Hydrological Functioning of Forested Catchments, Central Himalayan Region, India.

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Research

Keywords: Forested Catchments, Stormflow, Baseflow, Soil moisture, Sediments, Western Himalayan Region

Posted Date: June 8th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-23279/v2

Version of Record: A version of this preprint was published on November 24th, 2020. See the published version at https://doi.org/10.1186/s40663-020-00275-8.

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 to recognize for availability and quality of water at catchment scale. Therefore, present study aims to understand hydrological response of two forested catchments (namely, Arnigad and Bansigad) in the Central Himalayan Region.

Methods: Three-year data (March, 2008 to February, 2011) were collected from meteorological and hydrological stations installed at Arnigad and Bansigad catchments. The present paper displays mean hydrological response of forested catchments 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 at both the catchments. At Arnigad, 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 at 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. Forest ecosystem at Arnigad improved the hydrological functioning by: reducing stormflow (82%), and enhancing: baseflow (52%), soil moisture (13%), steady infiltration rate (22%) and lag time (~15 minutes) relative to Bansigad. These enhanced values indicated soil capability to store water at forested catchment (Arnigad) and helped to understand the volume of water (discharge) that was available during dry-period. The decrease of denudation rate (at Arnigad) by 41% resulted decrease in suspended sediment (18%) and bed load (75%) compared to Bansigad. Further, the enhancement of dissolved solids in stream resulted due to maximum organic matter generated in forest floor of Arnigad.

Conclusion: This study accomplishes 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 at Arnigad catchments through different mechanisms of forest components at catchment-scale in the Central Himalayan region.

1. Introduction

Catchments, as environmental systems, are characteristically complex and heterogeneous (Kirchner, 2016), consisting of wide range of processes (natural / anthropogenic) which may function simultaneously, affect spatial and temporal variability of the system (Zabaleta and Antiguedad 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 these 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, disturbs food chain and habitat (Thompson et al. 2011; Jones 2013), which in turn leads to serious damage in several ecological 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). Large number of headwater catchments in the Central Himalayan Region (CHR) in India are covered with dense forests (Tiyagi et al. 2013), which provide numerous ecosystem services to millions of people living in these regions (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. 2013, Chauhan et al. 2017 and Qazi et al. 2017, 18) suggest that forest plays 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; Gopalkrishnan et al. 2011; Tiwari et al. 2017), which disrupts 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 lacking in these regions.

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: densely 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 average hydrological scenario of the catchments. Such understanding is necessary to improve our ability to manage multiple water resources at catchment-scale, and to meet needs of local people without adversely affecting the environment.

2. Description Of Study Area

2.1 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 degraded-forested catchment, Bansigad (190.5 ha; 30° 27′ N, 78° 2.5′E) were selected in the Mussoorie area, CHR (Figure 1). Both catchments are located near (~1.5 km areal distance) to 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, therefore, no forest cover change was noticed during the study period.

2.2. Characteristics of Vegetation:

Arnigad and Bansigad catchments are dominated by Oak forest (*Quercus leucotrichofora*), having 237 ha and 124 ha of Forest Canopy Cover (FCC), respectively (Figure 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 x 10 m) were laid down at each site of both the catchments. TD was higher at Arnigad catchment (487 trees/ha ± 210) as compared to Bansigad catchment (380 trees/ha ± 194). Diameter at Breast Height (DBH) was measured at each quadrate (at 1.73 m height) by using inch tape. Average DBH was also higher at Arnigad (30.57 cm ± 8) as compared to Bansigad (16 cm ± 7). At Bansigad, out of 15 quadrates selected at three sites, species composition was found to be 64% of Oak, 17% of Cupressus, and 19% of others (which includes Bhimal, Parang, Kail, Khadki, Terbara, Jungli Nashpati), whereas at Arnigad, the species composition was 98% of Oak and 2% were others. Different forest coverage was the only differences between two catchments i.e. FCC (91%), TD (28%) and DBH (98%) were higher at Arnigad as compared to Bansigad. The percentage differences of FCC, TD and DBH were calculated as ((A-B)/B*100), where 'A' and 'B' represents Arnigad and Bansigad, respectively.

2.3. 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), maximum of which (80%) occurred during summer months (June to September) while 30% occurred during the winter months (Sharma *et al.,* 2012). Maximum annual temperature was 28^{o}C and was observed in May, while minimum annual temperature was 6^{o}C and was observed in January (Sharma et al. 2012).

3. Methodology

3.1.Rainfall Measurements:

In order to measure rainfall, two types of rain gauges were used: a tipping bucket rain gauge (Rainwise, USA; 325 cm^2 orifice, 0.25 mm per tip) and manual rain gauge (RK Engineering, India; 2000 cm^2 orifice). The data from the tipping bucket rain gauges were cross-checked with the manually rain gauges (1-day temporal resolution), which were installed at the same measurement site. Both types of rain gauges were installed at two elevations (at ~1700 m and ~1900 m a.m.s.l.) at each catchment. There was no significant difference between rainfall sums measured at two different stations at both Arnigad and Bansigad. Apparently, the elevation difference between the two stations was inadequate, while, the slope, aspect and other morphometric characteristics which are vital factors affecting rainfall catch in the CHR (Katiyar and Striffler 1984), were almost similar at both the catchments (Table 1).

3.2. Discharge Measurements:

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

3.3. 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 (Figure 1). The sensors at each site were installed at 25 cm, 50 cm and 80 cm depths, respectively. The soil matric potentials from all the sensors were monitored twice in a month 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 by using pressure plate apparatus for the pressure 0.1, 0.33, 0.5, 0.7, 1, 3, 5, 7, 10 and 15 bar. 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 of catchments (Thompson 1999).

3.4 Annual Water Budget:

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

$Q_t = P - ET \pm \Delta S \pm \Delta G$ Equation 1

where Q_t is total streamflow, P is rainfall, ET is evapotranspiration, ΔS is the change in soil moisture storage (i.e., water present in soil), and ΔG is the change in groundwater storage. The corresponding changes in soil moisture (ΔS) and groundwater (ΔG) 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, ΔS and ΔG, gave apparent annual evapotranspiration losses (ET) of catchments. Average values of three respective water years were used in this study.

3.5. Sediment Measurements:

The water samples of 1-liter bottles were collected at the gauging sites of the mainstream (Figure 2). The collected water samples were analyzed by following a grab sample method (International Atomic Energy Agency 2005). Whatman-72 filter paper were used for the separation of suspended sediments from the water samples. During the wet-period (June-September), the sampling was done three times in a day: 8:00 AM, 2:00 PM and 8:00 PM whereas during the dry-period (October-May), sampling frequency was done on daily basis (8:00 AM). The suspended sediment concentration (mg l^{-l}) was converted into suspended sediment load, SSL (t km^{-2}) by using conversion factor, discharge and area of the catchments.

Total Dissolved Solids were measured by 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 in every two weeks as there was no significant change in TDS. The concentration of TDS (ppm) was converted into total dissolved load, TDL (t km^{-2}) by using conversion factor, discharge and area of the catchments.

Bed load (BL) was estimated by following Hedrick *et al.,* 2013. The pond like structure (6 x 4.8 m for Arnigad and 12 x 6.62 m for Bansigad) at gauging sites were constructed so that sediments could accumulate within them. It was presumed 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 t m^{-3} (BBMB, 1997) was used for the conversion of these volumes into mass. The measurement of accumulated BL followed by mechanical cleaning was done every month, however, during wet-period, the frequency of measurements followed by cleaning was 5-6 times in every 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 P provides favorable conditions for mass wasting (Korup and Weidinger, 2011). Long-term mass wastage or denudation rates were estimated by following Gregory and Walling 1973:

See equation 2 in the supplementary files.

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

3.6. Infiltration Measurements:

Infiltration tests were conducted with the help of double-ring infiltrometers in March 2010 when the soil profile has 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. Eight infiltration tests (4 at each) were conducted at both catchments.

3.7. 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 Auger. All soil samples were collected at six representative sites (three at each catchment) (Figure 1). The 3 sites spanned a gradient from ridgeline to catchment outlet (1650-2230 m a.m.s.l. for Arnigad and 1620-2170 m a.m.s.l. for Bansigad). The soil samples were analyzed for Organic matter (Walkley and Black 1934), texture and porosity (Black 1965).

3.8. Statistical Analysis:

T-tests were used in order to calculate statistical differences. The percentage differences of all parameters between Arnigad and Bansigad were calculated as ((A-B)/B*100), where ‘A’ and ‘B’ represents Arnigad and Bansigad, respectively.

3.9. Lag Time Analysis:

In order to understand the response of catchments after P, around 40 hydrographs (during wet-period) were analyzed to determine lag time between P and discharge. The lag time was analyzed by calculating the delay between the maximum P 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 (m^3 s^{-1}) released from catchments after P events.

4. Results

4.1. 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 at both the catchment’s functioning by providing ~78% (for each catchment) of the annual P of 2922 mm, (Figure 3). Patterns and amount of monthly P 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 P ranged from 11 to 909 mm at both the catchments. Winter P 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, P exceeds thresholds (~10% of annual P) and hyetograph starts rising. July, August and September were the peak months whereas October, the falling limb of the hyetograph (Figure 4 A).

4.2. 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 (Figure 3). Generally, during last week of June, Q_t of Arnigad and Bansigad reached values of 48 mm and 14 mm (~3% and 1% of annual flow) and after that Q_t started rising instantly (Figure 4A). Bansigad had greater seasonality due to lack of flow during the pre-wet-period (March-May), whereas Q_t was maintained year the round at Arnigad. Seasonal (wet-period) and annual Q_t at Arnigad were lower by ~34% and 13%, respectively relative to Bansigad.

Mean stormflow production at the Arnigad was modest with the sum of 167 mm yr^{-1} (10% of annual Q_t) and occurred during the main wet-period (90%). Conversely, stormflow was much higher for the degraded catchment 914 mm 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 mm yr^{-1} and 949 mm yr^{-1} (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 important contributor for making stream perennial during dry-period as compared to Bansigad. The contribution of stormflow and baseflow significantly varied from January to December and its temporal variation is presented in Figure 4B. Recession rates of the baseflow for the Bansigad catchment during the dry-period were much faster, with reservoir response factor of ~0.028 day^{-1}, whereas it was ~0.0083 day^{-1} for the dense forest at Arnigad (Figure 5). The exponential recession curve of the outflow from groundwater reservoirs in either catchment (Figure 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 (Figure 6) for the studied catchments displayed that though there was no significant difference in annual P, however, there was significant difference in annual Q_t, ΔS, ΔG storage and ET, respectively, between catchments. Averagely, 43% (Arnigad) and 36% (Bansigad) of P was lost as ET, which means only 55% and 64 % of P was available as Q_t at Arnigad and Bansigad catchments (Figure 6).

4.3. Soil Moisture Behavior:

Temporal behavior of SM at different depths is presented in Figure 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 (Figure 7B). At Arnigad, SM at 80 cm depth held maximum SM than 50 cm.

4.4. Infiltration Rate:

Variations of initial and steady infiltration rate at Bansigad were smaller (50-64 cm hr^{-1} and 13-32 cm hr^{-1}) as compared to Arnigad (20-134 cm hr^{-1} and 8-30 cm hr^{-1}). Initial infiltration rate was lower by 29%, however, steady infiltration rate was higher by 21% at Arnigad relative to Bansigad (Table 2).

4.5. Characteristics of Soil:

Soil texture at Arnigad was having higher amount of the Silt and clay (13% and 23%) fractions as compared to Bansigad. Organic matter (OM) and porosity were also higher (35% and 8%) at Arnigad as compared to Bansigad. The results revealed that soil texture was better at forested catchment (Arnigad) as compared to degraded forest (Bansigad) catchment. Figure 8 shows the variations of soil properties along depth.

4.6. Sediment Budget:

Temporal variations of different types of sediments in Q_t including SSL, TDL and BL is presented in Figure 9A, B and C). There was a huge temporal variation (monthly) in SSL ranging 0.28 - 738 t km^{-2} and 0 -1265 t km^{-2} at Arnigad and Bansigad, respectively. Arnigad experiences 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. The average annual budget of SSL was 1112 t km^{-2} (Arnigad) and 2143 t km^{-2} (Bansigad) respectively, resulting that suspended sediment budget was two-fold higher at Bansigad as compared to Arnigad (Figure 9D).

Mean monthly TDL at Arnigad ranged between 21-153 t km^{-2} and at Bansigad it ranged between 0.2-177 t km^{-2}. The TDL was consistently found higher than SSL during drier months. Mean annual yield of TDL at Arnigad and Bansigad was 698 t km^{-2} and 488 t km^{-2}, respectively (Figure 9D), resulting higher TDL at Arnigad.

The volume of BL (monthly) flowing in the Arnigad stream was in the range of 0.03-17.28 m^3, whereas it was 74.64 m^3 at Bansigad and from March-mid June, no bedload material was observed. Mean monthly BL accumulation ranged between 0.09 to 4.92 t km^{-2} and 0.5 to 37.5 t km^{-2} at Arnigad and Bansigad, respectively. The average bed material deposited annually was 19 t km^{-2} (Arnigad) and 114 t km^{-2} (Bansigad), respectively, which indicated that BL accumulation was higher (6 fold) at Bansigad relative to Arnigad (Figure 9D).

Mass wastage has been considered the dominant erosional processes on hillslopes and the denudation rate was calculated for both the catchments. The average denudation rates were 0.68 mm yr^{-1} (Arnigad) and 1.02 mm yr^{-1} (Bansigad), respectively, resulted that Bansigad losses its mass (1.5 fold) at higher rate as compared to Arnigad.

5. Discussion

5.1 Forest Cover Impacts on Streamflow Regulation

Studies concerning the impact of forest cover changes on the magnitude of Q_t in Himalayan regions are rare (Sharma et al. 2007; Ashraf et al. 2013; Tiyagi et al. 2014); however, studies related to components of Q_t (baseflow and stormflow) are even the rarest in the Himalayan regions. During the study period, the annual cycle of P represented both dry and wet-period (Figure 3), thus allowed to study baseflow and stormflow conditions of the catchments. In the same line, Q_t at the catchments also showed distinctive behavior during dry and wet-periods (Figure 3), due to highly seasonal P 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 2^{nd} order polynomial relationship between P and Q_t (Figure-10 A) allowed the identification of P threshold (~200 mm), and when this threshold exceeds, Q_t generation increased significantly at both the catchments (Figure-10 A). The same threshold value (~200 mm), which accounts as ~10% of annual P were also observed in Figure 4B. This P threshold averagely occurred during mid of June, and before June, the low magnitude P (below 200 mm per month) potentially contributes to satisfies several hydrological processes e.g., initial infiltration, SM, ground water stress and ET (Tarboton 2003) at both the catchments. The P 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 are vital for sustenance of streams and regulation of 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%), Figure 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 (Figure 6). Despite having higher ET, 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, resulted in better soil formation at Arnigad catchment (Figure 8), further led 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, resulted 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 (Arnigad) in controlling SM retention was critical to retaining moisture within the soil. P moving in macropores resupply to groundwater, known as groundwater recharge. Groundwater released water with a slow recession rate (Figure 5) subsequently during dry-period to Qt 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 (Figure 4A). The study indicated that both streams were dependent on P for Q_t generation, but the P 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 (Figure 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 day^{-1} compared to Arnigad catchment (0.0083 day^{-1}). The faster recession rate at Bansigad, diminished Qt completely during dry-period, however, at dense forest (Arnigad) the baseflow was higher by ~52% annually, helped to maintain Q_t year the round. Hence, the higher proportion of the stormflow at Bansigad, indicated higher probability of water resources 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. 2016).

The 40 selected hydrographs revealed the response of catchments after P, exhibited 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 hour. If the time gap between two consecutive P were larger, lag time of hydrographs also became larger and during wet-period when the catchments were fully saturated with SM, few P events immediately become runoff/stream discharge. Among 40 hydrographs, it was observed that only three P 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 soil was fully saturated. Therefore, this time period gave an opportunity to compare both volume of water (discharge) and lag time between catchments. Therefore, these 3-hydrographs along with corresponding hyetographs at same time period from 29.07.08 to 31.07.08 and at same interval (15-minute interval) were analyzed in detail (Figure 11). There was no significant difference ($p = 0.05$) in P events between Arnigad (36-109 mm) and Bansigad (47-118 mm), however, there was significant difference in discharge between Arnigad (0.60-0.81 m^3s^{-1}) and Bansigad (0.81-1.32 m^3s^{-1}), respectively. Further, lag time of these three events were: 0:45, 0:45 and 0:30 hr (Arnigad) and 0:30, 0:30 and 0:15 hr (Bansigad), respectively (Figure 11). The shape of the different hydrographs varied with each individual P event. The analysis revealed that during wet-period, Arnigad releases lower volume of water and took averagely 15 minutes extra (compared to Bansigad) to reach to gauging site and potentially this behaviour of hydrographs (at Arnigad) may possibly be because of many combined factors: (i) slow recession rate of baseflow at Arnigad (Figure 5), (ii) higher potential of forest soil to store water at Arnigad (Figure 7) and (iii) higher infiltration rate (table 2). Therefore, the volume of water that was stored (at Arnigad) during P events and longer lag time supported the flow to release during a recession, helped in maintaining baseflow during dry-period, which is important ecosystem function of the catchment. Hence, the study indicates that forest cover at Arnigad showed significant and positive relationship with both baseflow and stormflow. These results are needed to effectively manage current and future land use and water resources problems in CHR.

The Non-linear relationships between Q_t and SM (Figure 10 B) allowed the identification of threshold value (~35%) of SM. When the SM threshold was exceeded, baseflow was activated, increased significantly and became a major contributor to stormflow. A clear threshold (~35%) between SM and Q_t, revealed the importance of initial moisture conditions, which determined the extent of the saturation and controls the Q_t production of the entire catchment (Penna et al., 2010). The threshold value (0.35) was very close to mean field capacity (0.35 and 0.33) at 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 have observed SM threshold as: 45% (Penna et al. 2011; Song and Wang 2019), 26% (Farrick and Branfireun 2014) and 23% (James and Roulet 2007) supported the importance of initial moisture conditions and above the SM threshold, Qt activation indicated the occurrence of Qt from the hillslope. The difference in threshold values might be due to difference in topography, climate, land use characteristics, soil characteristics and sampling designs. Therefore, our results showed that two factors: SM and P were responsible for Q_t activation and generation. Figure 4A and B, indicates that June month was the transition period, when hydrological functioning (Q_t activation and generation) of the catchments begins to activate and October was again a transition period when hydrological functioning begins to inactivate. The non-linear behavior is common in hydrological systems (Zuecco et al. 2018) and this 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 (Figure 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 lead to higher infiltration (Figure 12B). Both SM and vegetation were closely linked with each other; SM positively influence 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 SM (Pielke et al. 1998; Wang et al. 2006). Hence, the present study supported the fact that forests/vegetation leads strong bond with SM and interestingly SM also showed positive and direct impact on infiltration rate (Figure 12C). Further work is required in future to understand these relationships at different spatial and temporal scale in CHR. However, these results are very much helpful to farmers, land managers and policy developers for the conversation and sustainable development of forest, soil and water resources, important in this region.

5.2. Soil Moisture Variation at Different Soil Profiles:

Temporal variations of SM at different depths under different forest covers are shown in Figure 7A. It was observed that SM at all different profiles was responsive to P events, though few events might have been missed as the data was measured at bi-weekly. The annual cycle of both the P and SM follows the same path with unimodal variation (Figure 7A), and SM reached its maximum during wet-period, when ~78% of annual P occurred. Furthermore, SM at all soil layers were below FC during dry-period, whereas, it was above FC during wet-period at both catchments (Figure 7A). Such behavior indicated that SM was mainly regulated by P (Varikoden and Revadekar 2018). It is observed from Figure 7A and B, that during the wet-period, the surface layers at both the catchments were wetter than other deeper layers. This was because low intensity P were likely to be retained at the soil surface layer (Li et al. 2016). The difference in SM at surface layer was even more distinct at Bansigad catchment, showed low interception losses due to degraded forest at Bansigad, resulting large volume of P could reach to the ground surface (Liu et al. 2018; **Venkatraman and Ashwath** 2016) and therefore, the Bansigad catchment showed higher (4%, annually) moisture regimes at surface layer than Arnigad (Figure 7B). At Arnigad catchment, SM was maximum at 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 influence of 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 direction (Venkatesh et al. 2011). Annually, SM at Arnigad at 50 cm and 80 cm was enhanced by 13% and 31% in comparison with Bansigad (Figure 7B). These enhanced values indicated potential for soil water storage at forested catchment (Arnigad) and release the water slowly during the subsequent dry-period, which consequently helps in regulation of sustained stream flows in the Himalayan region. This can be further supported by the Figure 12, which shows that Arnigad had higher OM (21-89%) and higher porosity (3-11%) than Bansigad which helps Arnigad in retaining SM and upholding 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 at dense forested catchment (Arnigad) was better as compared to the degraded forested catchment (Bansigad). Therefore, the present study suggests that forests plays important role in SM functioning at local sites (Bruijnzeel 2004) and provides hydrological service 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.

5.3. 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. P during the monsoon was the main driver and contributes significantly in annual sediment transportation (95%) in both the studied catchments (Figure 9A). While, forests regulated sediment transport activity in these catchments through different 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, 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 decrease of surface erosion by reduction of kinetic energy of raindrops (Fukuyama et al. 2010; Nanko et al. 2015). On the other hand, degraded forest along with high intensity P triggers loosened material and debris (Fuller et al. 2003), leads to landslides (Struck et al. 2015), and further to higher sediment production at Bansigad stream (Tyagi et al. 2014), continuously disturbing the natural system (Mukherjee, 2013) of the Bansigad catchment. The lower (75%) deposited BL material at Arnigad catchment (Figure 9C) was because of the standing trees, felled logs and understory of dense forest, which slow down the movement of big boulders, gravel and debris (Qazi et al. 2018). Moreover, the strong tree root system and organic humus layer supports slope stability, decreases landslides and debris flows frequency (Imaizumi et al. 2008; Nepal et al. 2014; Goetz et al. 2015), hence BL material couldn't reach to the Arnigad stream relative to Bansigad stream. Hartanto et al. 2003; Imaizumi et al. 2019 also supports that large amount of sediments are captured by woody debris on hillslopes. Therefore, the present study ensures that forest plays important roles in regulating sediment transportation and forest plantation and conservation can be considered as an important way to improve the environment.

Interestingly, the concentration of dissolved material in streams at Arnigad was also enhanced by 114% (annually) as compared to Bansigad (Figure 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 to streams in dissolved form (Markewitz et al. 2004; Andrade et al. 2011; Cost et al. 2017). Hence, the dissolved OM effects TDS in the stream. Dry-period has significant impact on wide range of TDS at Bansigad, because TDS becomes more concentrated with decrease in discharge (Tipper et al. 2006; Calmels et al. 2011). TDS at both the catchments was the permissible limit according to WHO 2003; BIS 2012.

In the Himalayan region, high relief coupled with intensive P during monsoon provide favorable conditions for mass wasting (Korup and Weidinger 2011), which cause serious long-term problems e.g. functioning of hydropower plants, dam and river management, environmental flow, 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 (Figure 9D) and denudation rate by 41% at Arnigad compared to Bansigad, further confirms the crucial role of trees and forests in preventing mass wastage which in turn maintains balances ecological functioning, biological diversity, landslides etc. at long term scale.

6. Conclusion

During the study period, P was quite variable and comprised both dry-period and wet-period, thus allowed to study baseflow and stormflow conditions of the catchments. The annual hyetograph analysis revealed that the P at both the catchments was highly seasonal, and wet-period plays a key role in hydrological functioning of catchments. The identification of P threshold values of both the catchments (200 mm per month) can be helpful to predict Q_t generation which are 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 and makes stream perennial, however, baseflow was not available at Bansigad during few months of dry-period and makes stream intermittent. The analysis revealed that both streams were dependent on P for Q_t generation, but the timescale over which precipitation at Arnigad can sustain baseflow was greatly enhanced relative to Bansigad.

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 become major contributor to stormflow. Therefore, the study estimated the threshold, responsible for Q_t activation and generation, and 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 at Bansigad catchment. The different components of forests at Arnigad catchment helped in reduction (41%, relative to Bansigad) of denudation rate of soil. Therefore, the present study suggests that P during wet-period was the main driver for controlling hydrological processes, whereas, forests provided substantial services by regulating water balance, SM and sediment budget at Arnigad catchments. Moreover, forest also helped in maintaining soil properties and infiltration rate 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 meets needs of local people without adversely affecting the environment.

7. Declarations

Ethics approval and consent to participate

The subject has no ethic risk.

Consent for publication

The subject has no ethic risk

Competing interests

The authors declare that they have no competing interests.

Funding

Funding received from ICFRE and UCOST are greatly acknowledged.

Authors' contributions

Author contributed from data collection (from field) till manuscript development.

Availability of data and materials

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

Acknowledgement

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).

8. Abbreviations

CHR: Central Himalayan Region

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

ΔS: Change in soil moisture storage

ΔG: 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

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Tables

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
	Elevation (Z), m	Arc GIS	1650 - 2230	1620-2170	
	Perimeter (Pe), km	Arc GIS	7.54	6.31	
	Slope (S), degree		21.86*	23.61*	
	Stream Order (U)	Arc GIS	Hierarchical Rank		Strahler, 1957
	Stream Number (Nu)	Arc GIS	7	7	
	Stream length (Lu), km	Arc GIS	6*	5*	Horton, 1945
	Mean stream length (Lsm), km	Lsm = Lu/Nu	1*	1	Strahler, 1964
	Basin Length (Lb), km	Arc GIS	2.50	1.55	
	Drainage density (Dd), km/km^2	Dd = Lu / A	2.10	2.53	Horton, 1932
	Texture ratio (T), km^{-1}	T = Nu / Pe	0.93	1.12	Horton, 1945
	Length of overland flow (Lg), m	Lg = [illegible]*Dd	1.05	1.26	Horton, 1945
	Drainage Area (A), km^2	Arc GIS	2.86	1.91	
	Circularity ratio (Rc)	Rc = 12.57 * (A/Pe^2)	0.63	0.60	Miller, 1953
	Elongation ratio (Re)	$Re = 2/Lb*(A/\pi)^{0.5}$	0.76	1.00	Schumm, 1956
	Form Factor (Ff)	Ff = A / Lb^2	0.46	0.79	Horton, 1932

Constant of channel maintenance (C), km^2/km	C = 1 / Dd	0.48	0.40	Schumm, 1956
Drainage Frequency (Fμ), km^{-2}	Fs = Nu / A	2.45	3.67	Horton, 1932
Basin relief (R), m	R = Z - z	580	550	
Relief ratio (Rr)	Rr = R / Lb	232	355	Schumn, 1956

* Mean value

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

Catchment	Site Nos.	Initial Infiltration rate (cm hr^{-1})	Steady Infiltration rate (cm hr^{-1})
Arnigad	1	101	29
	2	134	30
	3	20	8
	4	77	19
Average		**55**	**23**
Bansigad	1	52	13
	2	50	25
	3	32	22
	4	64	32
Average		**77**	**19**

Figures

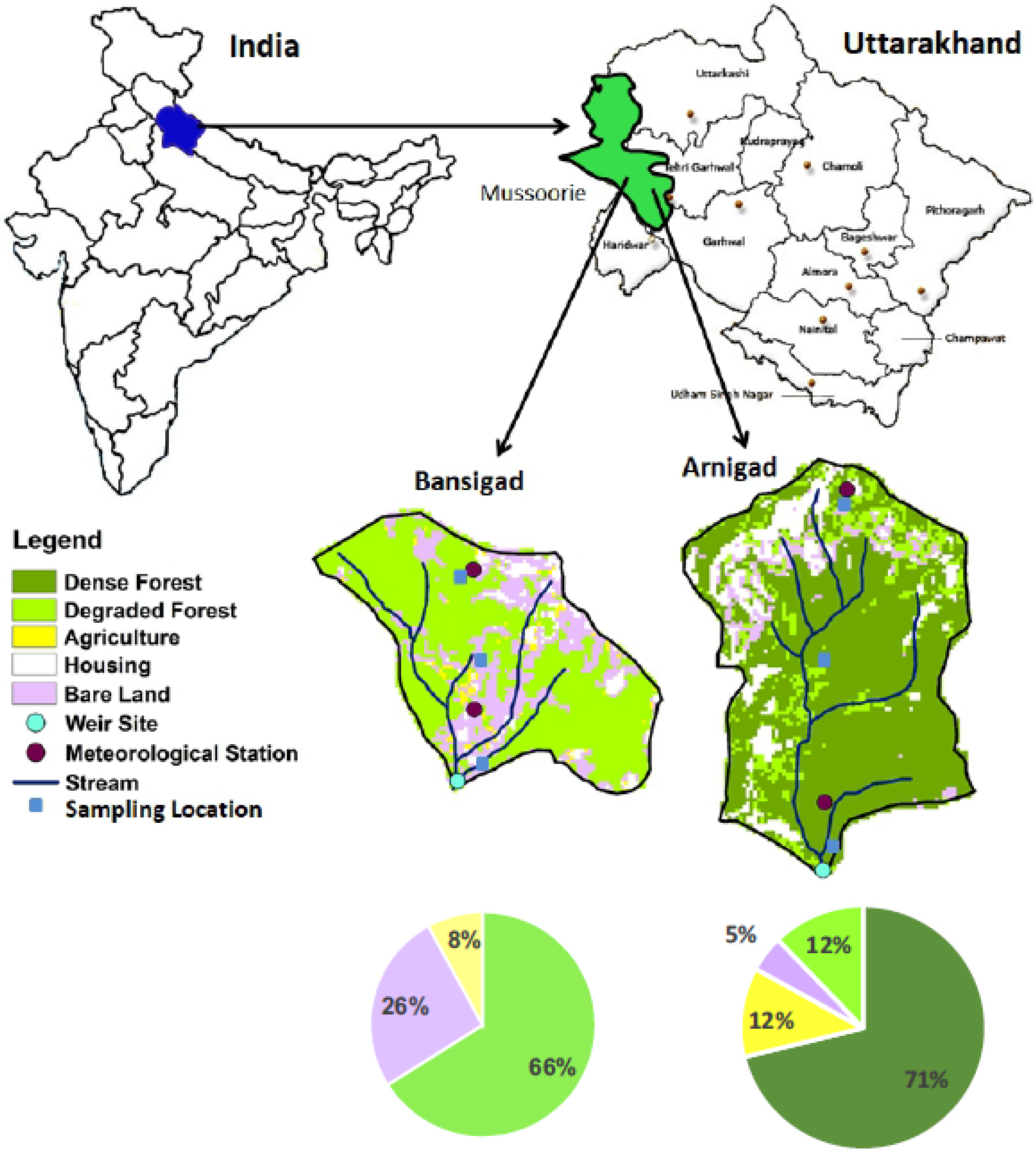

Figure 1

Two small neighboring headwater catchments, i.e. the dense-forested catchment, Arnigad (285.7 ha; 30o 27′ N, 78o 5.5′ E) and degraded-forested catchment, Bansigad (190.5 ha; 30o 27′ N, 78o 2.5′E) were selected in the Mussoorie area, CHR (Figure 1)

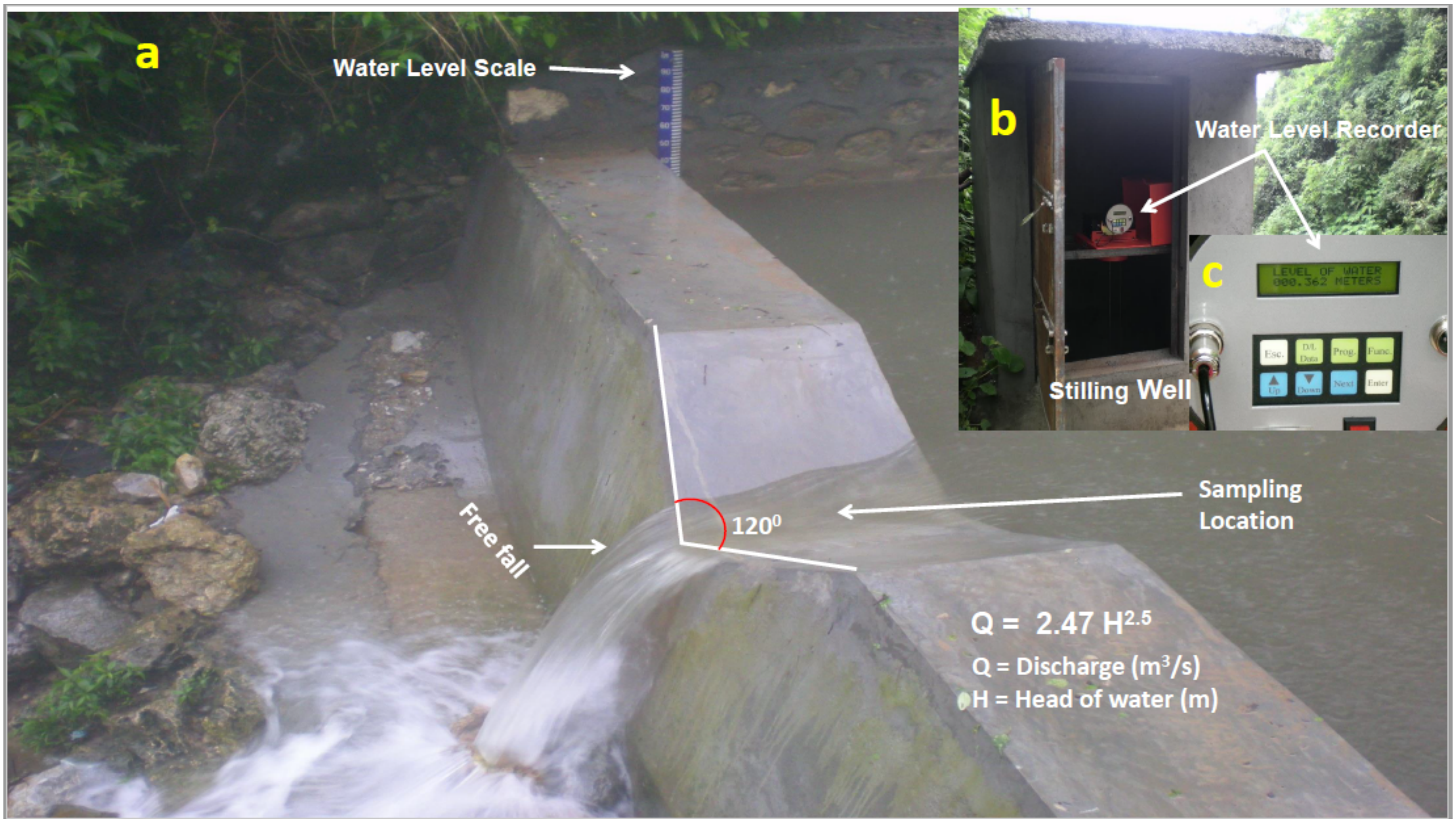

Figure 2

A rectangular weir with a sharp-crested 120o V-notch was constructed for better gauging of low flows at both the catchments (Figure 2)

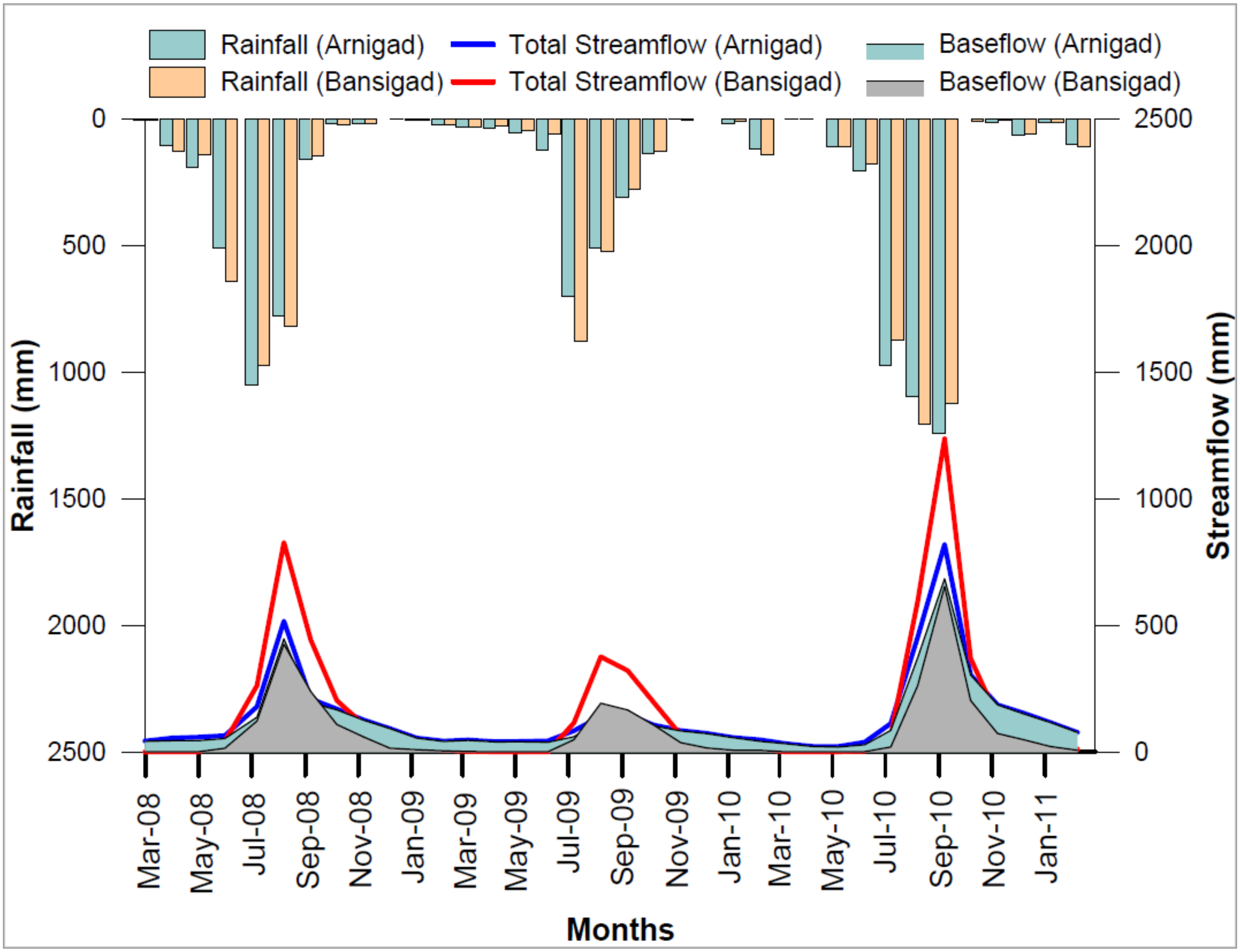

Figure 3

The wet-period played a substantial role at both the catchment's functioning by providing ~78% (for each catchment) of the annual P of 2922 mm, (Figure 3)

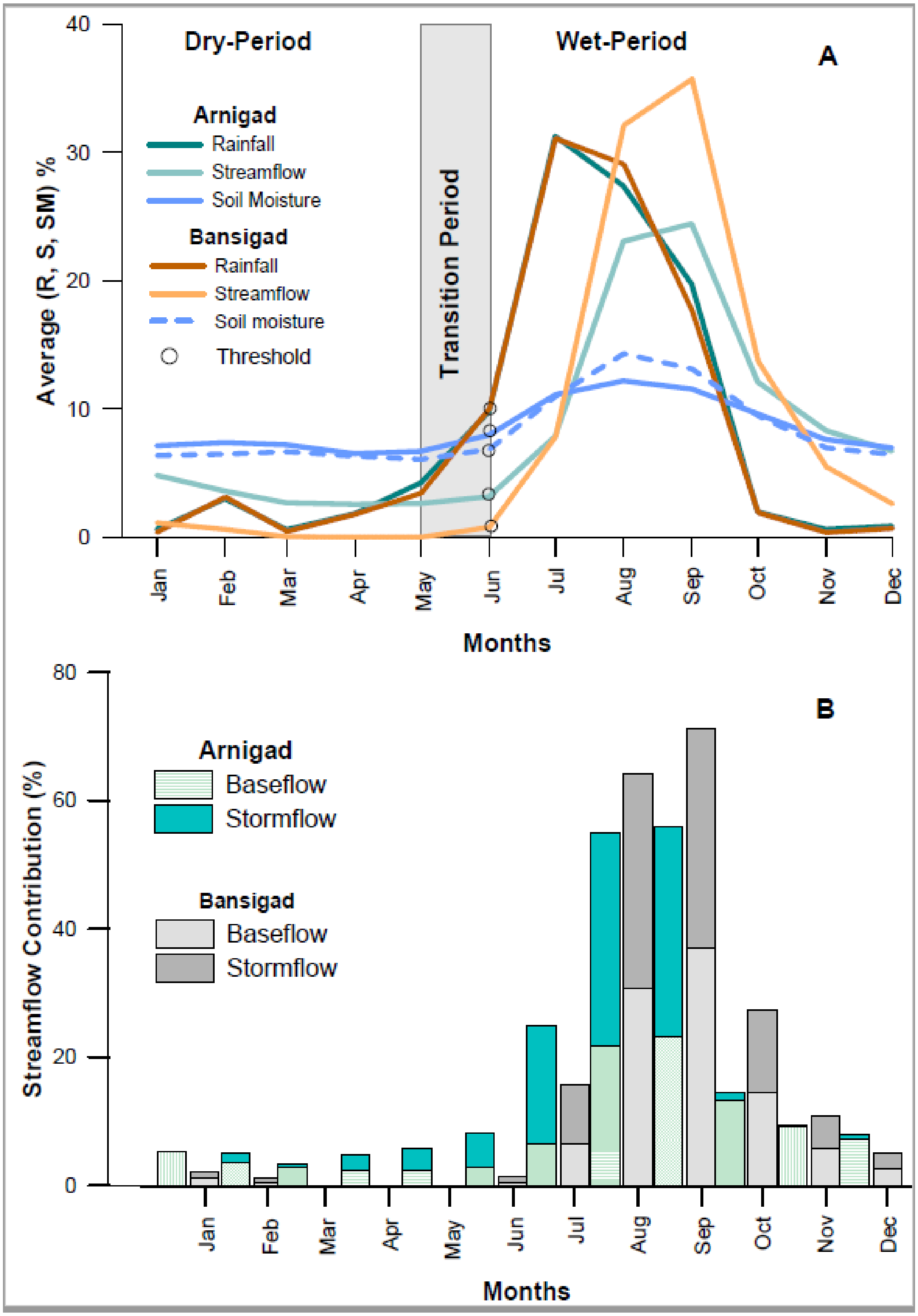

Figure 4

Winter P 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, P exceeds thresholds (~10% of annual P) and hyetograph starts rising. July, August and September were the peak months whereas October, the falling limb of the hyetograph (Figure 4 A). The contribution of stormflow and baseflow significantly varied from January to December and its temporal variation is presented in Figure 4B.

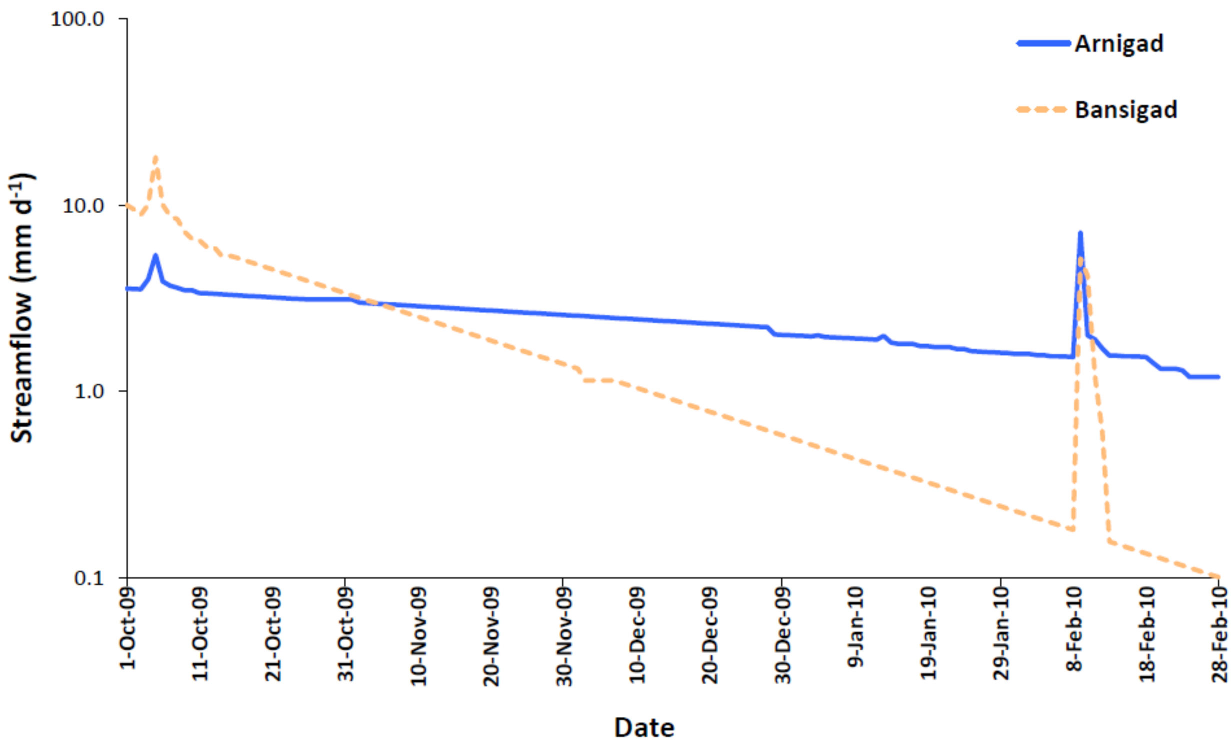

Figure 5

Recession rates of the baseflow for the Bansigad catchment during the dry-period were much faster, with reservoir response factor of ~0.028 day-1, whereas it was ~0.0083 day-1 for the dense forest at Arnigad (Figure 5). The exponential recession curve of the outflow from groundwater reservoirs in either catchment (Figure 5) did not deviate from linear reservoir theory, indicating negligible leakage losses and hence letting direct comparison between the two catchments.

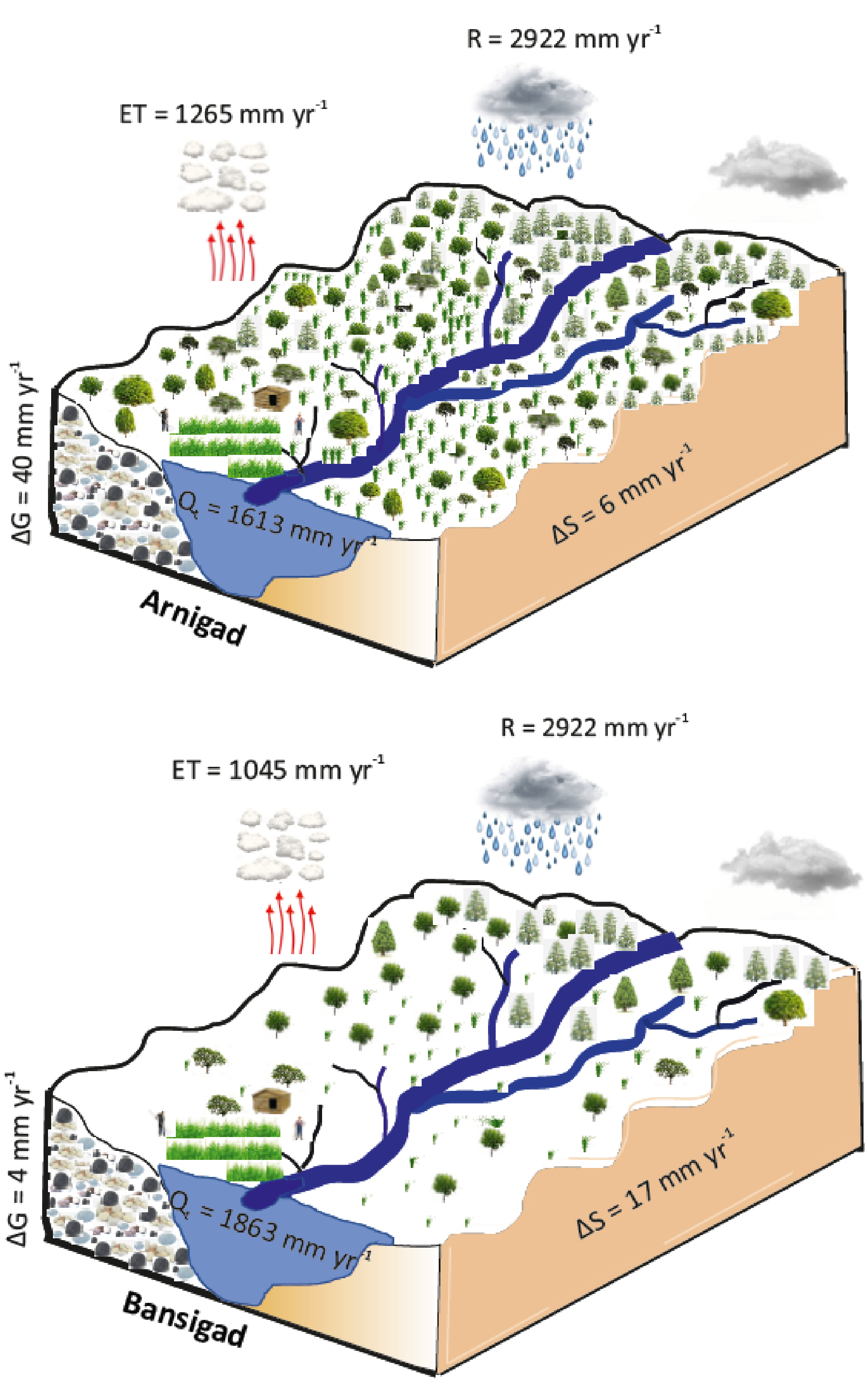

Figure 6

The annual water budgets (Figure 6) for the studied catchments displayed that though there was no significant difference in annual P, however, there was significant difference in annual Qt, ΔS, ΔG storage and ET, respectively, between catchments. Averagely, 43% (Arnigad) and 36% (Bansigad) of P was lost as ET, which means only 55% and 64 % of P was available as Qt at Arnigad and Bansigad catchments (Figure 6).

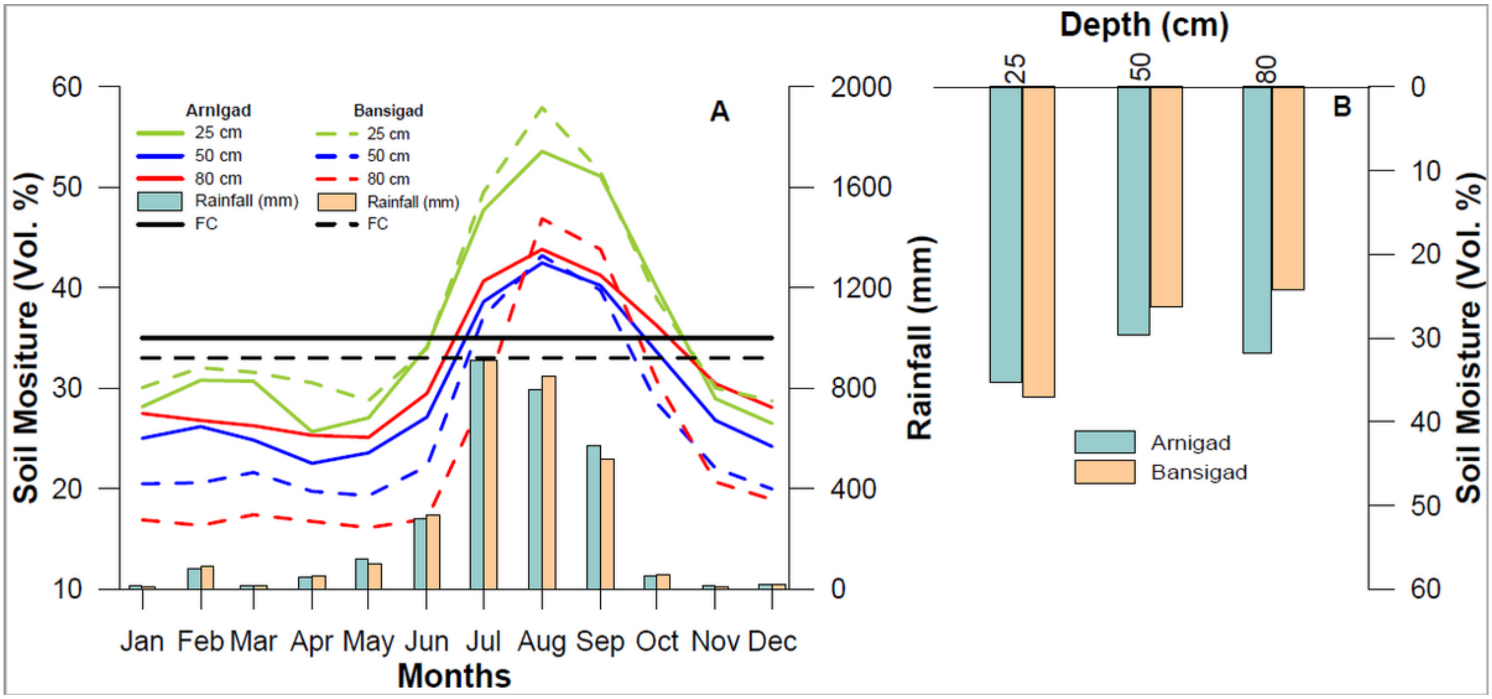

Figure 7

Temporal behavior of SM at different depths is presented in Figure 7A. 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 (Figure 7B).

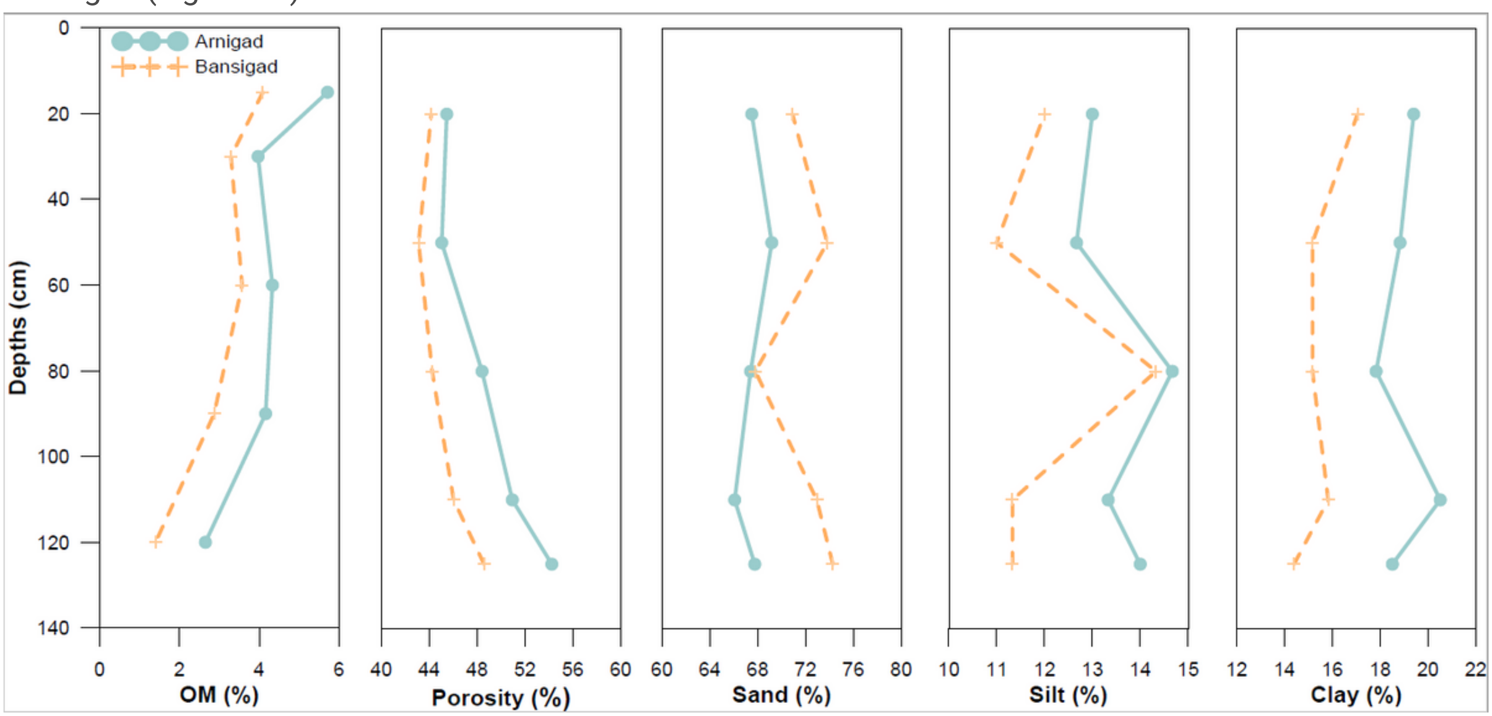

Figure 8

Figure 8 shows the variations of soil properties along depth.

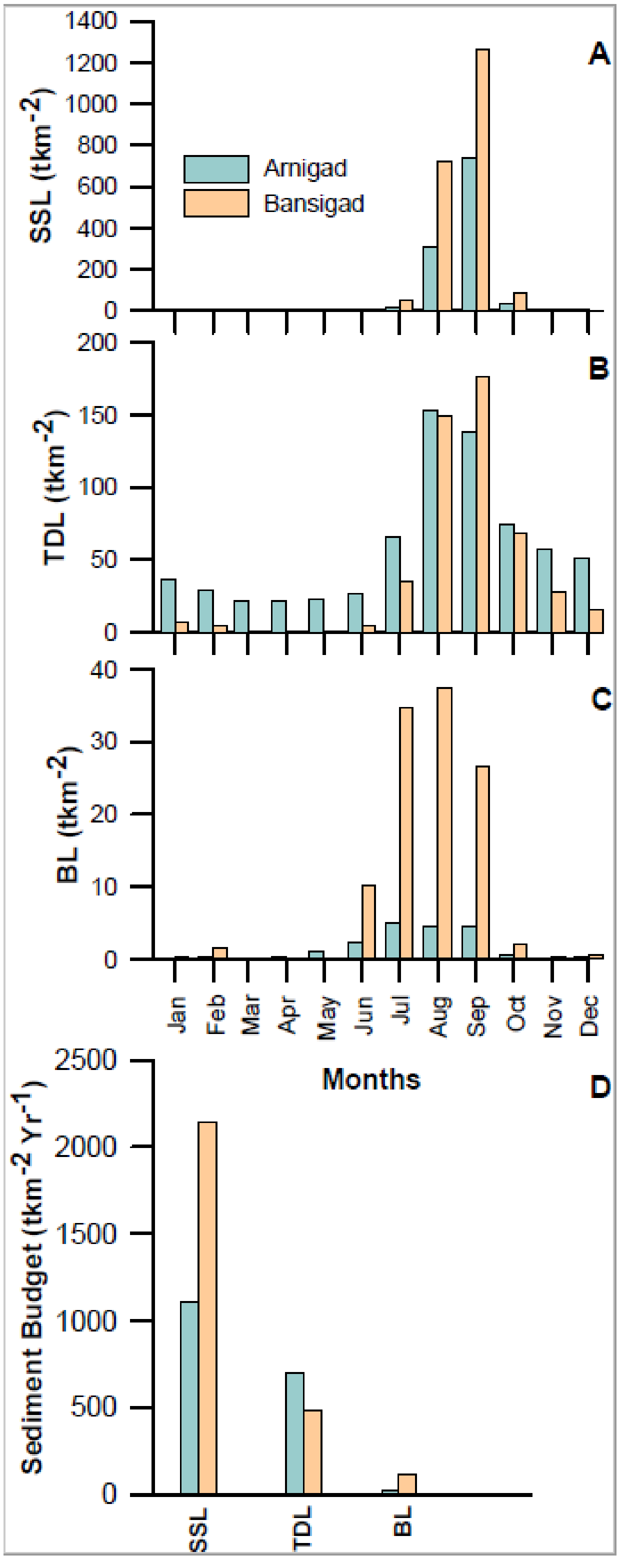

Figure 9

Temporal variations of different types of sediments in Qt including SSL, TDL and BL is presented in Figure 9A, B and C). The average annual budget of SSL was 1112 t km-2 (Arnigad) and 2143 t km-2 (Bansigad) respectively, resulting that suspended sediment budget was two-fold higher at Bansigad as compared to Arnigad (Figure 9D).

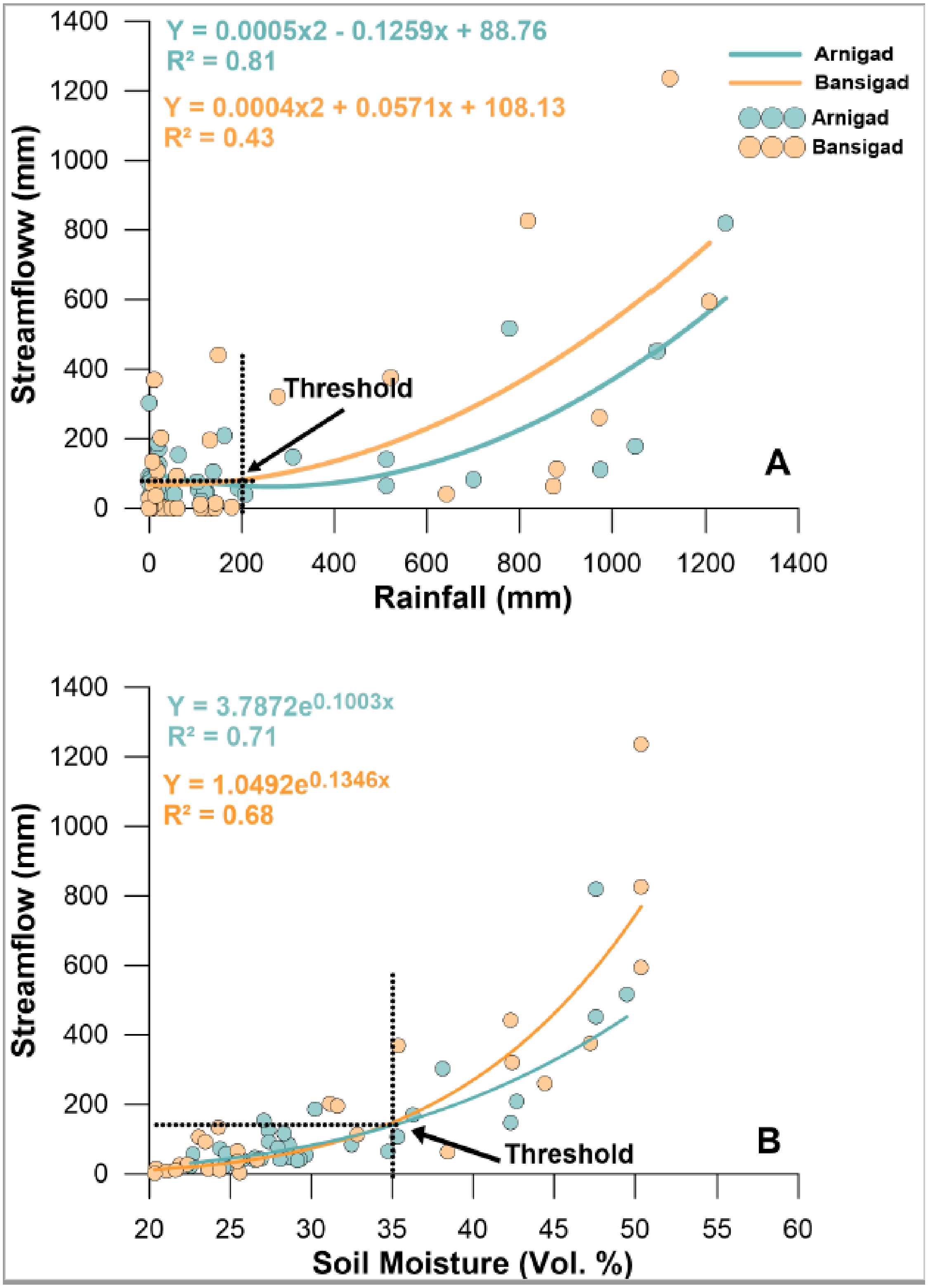

Figure 10

The Non-linear relationships between Qt and SM (Figure 10 B) allowed the identification of threshold value (~35%) of SM. When the SM threshold was exceeded, baseflow was activated, increased significantly and became a major contributor to stormflow.

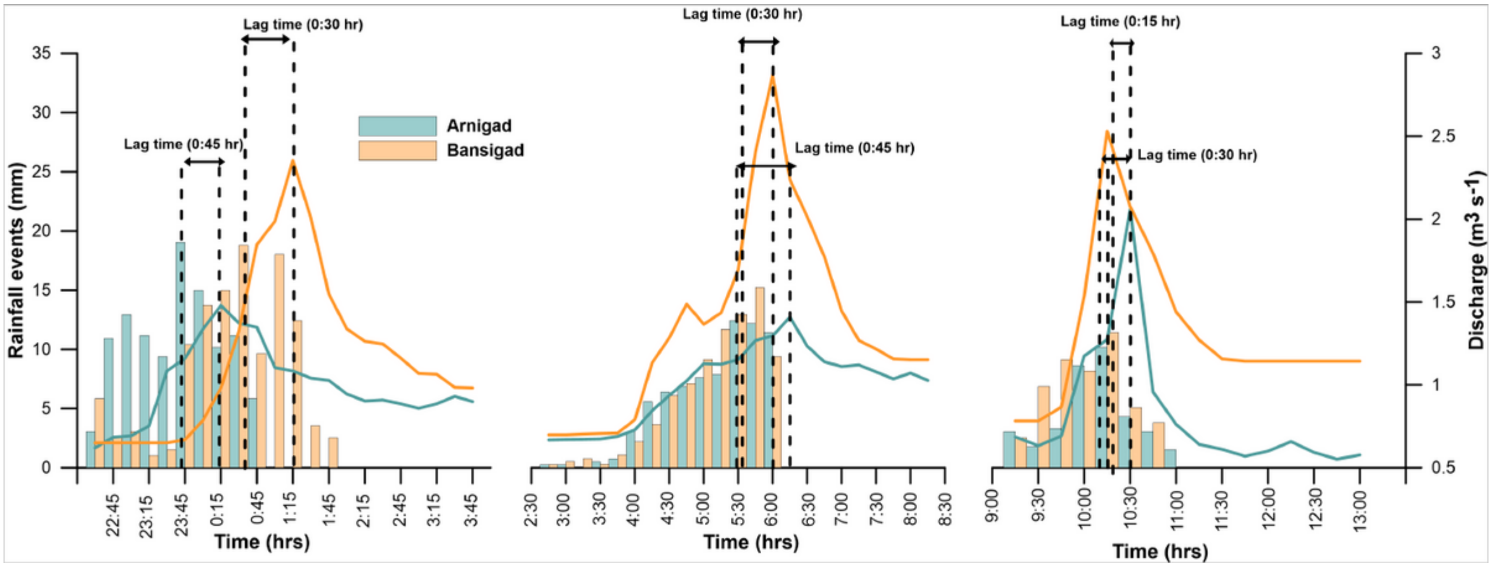

Figure 11

Among 40 hydrographs, it was observed that only three P 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 soil was fully saturated. Therefore, this time period gave an opportunity to compare both volume of water (discharge) and lag time between catchments. Therefore, these 3-hydrographs along with corresponding hyetographs at same time period from 29.07.08 to 31.07.08 and at same interval (15-minute interval) were analyzed in detail (Figure 11).

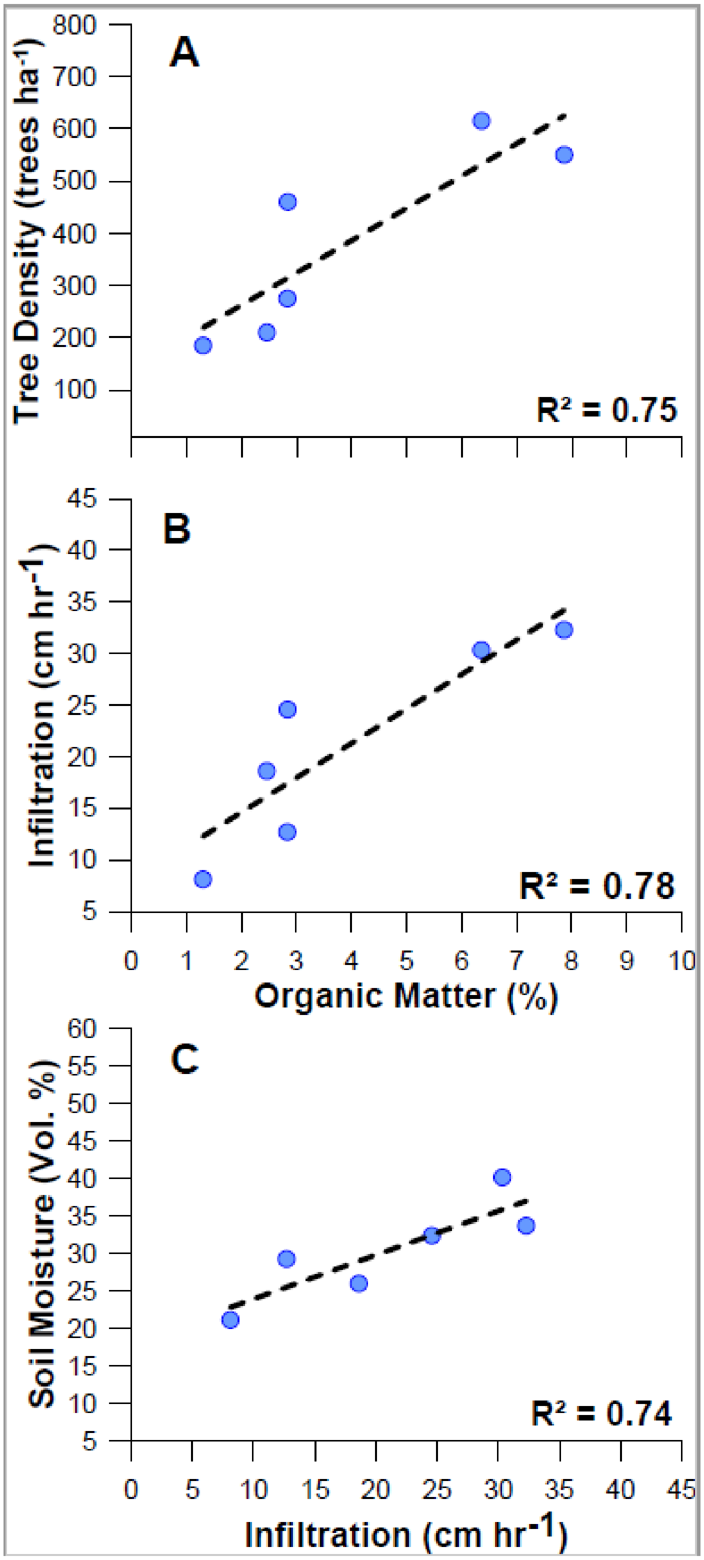

Figure 12

OM showed direct positive linear relationship with tree density (Figure 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 lead to higher infiltration (Figure 12B). Both SM and vegetation were closely linked with each other; SM positively influence 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 SM (Pielke et al. 1998; Wang et al. 2006). Hence, the present study supported the fact that forests/vegetation leads strong bond with SM and interestingly SM also showed positive and direct impact on infiltration rate (Figure 12C).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- equations.docx