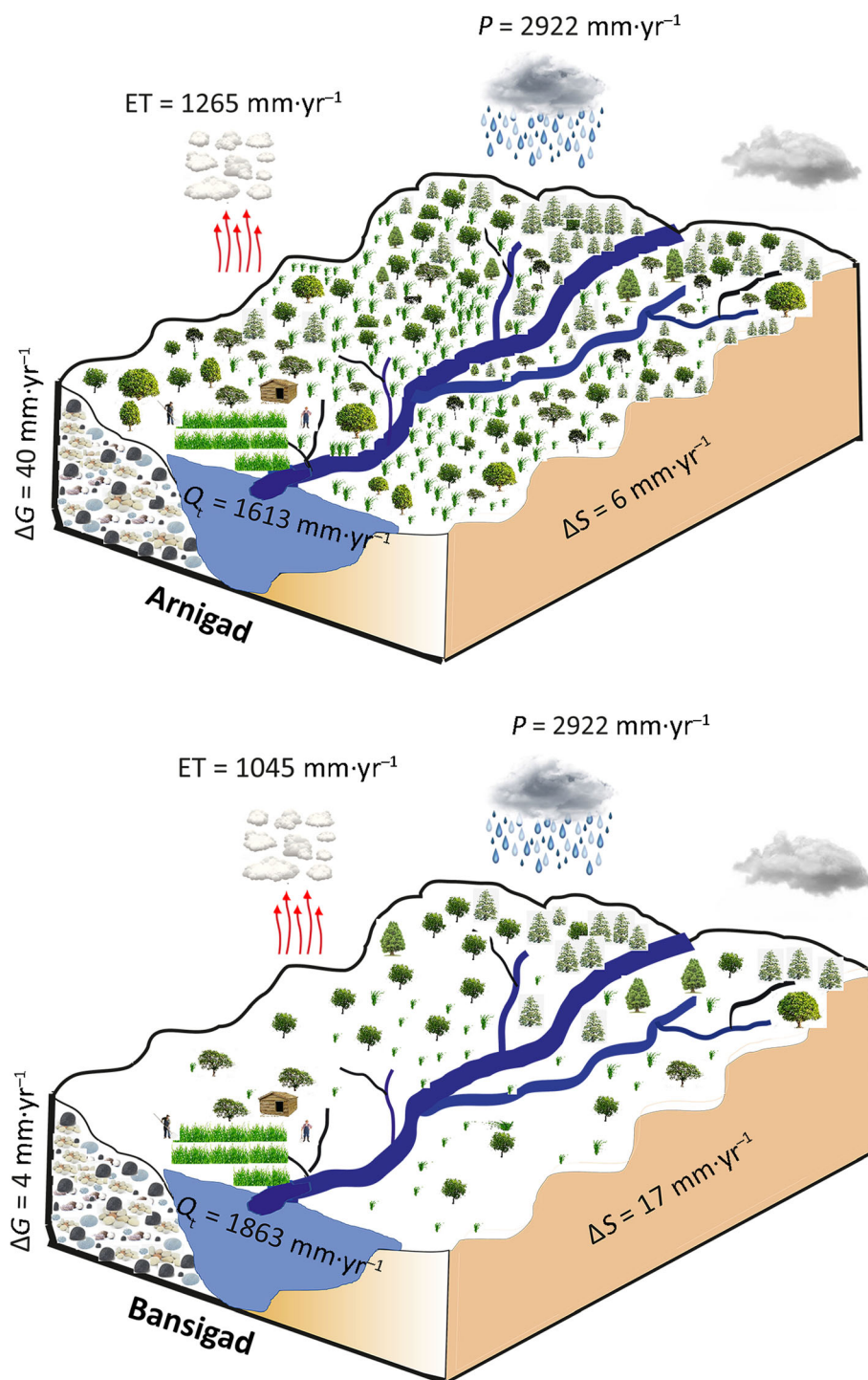
**Sediment budget**

Temporal variations of different types of constituents in *Q<sub>t</sub>* including SSL, TDL and BL are presented in Fig. 9a, b and c. A very large temporal variation (monthly) in SSL was observed ranging 0.28–738 and 0–1265 t·km<sup>-2</sup> at Arnigad and Bansigad, respectively. Arnigad experienced the lowest SSL from March to May, whereas the stream remained dry during these months at Bansigad. The wet-period contributed 95% (of the annual load) of SSL, which substantially affected annual sediment behavior at both the catchments.



**Fig. 5** Contrasting baseflow recession patterns at the Arnigad and Bansigad catchments (October 2009–February 2010). Note the logarithmic scale on the y-axis





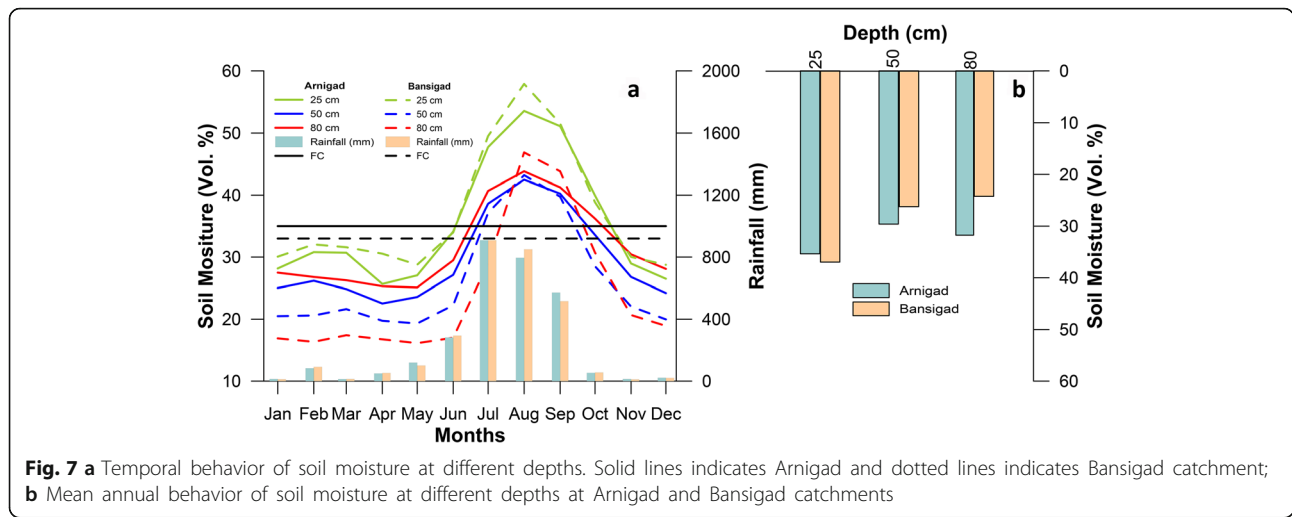
**Fig. 6** Mean annual water budget of Arnigad and Bansigad catchments

The average annual budget of SSL was  $1112 \text{ t}\cdot\text{km}^{-2}$  (Arnigad) and  $2143 \text{ t}\cdot\text{km}^{-2}$  (Bansigad) respectively, almost making suspended sediment budget of Bansigad double that of Arnigad (Fig. 9d).

Mean monthly TDL of Arnigad ranged between 21 and  $153 \text{ t}\cdot\text{km}^{-2}$ , while that of Bansigad ranged between

0.2 and  $177 \text{ t}\cdot\text{km}^{-2}$ . The TDL was consistently found to be higher than SSL during drier months. Mean annual yield of TDL at Arnigad and Bansigad was  $698$  and  $488 \text{ t}\cdot\text{km}^{-2}$ , respectively (Fig. 9d).

The volume of BL (monthly) flowing in the Arnigad stream was in the range of  $0.03$ – $17.28 \text{ m}^3$ , whereas it was  $74.64 \text{ m}^3$  at



Bansigad where March-mid June, no bedload material was observed. Mean monthly BL accumulation ranged from 0.09 to 4.92 t·km<sup>-2</sup> and from 0.5 to 37.5 t·km<sup>-2</sup> at Arnigad and Bansigad, respectively. The average bed material deposited annually was 19 t·km<sup>-2</sup> (Arnigad) and 114 t·km<sup>-2</sup> (Bansigad), respectively, which indicated that BL accumulation was higher (6 fold) at Bansigad relative to Arnigad (Fig. 9d).

Mass wastage has been considered the dominant erosional process on hillslopes and the denudation rate was calculated for both the catchments. The average denudation rates were 0.68 mm·yr<sup>-1</sup> (Arnigad) and 1.02 mm·yr<sup>-1</sup> (Bansigad), respectively, indicating that Bansigad losses its mass at about 1.5 times higher rates than Arnigad.

## Discussion

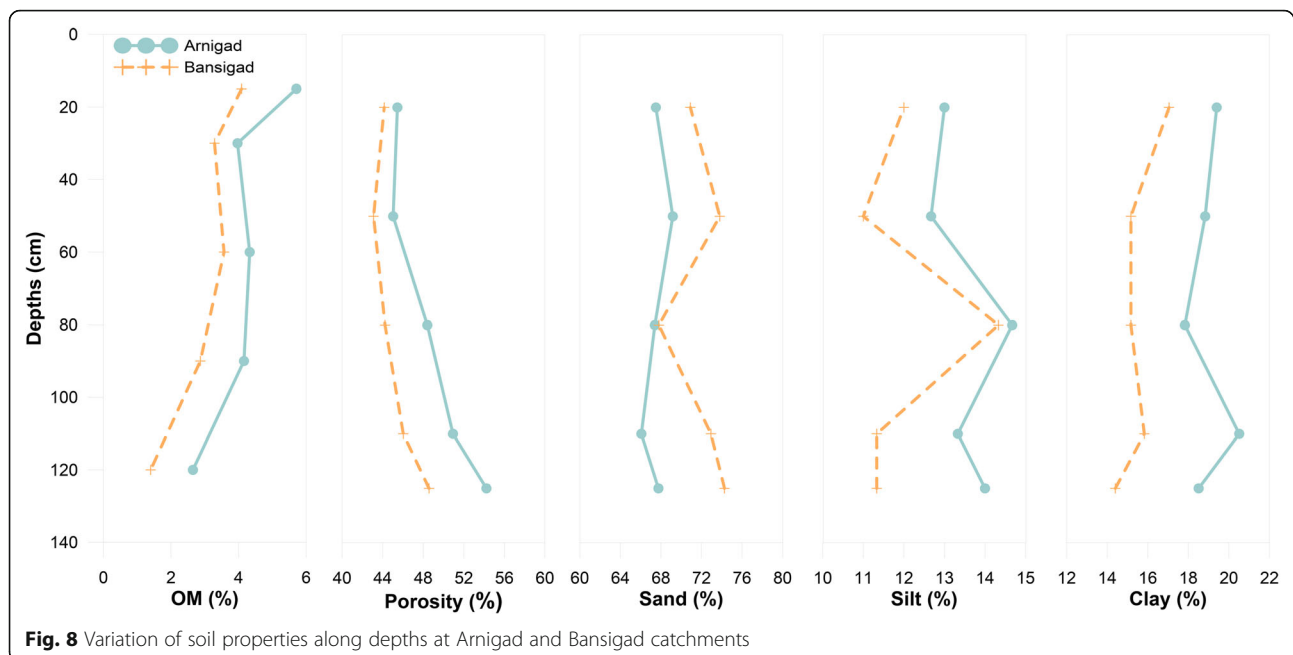
### Forest cover impacts on streamflow regulation

Studies concerning the impact of forest cover changes on the magnitude of  $Q_t$  in Himalayan region are rare (Sharma et al. 2007; Ashraf 2013; Tiyaqi et al. 2014); however, studies related to components of  $Q_t$  (baseflow and stormflow) are even more rare in the region. During the study period, the annual cycle of rainfall represented

both dry and wet-period (Fig. 3), thus allowing study of baseflow and stormflow conditions of the catchments. In the same line,  $Q_t$  of the catchments also showed distinctive behavior during dry and wet-periods (Fig. 3), due to highly seasonal rainfall in the CHR (Banerjee et al. 2020). Dry-period represented the greater part of annual hyetograph, however, wet-period represented the main driver for the  $Q_t$  generation. The 2nd order polynomial relationship between rainfall and  $Q_t$  (Fig. 10a) allowed the identification of rainfall threshold (~200 mm), and when this threshold exceeded,  $Q_t$  generation increased significantly in both the catchments (Fig. 10a). The same threshold value (~200 mm), which accounted for ~10% of annual rainfall was also observed in Fig. 4b. This rainfall threshold mostly occurred during mid-June, and before June, the low magnitude rainfall (below 200 mm per month) potentially catered to several hydrological processes e.g., initial infiltration, SM, ground water stress and ET (Tarboton 2003) in both catchments. The rainfall threshold values of both the catchments can be helpful to predict  $Q_t$  generation (Kirkby et al. 2005; Gioia et al. 2008; Kampf et al. 2018), which is vital for not only

**Table 2** Infiltration rates at different sites of Arnigad and Bansigad catchments

Catchment	Site Nos.	Initial infiltration rate (cm·hr <sup>-1</sup> )	Steady infiltration rate (cm·hr <sup>-1</sup> )
Arnigad	1	101	29
	2	134	30
	3	20	8
	4	77	19
	<b>Average</b>	<b>55</b>	<b>23</b>
Bansigad	1	52	13
	2	50	25
	3	32	22
	4	64	32
	<b>Average</b>	<b>77</b>	<b>19</b>

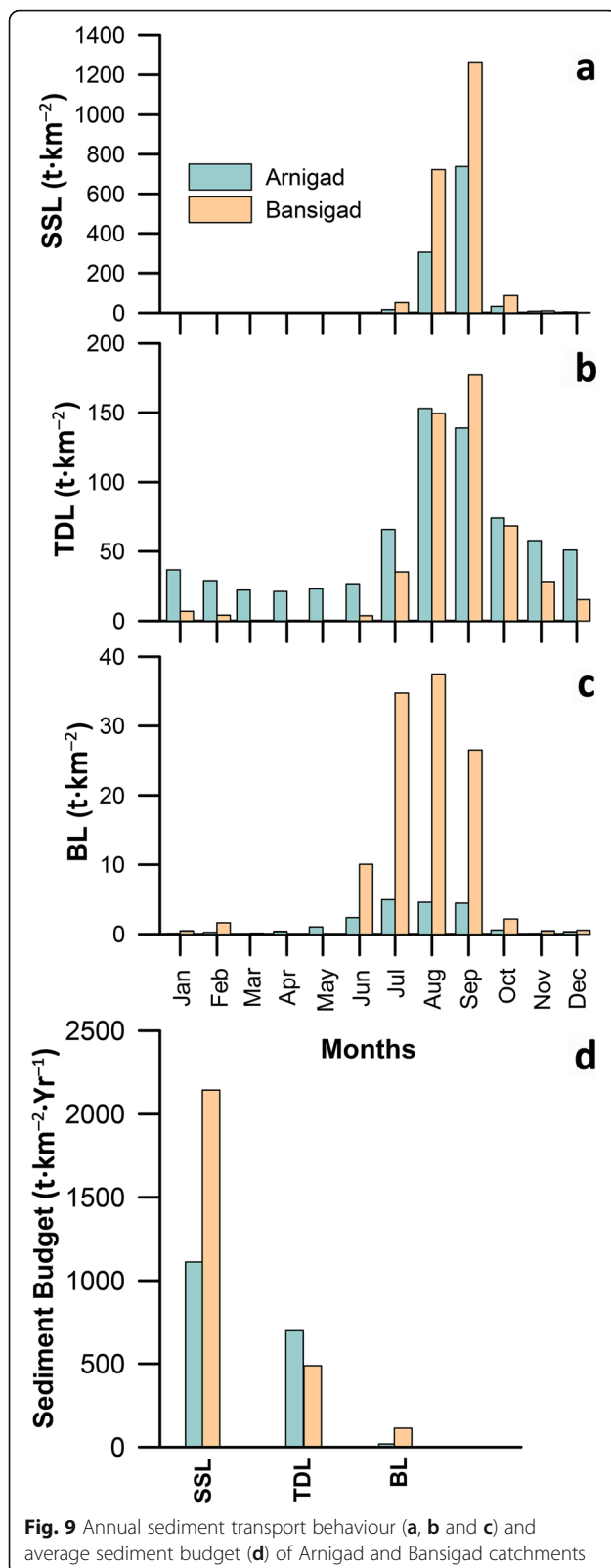


sustaining streams, but also regulating numerous ecological processes (Poff et al. 1997; Doll et al. 2015). Separation of hydrographs (Arnigad and Bansigad) into stormflow (6% and 31%) and baseflow (50% and 32%) (Fig. 4a and b), vastly improves our understanding of  $Q_t$  regulation at catchment-scale and surely will be helpful for water resource management (Nepal et al. 2014) in the CHR.

Arnigad catchment showed lower annual  $Q_t$  and higher ET compared to the Bansigad catchment (Fig. 6). Despite having higher ET, Arnigad's annual baseflow component was higher by ~52% relative to Bansigad. This was because of forest floor components (i.e. litter layer, or the accumulation of leaves, twigs, and other vegetative debris), which increased OM, porosity, clay and silt content in soil, and resulted in better soil formation in Arnigad catchment (Fig. 8), further leading to higher SM retention (O'Geen 2013) relative to Bansigad. Furthermore, these forest floor components might also act as effective shade barrier on the soil surface and reduce the rate of air exchange between the soil and the atmosphere, resulting in SM retention (Edwards et al. 2015). Besides, higher TD and DBH at Arnigad, indicated deep rooting which facilitate rapid drainage to deeper layers via macropores (Noguchi et al. 1997; Bargués Tobella et al. 2014). Their dominance (in Arnigad) in controlling SM retention was critical to retaining moisture within the soil. Rainfall moving in macropores resupply to groundwater, known as groundwater recharge. Groundwater released water with a slow recession rate (Fig. 5) subsequently during the dry-period to  $Q_t$  through contributions known as baseflow,

which makes the stream perennial (at Arnigad) with a mean baseflow of ~83 mm (~6% of annual baseflow). Whereas, mean baseflow of only ~30 mm (~3% of annual baseflow) was available till February month which was not sufficient to make Bansigad stream sustainable during few months (March to May) of dry-period (Fig. 4a). The study indicated that both streams were dependent on rainfall for  $Q_t$  generation, but the rainfall at Arnigad sustained baseflow during dry-period through different mechanism of forest components. Furthermore, the baseflow and stormflow at Bansigad showed larger variations as compared to Arnigad (Fig. 4b), the large variation was due to the faster recession rates at Bansigad catchment during the dry-period, with reaction/response factors of  $0.028 \text{ day}^{-1}$  compared to Arnigad catchment ( $0.0083 \text{ day}^{-1}$ ). The faster recession rate at Bansigad, diminished  $Q_t$  completely during dry-period, however, for dense forest (Arnigad) the baseflow was higher by ~52% annually, helping to maintain  $Q_t$  year round. Hence, the higher proportion of the stormflow at Bansigad, indicated higher probability of water resource problems such as flooding in the wet-period and drought in the dry-period. Baseflow recessions are important for the management of both ground water and surface water resources during dry-period (Miller et al. 1953).

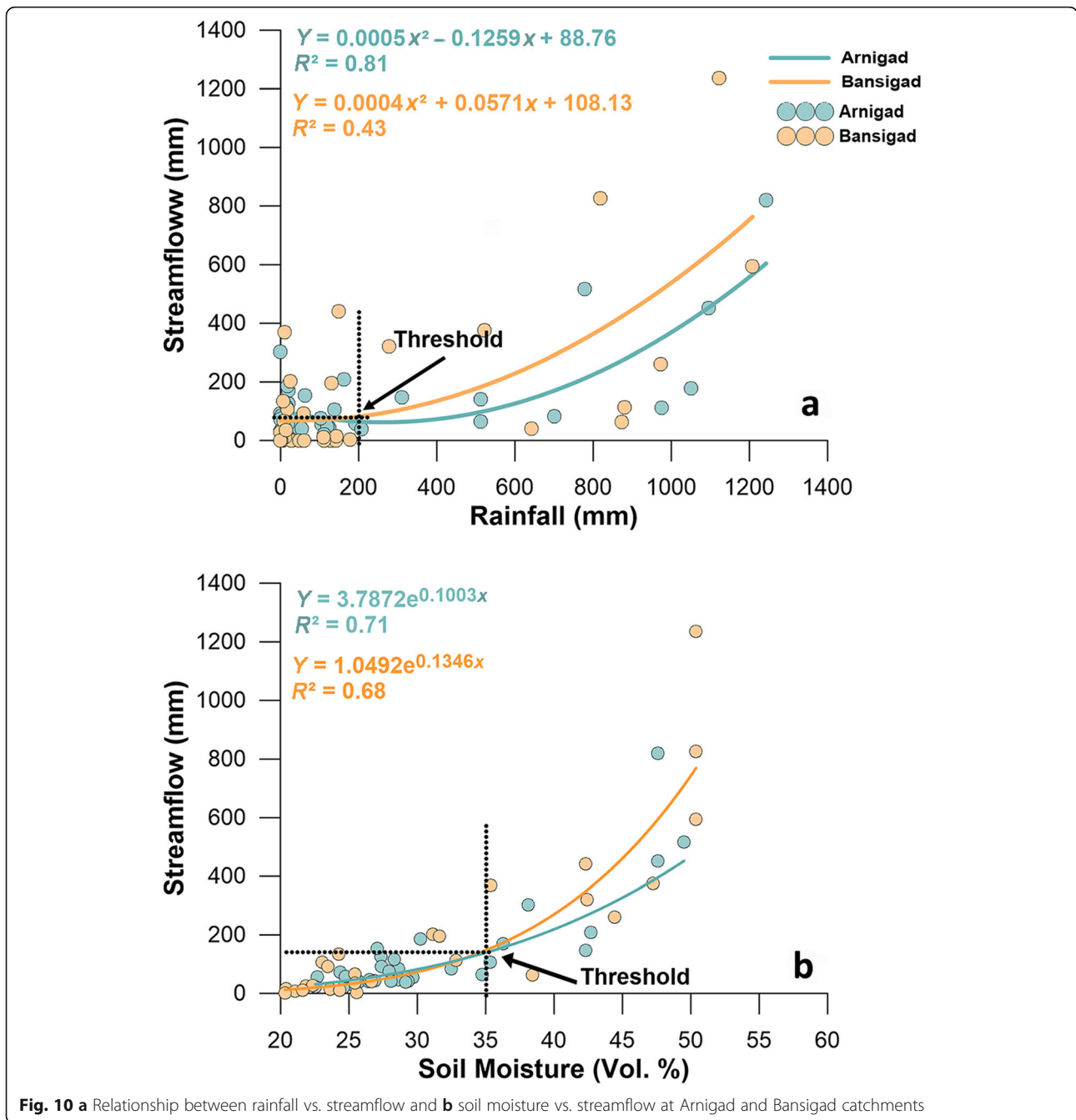
The 40 selected hydrographs revealed the response of catchments after rainfall, showing that the lag time generally increased for small and early wet-period events and decreased for larger events. Lag time of both the catchments ranged between 0:15 to 0:45 h. If the time gap between two consecutive rainfalls were larger, lag time of hydrographs also became larger and during wet-



**Fig. 9** Annual sediment transport behaviour (a, b and c) and average sediment budget (d) of Arnigad and Bansigad catchments

period when the catchments were fully saturated with SM, a few rainfall events immediately become runoff/stream discharge. Among 40 hydrographs, it was observed that only three rainfall events started and finished at same time period (29.07.08 to 31.07.08) at both the catchments. Furthermore, these events occurred in July, peak of the monsoon, and it is obvious that the soil was fully saturated. Therefore, this time period gave an opportunity to compare both volume of water (discharge) and lag time between catchments. Hence, these 3-hydrographs along with corresponding hyetographs for the same time period from 29.07.08 to 31.07.08 and at same interval (15-min interval) were analyzed in detail (Fig. 11). There was no significant difference ( $p = 0.05$ ) in rainfall events between Arnigad (36–109 mm) and Bansigad (47–118 mm), however, there was significant difference in discharge between Arnigad ( $0.60\text{--}0.81\text{ m}^3\cdot\text{s}^{-1}$ ) and Bansigad ( $0.81\text{--}1.32\text{ m}^3\cdot\text{s}^{-1}$ ), respectively. Further, lag time of these three events were: 0:45, 0:45 and 0:30 h (Arnigad) and 0:30, 0:30 and 0:15 h (Bansigad), respectively (Fig. 11). The shape of the hydrographs varied with each individual rainfall event. The analysis revealed that during wet-period, Arnigad releases lower volume of water, which took on average additional 15 min (compared to Bansigad) to reach the gauging site. This behaviour of hydrographs (in Arnigad) may possibly be to the combined effect of (i) slow recession rate of baseflow for Arnigad (Fig. 5), (ii) higher potential of forest soil to store water in Arnigad (Fig. 7) and (iii) higher infiltration rate (Table 2). Therefore, the volume of water that was stored in Arnigad during rainfall events and the longer lag time helped in releasing water during recession, and maintaining the baseflow during dry-period, which are important ecosystem functions of the catchment. Thus, the study indicates that the forest cover in Arnigad showed significant and positive relationship with both baseflow and stormflow. These relationships can be applied to other catchments to effectively manage current and future land use and water resource problems in CHR.

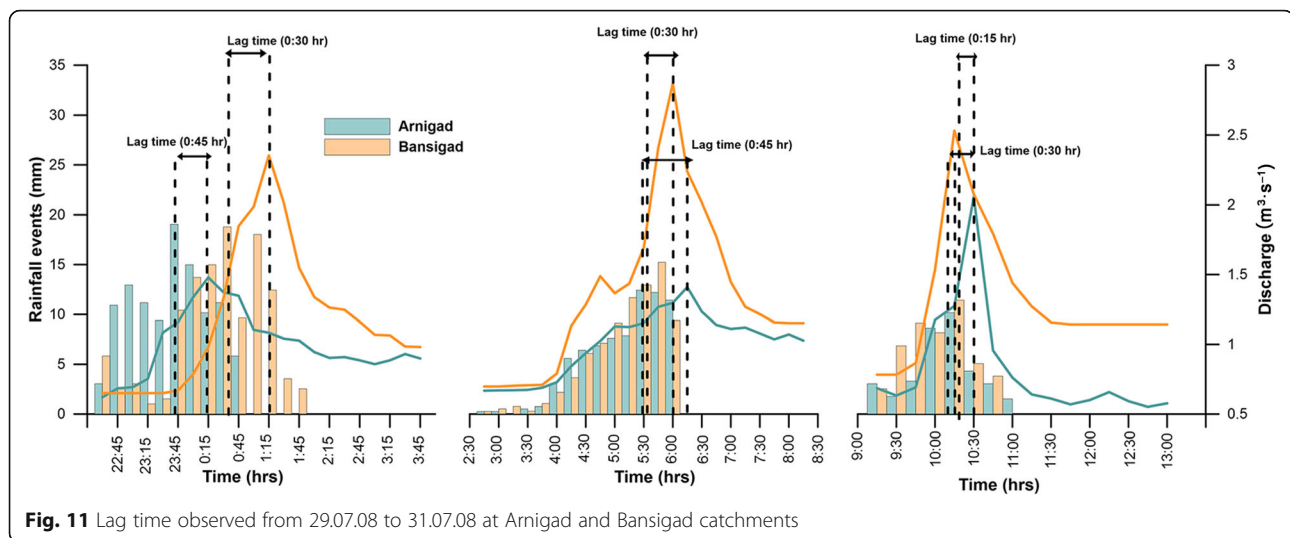
The Non-linear relationships between  $Q_t$  and SM (Fig. 10b) allowed the identification of threshold value ( $\sim 35\%$ ) of SM. When the SM threshold was exceeded, baseflow got activated, increased significantly and became a major contributor to stormflow. A clear threshold ( $\sim 35\%$ ) between SM and  $Q_t$ , revealed the importance of initial moisture conditions, which determined the extent of saturation and controlled the  $Q_t$  production for the entire catchment (Penna et al. 2010). The threshold value (0.35) was very close to mean field capacity (FC), which was 0.35 and 0.33 for Arnigad and Bansigad, respectively. This further confirms that the activation of  $Q_t$  occurred only after soil attained threshold SM value of 35%. Other studies observed SM threshold at 45% (Penna et al. 2011; Song and Wang 2019), 26%



(Farrick and Branfireun 2014) and 23% (James and Roulet 2007) highlighting the importance of initial moisture conditions. The difference in threshold values might be due to difference in topography, climate, land use characteristics, soil characteristics and sampling designs. Results of the present study showed that two factors: SM and  $P$  were responsible for  $Q_t$  activation and generation. Figure 4a and b, indicates that June was the transition period, when hydrological functioning ( $Q_t$  activation and generation) of the catchments began to activate and October was again a transition period

when hydrological functioning began to deactivate. Non-linear behavior is common in hydrological systems (Zuecco et al. 2018) and these thresholds can be used as a classification tool to better conceptualize runoff response behavior under a range of weather conditions (Ali et al. 2013, 2015).

OM showed direct positive linear relationship with tree density (Fig. 12a). Higher tree density means higher OM in soil, which helps in binding soil particles together into stable aggregates, increasing porosity (Zuazo and Pleguezuelo 2008; Tobella et al. 2014), and finally



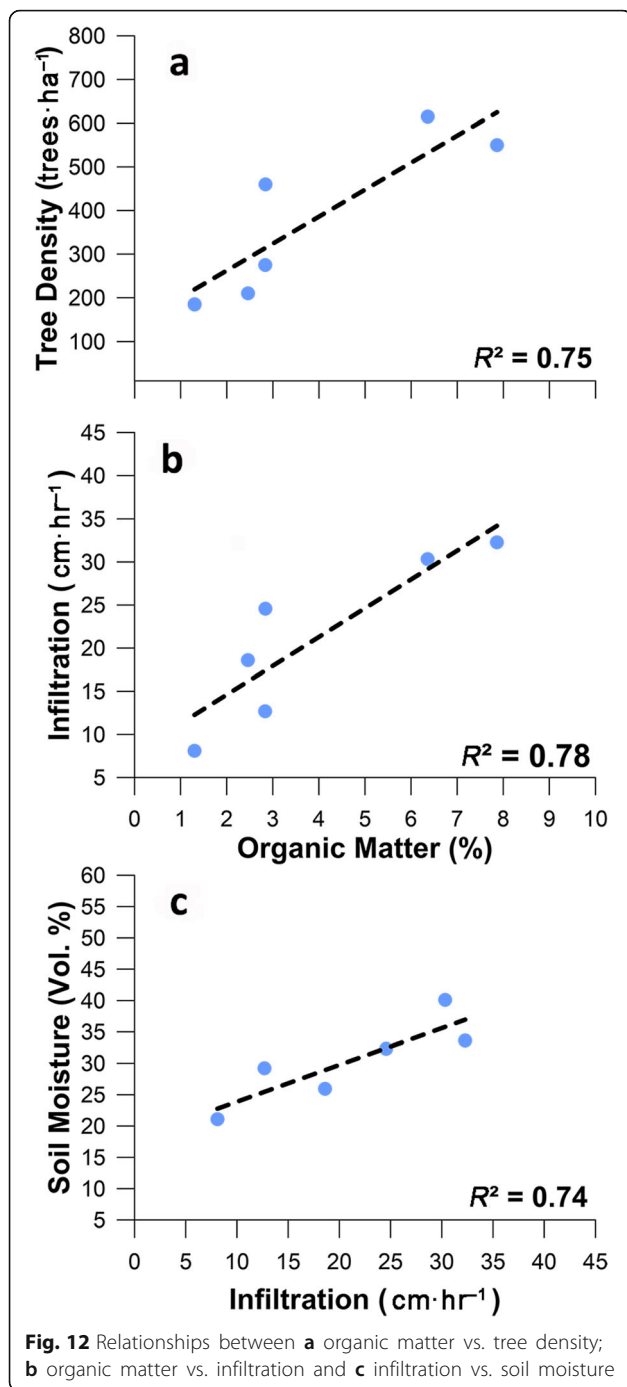
**Fig. 11** Lag time observed from 29.07.08 to 31.07.08 at Arnigad and Bansigad catchments

leading to higher infiltration (Fig. 12b). Both SM and vegetation are closely linked; SM positively influences vegetation growth (Wang et al. 2007), whereas vegetation displays complex relationship with SM. More vegetation either conserve more water, causing retention of SM or consumption of water itself, causing the depletion of SM (Pielke et al. 1998; Wang et al. 2006). Hence, more vegetation may correspond either to increase (Bounoua et al. 2000; Buermann et al. 2001) or to decrease of SM (Pielke et al. 1998; Wang et al. 2006). The present study supports the strong interlinkages of forests/vegetation with SM; interestingly SM also showed positive and direct impact on infiltration rate (Fig. 12c). Further work is required in future to understand these relationships at different spatial and temporal scale in CHR. However, the results from the present study will be of help to farmers, land managers and policy developers in conserving and sustainably developing forest, soil and water resources in this region.

#### Soil moisture variation at different soil profiles

Temporal variations of SM at different depths under different forest covers are shown in Fig. 7a. It was observed that SM at all the profiles was responsive to rainfall events, though a few events might have been missed as the parameters were measured at fortnightly intervals. The annual cycle of both rainfall and SM follows the same path with unimodal variation (Fig. 7a), and SM reached its maximum during wet-period, when ~78% of annual rainfall occurred. Furthermore, SM at all soil layers were below FC during dry-period, whereas, it was above FC during wet-period at both catchments (Fig. 7a). Such behavior indicated that SM was mainly regulated by  $P$  (Varikoden and Ravadekar 2018). It is observed from Fig. 7a and b, that during the wet-period, the surface layers at both the catchments were wetter than the

deeper layers. This was because low intensity  $P$ 's were likely to be retained at the soil surface layer (Li et al. 2016). The variability in SM of the surface layer was even more distinct in Bansigad catchment, showing low interception losses due to degraded forest, resulting in a large proportion of rainfall reaching the ground surface (Venkatraman and Ashwath 2016; Liu et al. 2018) and therefore, the Bansigad catchment showed higher (4%, annually) moisture regimes in surface layer than that for Arnigad (Fig. 7b). For Arnigad catchment, SM was maximum at a deeper layer (80 cm) than at 50-cm depth. This was possibly due to lower rate of water movement to the next soil layer or may be influenced by lateral flow (within the soil layer) from the upslope due to change in the saturated hydraulic conductivity properties (Venkatesh et al. 2011). Many studies (Gutiérrez-Jurado et al. 2007; Toro-Guerrero et al. 2018) from hillslopes or areas having steep slopes supported active response of lateral flow to deeper soil layers, thus efficiently bypassing the shallower soils, which are more exposed to ET. Therefore, SM in the hillslopes varies both in the vertical and lateral directions (Venkatesh et al. 2011). Annually, SM at Arnigad at 50 and 80 cm was enhanced by 13% and 31% in comparison to Bansigad (Fig. 7b). These enhanced values indicated potential for soil water storage in the forested catchment (Arnigad), and slow release of water during the subsequent dry-period, which consequently helps in regulation of sustained stream flows in the Himalayan region. This is further supported by Fig. 12, which shows that Arnigad had higher OM (21%–89%) and higher porosity (3%–11%) than Bansigad helping Arnigad to retain SM and uphold sponge characteristics (Qazi et al. 2017). The lowest values of volumetric SM (mean monthly) were recorded as 25% (Arnigad) and 21% (Bansigad), indicating low (19%) storage deficit at Bansigad relative to Arnigad. Therefore,



water retention/flow regulation in dense forested catchment (Arnigad) was better in comparison to the degraded forested catchment (Bansigad). Thus, the present study suggests that forests play an important role in SM functioning at local sites (Bruijnzeel 2004) and provides hydrological services in different ways at catchment scale. However, further research work is required to understand the dynamics and transport of soil water content from shallow to deeper soil layers for potential ground water recharge.

### Forest cover impacts on sediment transportation/erosion behavior

Sediment transport is a function of several interacting factors including vegetation, climate, topography, parent material, and soil. Rainfall during the monsoon was the main driver and contributed significantly in annual sediment transportation (95%) in both the studied catchments (Fig. 9a), while forests regulated sediment transport activity in these catchments through various forest components (forest cover, understory, tree roots, and woody debris). Forest cover supported in reduction (18%) of suspended sediment production at Arnigad catchment through strong root system that holds soil particles tightly and doesn't allow natural forces (wind and water) to take away the upper-most layer of the soil. Moreover, the understory (shrubs, herbs, leaf litter etc.) at Arnigad also helped in decreasing surface erosion by reduction of kinetic energy of raindrops (Fukuyama et al. 2010; Nanko et al. 2015). On the other hand, it was found that the degraded forest along with high intensity rainfall triggered loosened material and debris (Fuller et al. 2003), leading to landslides (Struck et al. 2015), and further to higher sediment production in Bansigad stream (Tyagi et al. 2013), continuously disturbing the natural system (Mukherjee 2013) of the Bansigad catchment. The lower (75%) deposited BL material in Arnigad catchment (Fig. 9c) was because of the standing trees, felled logs and understory of dense forest, which slowed down the movement of big boulders, gravel and debris (Qazi and Rai 2018). Moreover, the strong tree root system and organic humus layer supports slope stability, decreases landslides and debris flow frequency (Imaizumi et al. 2008; Nepal et al. 2014; Goetz et al. 2015); hence BL material couldn't reach Arnigad stream unlike Bansigad stream. Hartanto et al. (2003) and Imaizumi et al. (2019) also reports that a large amount of sediments are captured by woody debris on hillslopes. The present study proves that forest plays important roles in regulating sediment transportation and forest plantation and conservation can be considered as an important means of improving the mountain environment.

Interestingly, the concentration of dissolved material in streams of Arnigad was also enhanced by 114% (annually) as compared to Bansigad (Fig. 9b). As both the catchments were located near to each other, the rock types and their erodibility are assumed to be the same. Apparently, the landuse or forest was the only element to account for higher dissolved solids at Arnigad catchment. Large quantity of OM are generated in the forest floor at Arnigad catchment, which decompose, percolate through rain water (Krishna and Mohan 2017), and reach streams in dissolved form (Markewitz et al. 2004; Andrade et al. 2011; Costa et al. 2017). Hence, the dissolved OM concentrations affect TDS in the stream.

Dry-period has significant impact on the wide range of TDS at Bansigad, because TDS becomes more concentrated with decreasing discharges (Tipper et al. 2006; Calmels et al. 2011). TDS in both the catchments was within the permissible limit according to WHO (1996) and BIS (2012).

In the Himalayan region, high relief coupled with intensive rainfall during monsoon provide favorable conditions for mass wasting (Korup and Weidinger 2011), which causes serious long-term problems affecting functioning of hydropower plants, dam and river management, environmental flows, biological diversity, reservoir siltation, landslides, etc. (Zokaib and Naser 2011; Hedrick et al. 2013; Sudhishri et al. 2014; Iwuoha et al. 2016). Reduction of annual sediment budget (Fig. 9d) and denudation rate by 41% in Arnigad compared to Bansigad further confirms the crucial role of trees and forests in preventing mass wastage, helping to sustain ecological functioning and biological diversity and reduces hazards e.g. landslides, in the long run.

## Conclusion

During the study period that comprised both dry-period and wet-period, thus allowing to study baseflow and stormflow conditions of the two studied catchments. The annual hyetograph analysis revealed that the rainfall at both the catchments was highly seasonal, and wet-period plays a key role in hydrological functioning of catchments. The identification of rainfall threshold values of both the catchments (200 mm per month) can be helpful to predict  $Q_t$  generation, which is vital for sustenance of streams and regulation of numerous ecological processes. The Arnigad catchment maintains its baseflow of ~83 mm per month (~6% of annual baseflow) during dry-period making the stream perennial; however, baseflow was not available at Bansigad during a few months of dry-period making the stream intermittent. The analysis revealed that both streams were dependent on rainfall for  $Q_t$  generation, but the time-scale over which rainfall at Arnigad can sustain baseflow was greatly enhanced relative to Bansigad.

The present study also highlighted the strong control exerted by SM on  $Q_t$ . A sharp threshold (~35%) existed between SM and  $Q_t$ , above which baseflow was activated, increased significantly and became a major contributor to stormflow. Therefore, the study estimated the threshold, responsible for  $Q_t$  activation and generation, which may serve as a foundation for future studies that predict  $Q_t$  response to climate and anthropogenic change in the CHR. Further, the continuous faster recession rates of baseflow, low potential of forest soil to store water (SM) and lower infiltration rates were responsible factors for the diminishing  $Q_t$  during a dry-period in Bansigad catchment. The various forest components in Arnigad

catchment helped in reduction (41%, relative to Bansigad) of soil denudation rate. Thus, the present study suggests that rainfall during wet-period was the main driver for controlling hydrological processes, whereas, forests provided substantial services by regulating water balance, SM and sediment budget in Arnigad catchment. Moreover, the forest also helped in maintaining soil properties and infiltration rates by adding OM to soil. Based on the findings, the paper concludes that our understanding of hydrological functioning at catchment scale advances our ability to improve water resource management in CHR and meet the needs of local people without adversely affecting the environment.

## Abbreviations

CHR: Central Himalayan Region; FC: Field capacity; FCC: Forest canopy cover; TD: Tree density; LISS: The linear imaging self scanning sensor; DBH: Diameter at breast height; AWLR: Automatic water level recorder; P: Rainfall;  $Q_t$ : Streamflow; ET: Evapotranspiration;  $\Delta S$ : Change in soil moisture storage;  $\Delta G$ : Change in groundwater storage; SSL: Suspended sediment load; TDS: Total dissolved solids; TDL: Total dissolved load; BL: Bed load; D: Denudation rates; SM: Soil moisture; OM: Organic matter

## Acknowledgements

Cordial thanks to Dr. Sharad Kumar Jain, Dr. Shive Prakash Rai and Dr. R.K. Tiwari for valuable support and Miss Smriti Srivastava for her support in GIS work. Author would also like to thank to DST for WOS-A project (No. SR/WOS-A/EA-1016/2015 (G)). Author thanks two anonymous reviewers for their valuable comments and suggestions. Author would also like to thank Dr. Pottakkal George Jose for language editing.

## Author's contributions

Author contributed from data collection (from field) till manuscript development. Author have read and approved the final manuscript.

## Funding

Funding received from ICFRE and UCOST are greatly acknowledged.

## Availability of data and materials

The data set generated for the study area is available from the corresponding author on reasonable request.

## Ethics approval and consent to participate

The subject has no ethical risk.

## Consent for publication

The subject matter has no ethical risk.

## Competing interests

The authors declare that they have no competing interests.

Received: 17 April 2020 Accepted: 9 November 2020

Published online: 24 November 2020

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