Bio-physical effects on infiltration, channel roughness and discharge: a comparative study involving ephemeral and perennial streams

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Abstract

Infiltration and channel roughness, two major factors that govern stream discharge were studied between ephemeral streams (ES) and similar-sized perennial streams (PS) for two ephemeral flow conditions: with surface flow (wet season) and with ceased flow (dry season). The highest infiltration was observed at the low flow areas around the thalweg of ES in the dry season. Also, the infiltration in the high flow areas close to the channel margin was higher in ES than PS in the wet season but was similar in the dry season. Similar infiltration rates in ES and PS were rather unexpected and was attributed to the vegetation mat formed by air-dried litter because of the rapid decrease in sediment moisture. In high flow areas of both stream types in the wet season, negative and positive correlations were observed for infiltration with biomass and sediment organic content, respectively. Also, in a few cases sediment moisture showed a positive correlation with infiltration. ES were two to three times rougher than PS and standing crop biomass and/or litter content increased stream roughness and decreased with herb diversity. Impact of vegetation parameters on roughness was more prominent in PS, whereas mean particle size had equally strong importance on roughness for both streams other than perennials in the dry season. Modelled (via HEC-HMS) and observed discharges had a better agreement for PS. The field observations, analytical solutions as well as hydrological modelling revealed ES to have a lower unit discharge than PS.

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Abstract

Infiltration and channel roughness, two major factors that govern stream discharge were studied between ephemeral streams (ES) and similar-sized perennial streams (PS) for two ephemeral flow conditions: with surface flow (wet season) and with ceased flow (dry season). The highest infiltration was observed at the low flow areas around the thalweg of ES in the dry season. Also, the infiltration in the high flow areas close to the channel margin was higher in ES than PS in the wet season but was similar in the dry season. Similar infiltration rates in ES and PS were rather unexpected and was attributed to the vegetation mat formed by air-dried litter because of the rapid decrease in sediment moisture. In high flow areas of both stream types in the wet season, negative and positive correlations were observed for infiltration with biomass and sediment organic content, respectively. Also, in a few cases sediment moisture showed a positive correlation with infiltration. ES were two to three times rougher than PS and standing crop biomass and/or litter content increased stream roughness and decreased with herb diversity. Impact of vegetation parameters on roughness was more prominent in PS, whereas mean particle size had equally strong importance on roughness for both streams other than perennials in the dry season. Modelled (via HEC-HMS) and observed discharges had a better agreement for PS. The field observations, analytical solutions as well as hydrological modelling revealed ES to have a lower unit discharge than PS.

Keywords

Bio-physical factors; Discharge; Ephemeral streams; Perennial streams; Infiltration; Stream bed roughness

1. Introduction

Headwater streams are streams with order less than four (Strahlers stream order) and can be of perennial or non-perennial nature with respect of its flow regime (Gomes & Wai, 2014). They are important not only to the headwater environments, but also to downstream waters as they are physically, biologically, and chemically connected (Gomes et al., 2020). Non-perennial streams can be further divided into intermittent (groundwater flows to the stream at certain flow regimes) and ephemeral (stream bed is well above the groundwater level) streams and are often interchangeable (in this paper all non-perennial streams will be referred to as ephemeral streams). Ephemeral streams account for more than half of the total length of rivers in the world (Datry et al., 2011), and even though not quantified, is noted for their role in flood control of downstream environments by aiding transmission (abstraction) losses.

Flooding in natural streams/rivers depend on the transmission losses such as evaporation, and channel bank and bed penetration that takes place after a rainfall event (Ghobadian & Fathi-Moghadam, 2013). Transmission losses are quantified by analyzing streamflow reductions, including infiltration through sediment layer of the stream bed, evapotranspiration back to the atmosphere, loss to terrestrial plain, and losses to stream banks (Ghobadian & Fathi-Moghadam, 2013; Gomes & Perera, 2021). Because of the difficulty in measuring evapotranspiration and other losses during flow, especially in upstream areas, infiltration is regarded as a major source of transmission losses (Shanafield &Cook, 2014). Infiltration of water through sediment in ephemeral and perennial stream channels and its flood plain areas can be a complex hydrodynamic phenomenon and could be affected by several ecosystem attributes such as soil properties and its composition (including soil surface characteristics, e.g., dead and live vegetation biomass) and biological activities in the soil (Assouline, 2013). The literature on the effects of vegetation on infiltration within the bankfull areas of ephemeral and perennial streams in mountainous and tropical climate areas by way of comparative studies are rather unfound. However, the behavior of infiltration capacity against vegetation is well studied in semi-arid and arid ecosystems (Saco et al., 2007). As per Subramanya (2013), vegetated surfaces promote infiltration compared to un-vegetated surfaces, since unvegetated surfaces promote surface soil packing. In addition, vegetated surfaces decrease the runoff due to friction (Thompson et al., 2010). Nevertheless, Gomes et al. (2020) observed that the vegetation composition was different even between closely located ephemeral and perennial streams. Therefore, transmission losses of these two stream types could be different, and quantification of the difference is one research gap we had identified.

Flood control can be done by the changing roughness elements of streams that affect discharge or flow velocity, for example a rough stream bed decreases discharge, which is important for flood risk reduction of downstream areas (Dorn et al., 2014). Different methods are practiced in determining the roughness coefficient of stream beds, such as through the relation of size and distribution of the soil particles of the streambed (e.g., Limerinos, 1970) through quantitative approaches of field conditions (e.g., Jarrett, 1985) by studying submerged and non-submerged vegetation by way of laboratory flume experiments (e.g., Conesa-García et al., 2018) and via high-resolution modern topography measurements such as bathymetric lidar (Ozdemir et al., 2013). However, there are only a few studies on ephemeral stream roughness (e.g., Aldridge & Garrett, 1973 ;Gillen, 1996), unlike for perennial streams (e.g., Gillen, 1996).

The aim of this study was to compare the infiltration and stream bed/bank roughness of comparable ephemeral and perennial streams of a headwater (mountainous) catchment in a tropical climate. The first objective was to capture the infiltration signature and to study the correlations of biomass (e.g., standing crop, and litter) and soil properties (e.g., soil moisture, organic content, mean particle size) with infiltration. The second objective was to observe the channel roughness of ephemeral and perennial streams. Lastly, the discharges of the stream types were compared by way of field observations, analytical methods, and hydrological modelling (using HEC-HMS software) in order to determine how well contributing factors such as infiltration and roughness represent in stream discharges of ephemeral and perennial streams.

2. Materials and Methods

2.1. Study area, an overview of streams, and sampling schedule

The study was carried out in three ephemeral and three perennial streams (stream order < 1) in Balangoda (Figure 1a), Ratnapura district, Sri Lanka. All streams were located a few kilometers away from each other with the same geological, climatic, and weather conditions. Balangoda belongs to the intermediate climatic zone, one of three major climatic zones in Sri Lanka (Meteorological Department of Sri Lanka 2020). Figure 1b shows the daily rainfall in Balangoda from 1985 to 2021 (Meteorological Department of Sri Lanka 2020). Normally the rain commences in mid-March to April (first inter monsoon) and gradually decreases after May. Again, increasing after August due to the latter stage of the southwestern monsoon and second inter monsoon. Second inter monsoon brings high-intensity rainfall until November. A sudden decrease in rainfall can be observed in January and the decrement would continue until February. January-February and July-August are the periods with low rainfall, and it was the case during the study period. The total annual precipitation in 2017, 2018 and 2021 was about 2800, 2500 and 2722 mm, respectively (Meteorological Department of Sri Lanka 2022). Ephemeral stream 1 and ephemeral stream 2 (hereafter referred to as E1 and E2, respectively) are located near Duwili Ella road, where E1 is located close to Duwili Ella waterfall. Perennial stream 1, perennial stream 2, perennial stream 3, and ephemeral stream 3 (hereinafter referred to as P1, P2, P3, and E3, respectively) are located near Kalthota road. Table 1 gives the location details and the general eco-hydrological description of the streams. Fieldwork for detailed sampling in 2017 was conducted on November 14^{th} and 21^{st} (wet season), and July 1^{st} (dry season). For the year 2018 detailed sampling was conducted on October 7^{th} and November 26^{th} (wet season) and July 11^{th} in the dry season. Detailed sampling included observations of all bio-physical parameters such as infiltration, vegetation composition, and stream observations such as wetted depth, wetted width, depth, and stream discharge. Since the study involved discharge modelling, water depths were observed in the furthest downstream cross section of the sampled reaches of E3 and P3 daily in July (dry season) and November (wet season) in 2021. In addition, in 2021 weekly measurements of stream discharges were made to obtain stage-discharge relationships for E3 and P3.

In the wet season, ephemerals showed surface flow, whereas in the dry season they were either characterized by disconnected pools without a surface flow or were completely dry. It should be noted that we did not observe high flow conditions during the wet seasons and water depths were about 8 % more and about 5% less than the maximum low flow depth of the perennial and ephemeral streams, respectively (low flow level was identified by observing channel cross-section features (see: Fritz et al., 2006)). During the dry season sampling, perennial streams showed a flow very close to low flow conditions (at extreme a 12% reduced depth than the maximum low flow depth), and groundwater inflow may have been a major contributor.

2.2 Details of sampling locations within the stream system

A 100 m representative longitudinal reach was selected from each stream. The transverse direction was divided into two regions to capture different flow stages. The first region was about one to two meters from the thalweg and corresponded to the low flow hydrologic floodplain of the channels (hereinafter low flow areas). In perennial streams, this region always had a flow, whereas in ephemeral streams water was seen only at certain periods, where it varied between observable surface flows, disconnected pools, and completely dry stream beds. The second transverse region was about two to five meters from the thalweg and corresponded to the high flow hydrologic floodplain of the channels (hereinafter high flow areas). It should be noted in many cases the high flow hydrologic floodplain boundary was closer to the channel margin (bankfull level). To capture the research objectives clearly, the low flow areas were sampled close to the thalweg, whereas high flow area sampling was carried out in mid to maximum elevation of high flow areas, i.e., close to the channel margin, but never went beyond it. It should be noted that differentiation of high flow and bankfull levels were possible only in certain stream cross-sections. In that regard, it is also appropriate to state that the sampling of the second transverse region (referred as highflow) was carried out approximately within the mid area between low flow and channel margins. The selection of sampling locations within these two regions was entirely random, unless there were special conditions that would make sampling biased (e.g., locations with outcrops). High flow areas of perennials had flowing water in total for about three months of each year, and ephemerals had flowing water in its high flow areas at most in total a month per year. Also, as per consultation with villagers and Forest department officers, there were years that ephemeral streams have not had a high flow condition.

2.2. Infiltration tests

A single ring infiltrometer with an internal diameter of 35 cm and length 55 cm, made up of Polyvinyl chloride and driven 7-10 cm beneath the ground was used for infiltration tests. The test procedure followed ASTM 3385-18 (American Society for Testing and Materials 2002), but was conducted only for 20 minutes, even if the steady infiltration rate was obtained or not. Long duration tests were impractical as within a single sampling session (i.e., within a day or two of a given season) about 100 tests needed completion. Relatively short infiltration experiments in field research are not rare (e.g., Schoener, 2016), and should be acceptable especially in comparative studies. The ponding height was kept at 40 cm for an undisturbed soil. A larger ponding area and height would result in slightly different results as it might affect the suction ability of the underlying soil (Assouline, 2013). The infiltration rate was calculated using Eq. (1). I is the infiltration rate for the first 20-minute period (m/s) (herein after infiltration rate), V is the volume of flow (ml), t is the time of flow (s) (t = 1200 s), A is the area of the ring (m^2).

$$\mathrm{I} = \left[\frac{\mathrm{V}}{\mathrm{t}\times\mathrm{A}}\right] \times 10^{-6} \qquad \text{(Eq. 1)}$$

2.3. Hydraulic Parameters and stage-discharge relationships

Five cross-sections were considered in each stream to observe velocity and cross-section dimensions. The velocity was measured at 0.6 of the water depth using a velocity meter (Flowatch Switzerland), and the float method was used if the water level was less than 5 cm. The slope of each cross-section was computed by measuring the vertical elevation difference and dividing it by the horizontal length of the stream surface using an Auto level (Sokkia Auto Level B40 Japan). Depths and widths were measured by a steel ruler and a measuring tape, respectively. The discharge (Q) was calculated using the area× velocity method (Subramanya, 2013) or with the bucket method as appropriate (Gomes & Wai., 2014). Bucket method was used by constructing a weir from boulders and gravel at a cross-section where flow could easily be converged. Discharges were measured in situ in 2017 (three days), and 2018 (three days) and 2021 (eight days). The discharges of the last cross section of E3 and P3 were used to develop stage-discharge relationships. Bankfull discharges were calculated using Manning's equation (Equation 2) (Subramanya, 2013). P is the wetted perimeter of the cross-section considered (m), S is the slope of the reach, and A is the flow area of the cross-section (m^2).

$$Q = \frac{A^{5/3} S^{1/2}}{n P^{2/3}} \qquad \text{(Eq. 2)}$$

2.4.Vegetation sampling

Vegetation biomass (standing crop) and surface litter were sampled in a 0.5 ×0.5 m area at six places per stream. All vegetation (herbs, forbs, graminoids, vines, and tree saplings shorter than 0.5 m) was considered. The role of tree samplings that were less than 0.5 m tall (about a year old) on infiltration and channel roughness were assumed to be similar to herbs, forbs, graminoids, and vines. Also, trees that were over two years old were rather unfound up to the channel margin. The standing crop biomass included the summation of above and below-ground components. The below ground biomass of ephemeral streams were relatively more than the perennial streams (60% vs 45%). Samples were washed thoroughly to remove sediment and other foreign matter. Each sample was oven-dried at 100 ºC until no weight loss was observed. Diversity of herbs was realized by Shannon-Wiener index (SWI) (Equation 3) (Gomes & Asaeda, 2009). P_i is the proportion of cover by the i^{th} species.

$$\text{SWI} = \sum_{i=1}^{n} P_i ln P_i \qquad \text{(Eq. 3)}$$

2.5. Sediment sampling and channel roughness

Sediment samples were collected up to a depth of 10 cm close to the places where infiltration tests were performed. The sediment samples were collected in plastic Ziploc bags to preserve moisture during transportation to the laboratory. Moisture content was taken as weight of water relative to the dry weight of the sediment (ASTM D2216 1998). Particle size distribution was determined by sieve analysis (ASTM D422-63 2007), and the particle size corresponding to 10% finer in the cumulative distribution (D10) and particle size corresponding to 50% finer in the cumulative distribution (D50; median particle size) were observed. The particle size distribution curves revealed that sediment of ephemeral low flow areas was gap graded (data not shown), which is a special case of a poorly graded sediment (Das & Sobhan, 2014).

The organic content of the sediment was arrived at by the loss on ignition test (ASTM D2974, 2014). Photographic analysis was done to obtain the particle size distribution of soil samples that contained cobbles and boulders (Ibbeken & Schleyer, 1986). Scaling and digitizing of the image was done in AUTO-CAD 2015 version.

Manning's roughness coefficient of low flow areas was calculated by Equation 2. Manning's coefficient for high flow areas (include stream banks) were estimated based on a general quantitative approach as described by Gillen (1996).

2.6 Discharge generation: analytically and hydrologic modeling

The hydraulic parameters that were observed were used to calculate the discharge by the Manning's equation for composite sections (Equation 2). In this regard the discharges governed by the low flow and high flow areas when the stream is under bankfull conditions were calculated separately for low flow and high flow sections and added to get the total discharge of the entire section (Subramanya, 2013) (the typical division using vertical lines are shown in Figures 1d and e). This was necessary as the Manning's roughness's were different in the wetted perimeters of low flow and high flow sections.

Hydrological modelling was performed using HEC-HMS 4.7.1 (Hydrologic Engineering Center - Hydrologic Modeling System, U.S. Army corps of Engineers) for the sites of coordinates 06º 38.054´N 080º 51.279´E (E3) and 06º 36.658´N 080º 49.815´E (P3) for dry and wet seasons of years 2017, 2018, and 2021 (each season one month where field sampling was done). However, only 2021 had the directly or indirectly (via stage-discharge relationships) observed field discharges for the modelled periods. The terrain data was obtained from a digital elevation model (DEM) file of Sri Lanka, acquired from the Survey Department of Sri Lanka, from which the catchment area inclusive of the sampling site was extracted. This DEM file was used in the HEC-HMS software to process the sinks and drainage paths, after which the streams were identified using a defined threshold area. Break points were assigned, and the elements were delineated accordingly to obtain the sub-catchments, junctions and reaches of the model. This process was repeated with varying threshold areas until a model comparable to the detailed survey maps and field characteristics observed by the team. The terrain data of the DEM file was then used to identify sub-basin characteristics (such as flowpaths, slopes, relief, and drainage density) and reach characteristics (length, slope, relief, and sinuosity). The input parameters and methods were assigned by field data observed. The loss method was defined to be initial and constant, where the constant loss is the infiltration rate after the initial loss into soil and saturation and can be equated to the hydraulic conductivity of the soil (measured for both seasons). Here, hydraulic conductivity is considered as the constant rate infiltration, and was obtained by the Horton’s equation (Subramaniya, 2013) using the field data. Horton’s equation was preferred over other empirical equations such as Kostiakov, since it will give a non-zero steady state (non-zero constant) infiltration rate (Ravi & Williams, 1998). An area weighted infiltration value was considered for each sub-catchment derived based on the infiltration values obtained for low flow, high flow and beyond the channel boundary (terrestrial) areas. The transform method was defined to be Clark-unit hydrograph, for which the sub-basin characteristics were used to calculate time of concentration and storage coefficient by assigning equations into the software. The base-flow was kept as zero as the ephemeral streams modelled do not have water inputs from other sources except from precipitation; however, it is not the case for perennials. The baseflow of perennial was too kept as zero for a fair comparison with ephemerals. Therefore, modelled flow rates are the direct runoff. A meteorological model was then linked to the basin model by defining a single gauge for the entire catchment (with a specified hyetograph). Control specifications and time series data were linked to the meteorological model and each other, where the rainfall was assigned to be daily (in incremental mm) and entered manually using the rainfall data obtained for the two seasons. The simulations were carried out from which the discharge at the sampling site was extracted and plotted temporally. The discharge generated by the model was converted to specific discharge (discharge per unit area) to compare the variability of discharge of different (Karlsen et al., 2016).

2.7 Data Analysis

All data are presented as mean ± standard deviation, unless otherwise stated. Assumption of normal distribution and the homogeneity of variances were checked using Kolmogorov–Smirnov and Levene's tests, respectively. Significant differences between two groups and more than two groups were realized by t-test and one-way ANOVA, respectively. In addition, Pearson's correlation was carried out to check the relationship between two variables. All statistical analyses were performed using IBM SPSS V.24 for $P < 0.05$ or $P < 0.1$.

3. Results

3.1. Spatiotemporal variation of infiltration rate

In wet season, ephemeral stream's high flow areas showed higher infiltration than the same region of perennial streams (Figure 2a), but it was the opposite in dry season (Figure 2b); however, the differences were not significant (t-test; $P > 0.05$). The ephemeral low flow areas showed exceptionally high infiltration rates in dry season and was considerably higher than any region of any stream type in any season. Also, the infiltration in low flow areas in the dry season showed a high variation and at certain locations went as high as 78 cm/min (data not shown). Interestingly, the infiltration rate in high flow areas of ephemerals in dry season was significantly less than that of the wet season.

The infiltration rate in the wet season was higher in the high flow areas of both streams than that of the dry season but was not statistically significant (one-way anova; $P > 0.05$). Reduced infiltration in the dry season indicated us to do additional infiltration tests beyond the bank full level (i.e., about 5 m from the thalweg) for both seasons. Infiltration tests beyond the bankfull level showed results comparable with the conventional understanding that dry season with less soil moisture and deep groundwater table showing significantly high infiltration rates (data not shown). Also, the infiltration rates of perennial and ephemeral streams were similar at locations beyond the bankfull level.

3.2. Spatiotemporal variation of sediment moisture content and correlation with infiltration

The sediment moisture content variation (Figure 3) against stream type and/or distances were observed to be insignificant for both seasons (one-way anova; $P > 0.05$). It was observed that the moisture content in the dry season of high flow areas was higher in perennial streams than that of ephemeral streams. A significant positive correlation ($r = 0.78$; $P < 0.05$) was found between infiltration rate and moisture content in high flow areas in the dry season of perennial streams, while no significant correlation was observed for any other case (Table 2).

3.3. Variation of sediment particle size-based parameters and correlation with infiltration

All the differences against stream type and region were observed to be insignificant for D50 or D10 (one-way anova; P > 0.05) (Figure 4). An uneven pattern (i.e., D50 decreased abruptly from low to high flow areas) was observed for both stream types. Also, at ephemerals' low flow areas, D10 was almost 40 folds less than its D50 (i.e., D50/D10; and similar values were obtained by C_u). This was only about 11 in perennial low flow areas. In the case of high flow areas, both streams showed a D50/D10 of about five. The presence of coarse mobile sediments and relatively immobile boulders in an irregular manner in mountainous steep stream beds were highlighted in several past studies (e.g., Yager et al., 2007). In general, D50 at ephemeral low flow areas was significantly higher (one-way anova; P < 0.05) than that of the perennials and was due to cobbles that were present on the ephemeral stream beds. Sediment in high flow areas had a lower D50 as compared to the low flow areas of both stream types (Figures 5a and b).

No significant correlation (P > 0.05) was observed between infiltration rate and D50 for any scenario. However, statistically significant positive correlations at P < 0.05 and P < 0.1 for perennial and ephemeral streams, respectively were observed between D10 and infiltration in high flow areas in the wet season.

3.4. Variation of litter, standing crop biomass and organic content and correlation with infiltration

Litter content was higher in ephemeral streams than that of perennial streams in both seasons (Figures 5a and b) with difference being significant (one-way anova; P<0.05). In contrast to litter, standing crop biomass was higher in perennial streams than that of ephemeral streams in both seasons; however, the differences were observed to be significantly different only in the high flow areas in the dry season (one-way anova; P<0.05) (Figures 9a and b). It should be noted that the instream perennial vegetation was mostly aquatic, and the remainder was emergent, whereas in ephemerals, it was mainly terrestrial.

In many cases, no significant correlation (Pearson r; P>0.05) was observed between infiltration and dead or live biomass in any of the regions of ephemeral or perennial streams in any season. However, wet season live biomass of both stream types in high flow areas showed a negative insignificant correlation with infiltration (r = -0.16 to -0.59; P > 0.1). Dry ephemeral beds (low flow areas) also showed a similar negative correlation with litter biomass.

Even though biomass did not show a direct effect on the infiltration capacity, biomass after decaying can contribute to the organic content of the soil enhancing infiltration by the formation of macro and mesopores (Eusufzai & Fujii, 2012). In general, the organic content of sediment showed a positive correlation with infiltration, which in many cases was opposite to the correlations of infiltration with biomass (Table 2).

All the differences of organic content against stream type and distances were observed to be insignificant for both seasons (one-way anova; P>0.05) (Figure 7). Organic content was higher in perennial streams in the wet season in both regions; however, in the dry season, ephemeral streams showed a higher organic content in both regions. A positive correlation (Pearson r = 0.73, P<0.05) was observed between infiltration and organic content in high flow areas for ephemeral streams in the wet season while for perennial streams a negative correlation (Pearson r = -0.78, P<0.05) was observed. In the dry season, the relationships were positive and significant in the high flow areas of perennial streams (Pearson r = 0.59; $P < 0.05$).

3.6 Variation of Manning's coefficient in low flow areas

Ephemeral channels, in general, were two to three times rougher than perennials under low flow conditions during the wet season, and the differences were statistically significant (one-way anova; $P<0.05$) (Figure 8). The positive impact of D50 on channel roughness was evident for all seasons and stream types (Table 3). Significant positive correlation between Manning's coefficient and D50 was observed in the wet season in perennial streams (Pearson r = 1, $P < 0.05$) as well as in ephemeral streams (Pearson r = 0.99, $P < 0.05$). Also, ephemeral streams in the wet season showed a statistically significant strong positive correlation between Manning's co-efficient and D10 (Table 3).

3.7 Discharge generation

There were no significant differences (one-way anova; $P>0.05$) observed between the analytical and observed low flow discharges of a given stream type (Figure 8). For all flow stages, the unit discharges of ephemeral streams were about two folds (low flow scenario) and 1.2 folds less than the perennial streams, but not significantly differed (one way ANOVA; $P<0.05$). Figure 9 shows the stage-discharge relationship of E3 and P3.

Direct discharges modelled for E3 and P3 showed similar patterns to rainfall. Also, the observed discharges, showed a close pattern to the modelled of the perennial stream in both seasons, and seems the observed discharge was about 1 m3/s more than the modelled. Therefore, 1 m3/s seemed to be the baseflow of P3. A weak agreement between the modelled and observed discharges of the ephemeral stream was observed in the wet season; the dry season there was no agreement at all.

4. Discussion

4.1 Hydrological permanence of streams, infiltration signature and role of soil moisture and particle size

High infiltration in ephemeral stream beds (or low flow areas) is reported in several past studies (Subramanya, 2013) and are referred as losing streams. Nevertheless, Schoener (2016) reported an infiltration rate of 0.16 cm/min (30 min observation period with last 15 min averaged) at Montoyas Arroyo watershed, New Mexico. Similarly, Batlle-Aguilar and Cook (2012) found the mean infiltration rate fluctuating between 0.02 and 0.13 cm/min in an ephemeral stream located in South Australia. Both these findings and other reported values (not necessarily from ephemeral streams) (e.g. Patle et al., 2019) were more than five folds lower than our steady state observations. Nevertheless, hydrologic soil group A, that includes gap or well graded gravel and/or coarse sand (as per classification by USDA soil classification and Unified soil Classifications) has infiltration over 2 cm/hour (ref?). Also, man-made rapid infiltration basins can have infiltration rates as high as 129 cm/hour (Moura et al., 2011), so does porous concrete (> 200 cm/hour; Andres-Valeri et al., 2018). Therefore, ephemeral streams can be taken as natural infiltration basins.

Comparable infiltration rates in perennial and ephemeral streams in the high flow areas was unexpected. This was mainly because ephemeral stream areas, especially the high flow areas, tend to be drier than its perennial counterparts due to the deep-water table (Fritz et al., 2006; Gomes et al., 2020), and this was also evident by sediment moisture content observations (high flow areas of ephemerals during the dry season showed only about half the soil moisture of perennials). The water table of perennial streams lie above the stream bed and the groundwater that flows continuously into it is one of the main, and perhaps the only source of water to the stream in the dry season (NC division of water quality, 2010). Also, in all cases the correlations between infiltration and sediment moisture were positive; this was something against the conventional understanding where a negative correlation is expected (Olorunfemi et al., 2014). Higher infiltration observed in high flow areas of ephemeral streams during the wet season than the dry season was also unexpected, since dry season soil is generally found to be more infiltration friendly (Subramanya, 2013). However, some past studies (e.g., Ruggenthaler et al., 2016) have highlighted the inverse relationship between infiltration capacities of the soil and moisture content for general soil conditions. Moist soils result in a reduction in capillary action and increase the velocity of the wetting front (Batlle-Aguilar & Cook, 2012). This may have shown the initial infiltration to be high in moist soils, and probably our experimentation period (20 minutes) was at least partially within the initial stage as defined by Batlle-Aguilar and Cook (2012). Under field conditions there can be several factors that govern infiltration, and some of those could be more influential than sediment moisture. Therefore, it was conspicuous that the infiltration responses cannot be understood only with the hydrological permanence signature.

The same argument can be extended to the influence of particle size since we only observed statistically significant correlations for both stream types in wet season only. Wang et al. (2017) observed D10 has a positive correlation with infiltration. However, in contrast Fischer et al. (2014) studying the floodplain of the Saale River as well as Schoener (2016) established that no correlation existed between particle size and infiltration. The higher D50 of the sediment in low flow areas of ephemeral streams was most likely due to sediment armoring, where flows mostly transport smaller particles, leaving larger ones behind (Bunte & Abt, 2001).

4.2 Variation of biological factors and infiltration

In both stream types, the biomass was high in the high flow area close to the riparian zone due to nutrient-rich soil (Gomes et al., 2020) and in addition for perennial streams high soil moisture (Zalewski, 2006). High litter content in ephemeral streams was due to primary production in the dry season by terrestrial vegetation within the channel as well as by litter supply from riparian (channel bank) vegetation (Gomes et al., 2020) that remains stationery until the flow recommences, where litter would be transported downstream by advancing wetting fronts (Datry et al., 2011).

In general, almost all correlations between biomass and infiltration were negative and somewhat similar observations were reported by Olorunfemi et al. (2014), where temporary hydrophobic conditions because of organic compounds were observed to be influential. Peng et al. (2004) too observed that the infiltration rate lowered with the increased vegetation cover due to micro-biotic soil crust over the ground surface. However, Thompson et al. (2010) observed infiltration increased as a power-law function of aboveground biomass in water-limited ecosystems. Similarly, Saco et al., (2007), Subramanya, (2013) and Newcomer et al., (2016) too highlighted enhancement of infiltration capacity with the presence of vegetation. Direct rainfall pack and densify the soil reducing the porosity and vegetation barricades the direct rainfall (Subramanya, 2013). In contrast to all above relationships, which were either positive or negative, Thompson et al. (2010) in a forest terrain, Durham found no significant correlation between vegetation biomass and infiltration capacity.

High organic content in high flow areas of perennial streams in the wet season could be due to rapid soil hydrological processes controlling the release of the organic content that can be utilized by the plants (Heisler & Weltzin, 2006); this process may have been slower in ephemeral high flow areas. The increase in organic content in the low flow areas of perennials in the wet season was due to the increased bio-geochemical cycling because of previous flood events that fueled heterotrophic activities in sediments (Brooks et al., 2007).

Increased organic matter indirectly contributes to soil porosity via increased soil faunal activities and increases infiltration (Thomsen et al. 1999; Eusufai & Fujii, 2012). However, this kind of relationship was only observed in ephemeral and perennial high flow areas during the wet and dry seasons, respectively. Comparable results were observed by a few past studies. As an example, Jing et al. (2015) in the Zhangijashan forest area observed a positive correlation between infiltration and soil organic (carbon) content as organic content affected the initial infiltration speed along with other factors such as pore space and soil texture. Franzluebbers (2002) observed that the stratification ratio of soil organic carbon (i.e., the organic carbon in 0–3 cm depth divided by that of 6–12 cm depth) was predictive of water infiltration rate. Similarly, Esteban Suárez et al. (2013) in Páramo ecosystems in northern Ecuador observed a significant decrease in infiltration capacity of the soil with the decrease of soil organic content.

4.3 Combined effect of moisture and litter on the infiltration signature

The unexpected considerable drop of infiltration in ephemeral high flow areas in the dry season was attributed to subsequent natural compaction of the sediment surface with the decrease in moisture content (Raper & Kirby, 2006). This also explains the hydrological difference between ephemeral high flow and low flow areas with respect to temporal change of moisture. The decrease in sediment moisture was at a higher rate in the ephemeral high flow areas due to the deep groundwater table. This led leaf litter to get dried by air faster than decomposition and decaying under a moist environment. In the case of ephemeral low flow areas, the moisture content decrease was not as fast as the high flow areas, since being the lowest points of the stream it was the last to lose water. This meant the leaf litter decomposition in low flow areas of ephemerals took place in a moist environment, some cases even under submerged conditions (Hardwick et al., 2022). Therefore, litter can get decomposed into fine particulate organic matter, thus not forming a litter mat such as in high flow areas.

4.4 Channel roughness of ephemeral streams

Standing crop biomass, litter, and particle size-related parameters resulted in increased roughness, and in certain cases showed significant correlations. The impact of biomass on increased roughness was more prominent in perennials and has been reported in past studies (e.g., Limerinos, 1970; Plakane, 2017). Limerinos (1970) further highlighted friction depends on the plant type. Nevertheless, past studies did not observe the impact of increased diversity on less roughness. The reasons for the reduced roughness was due to smooth packing when a wide range of plant types are present rather than a few types; this is similar to a sediment surface with well-graded particles which results in a smooth surface in contrast to poorly graded sediment.

Larger the D50, more it contributes to flow resistance by creating irregularities on the stream bed (Lau & Afshar, 2013). The penetration of solar radiation during low flow conditions aided periphyton growth and a slime layer over the surface particles (both contributes to the less friction) resulted in a lack of relationship between D50 and roughness in the dry season of perennial streams. The positive correlation between D10 and roughness was unexpected as greater the fine particle fraction smoother the stream (in sensu Wang et al., 2017). This could be explained by the fact that the D10 particle size was 40-fold less than the corresponding D50, making the contribution from fine particles uninfluential.

Manning's roughness coefficient is inversely proportional to the discharge through a stream channel (Subramanya, 2013). As the roughness of ephemeral streams was higher, they should convey a lower discharge. Hence, ephemeral streams have a better holding capacity than perennial streams and delay the flow to the downstream perennial sections. This further supported the understanding that ephemeral streams have flood control potential (Gomes et al., 2020), and obviously these streams would play a major role in flood control in tropical regions.

4.5 Discharge modelling and implications

The direct discharges generated by HEC-HMS showed higher discharges in E3 compared to P3, mainly due to the difference in contributing catchment areas at point of measurement (E3 had a higher contributing catchment area) and due to the lack of baseflow considered. The baseflow in ephemeral streams remain zero as they have no contribution from the groundwater table, and their only source of water input is precipitation (Datry et al., 2011). Whereas perennial streams are directly connected to the groundwater table, which is why they can maintain flow even during periods of little to no rainfall.

The results quantitatively proved inability to use popular and widely accepted software tools such as HEC-HMS for the modelling ephemeral catchments. The issue was the software could not be used to represent the significant changes of hydrologic conductivity within the ephemeral sub catchments, especially in dry season. Infiltration was several folds high in the low flow area of the stream, but what we could do in the model was to give a weighted average value for the entire sub-catchment. This assumption results in an underestimated infiltration volume. Nevertheless, the difference between the direct runoff generated by the model and the observed discharge would enlighten the contribution of ephemeral streams with respect to infiltration.

5. Conclusions and recommendations

This study showed infiltration capacity of dry ephemeral stream beds are in the likes of man-made infiltration trenches, and to have a low discharge proving their importance in flood control of downstream areas. The infiltration signature of streams was to a good extent independent of the hydrologic permanency and soil moisture content, but dependent on factors that may governed by the hydrologic permanency such as soil organic content and fine particle fraction.

The attempt to model the discharge of streams using HEC-HMS was successful only for perennials, and ephemerals showed a complete disagreement (dry season) or a minor agreement (wet season) between modelled and observed discharges.

Data availability

Some or all data used during the study are available from the corresponding author by request.

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Disclosure statement

Authors declare there is no conflict of interest in publishing the article.

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Figure 1

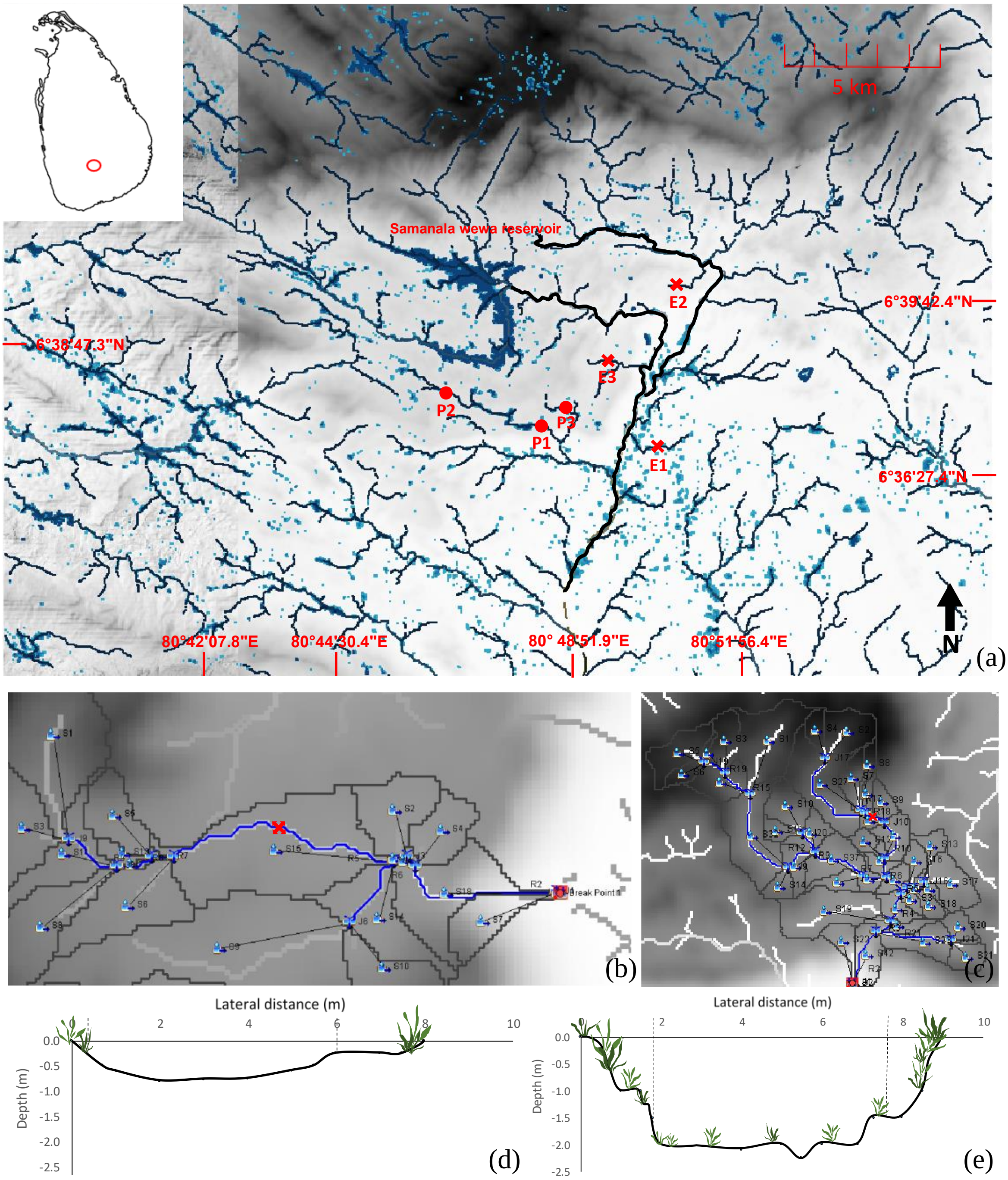
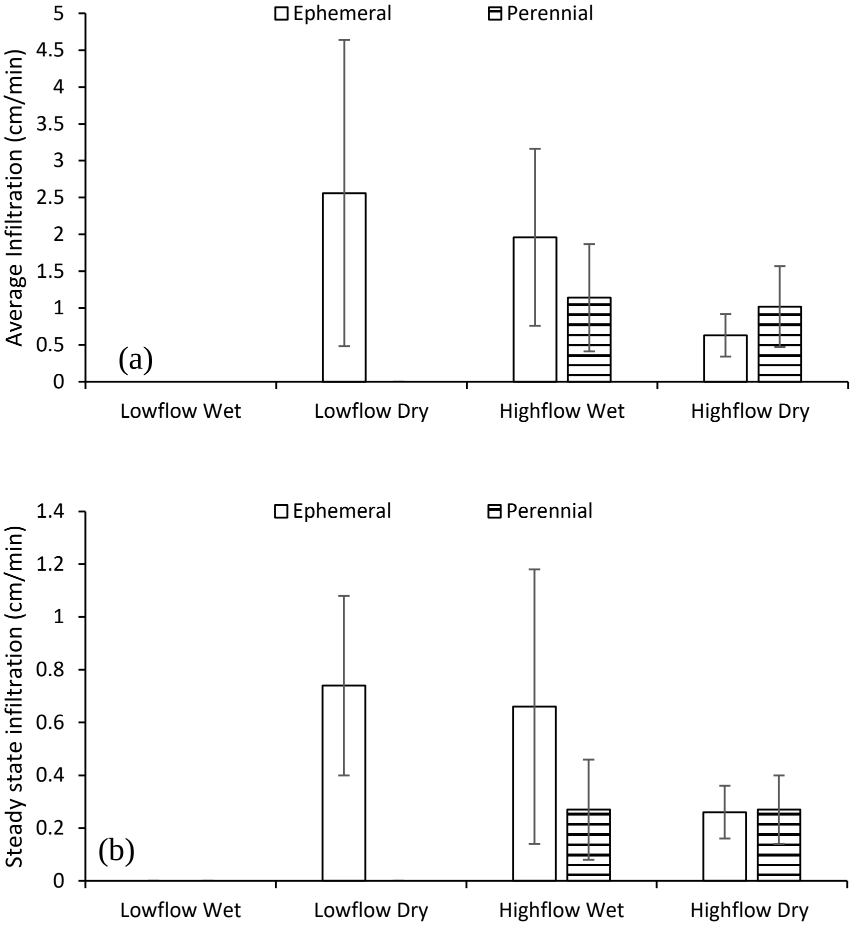

5 km
Samanala wewa reservoir
E1
E2
E3
P1
P2
P3
6°39'42.4"N
6°38'47.3"N
6°36'27.4"N
80°42'07.8"E
80°44'30.4"E
80° 48'51.9"E
80°51'56.4"E
N
(a)
(b)
(c)
Lateral distance (m)
Depth (m)
(d)
Lateral distance (m)
Depth (m)
(e)

Figure 2:



Ephemeral
Perennial
Average Infiltration (cm/min)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
(a)
Lowflow Wet
Lowflow Dry
Highflow Wet
Highflow Dry
Ephemeral
Perennial
Steady state infiltration (cm/min)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
(b)
Lowflow Wet
Lowflow Dry
Highflow Wet
Highflow Dry

Figure 3:

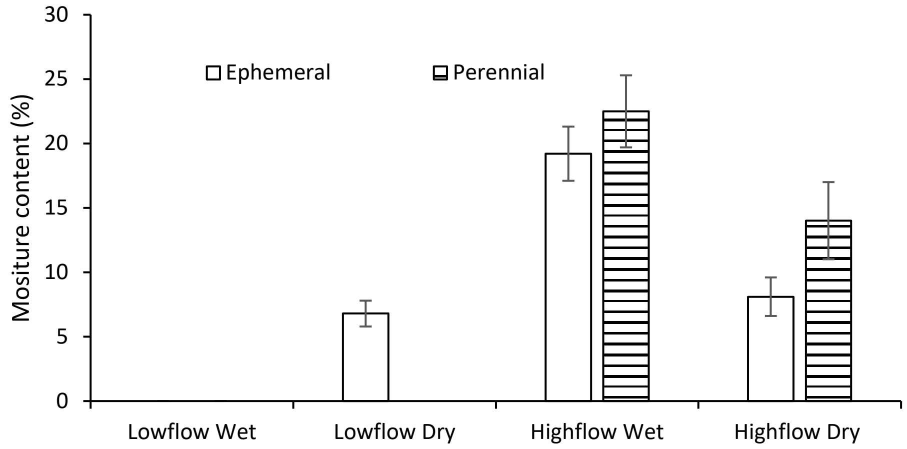

Mositure content (%)
30
25
20
15
10
5
0
Ephemeral
Perennial
Lowflow Wet
Lowflow Dry
Highflow Wet
Highflow Dry

Figure 4

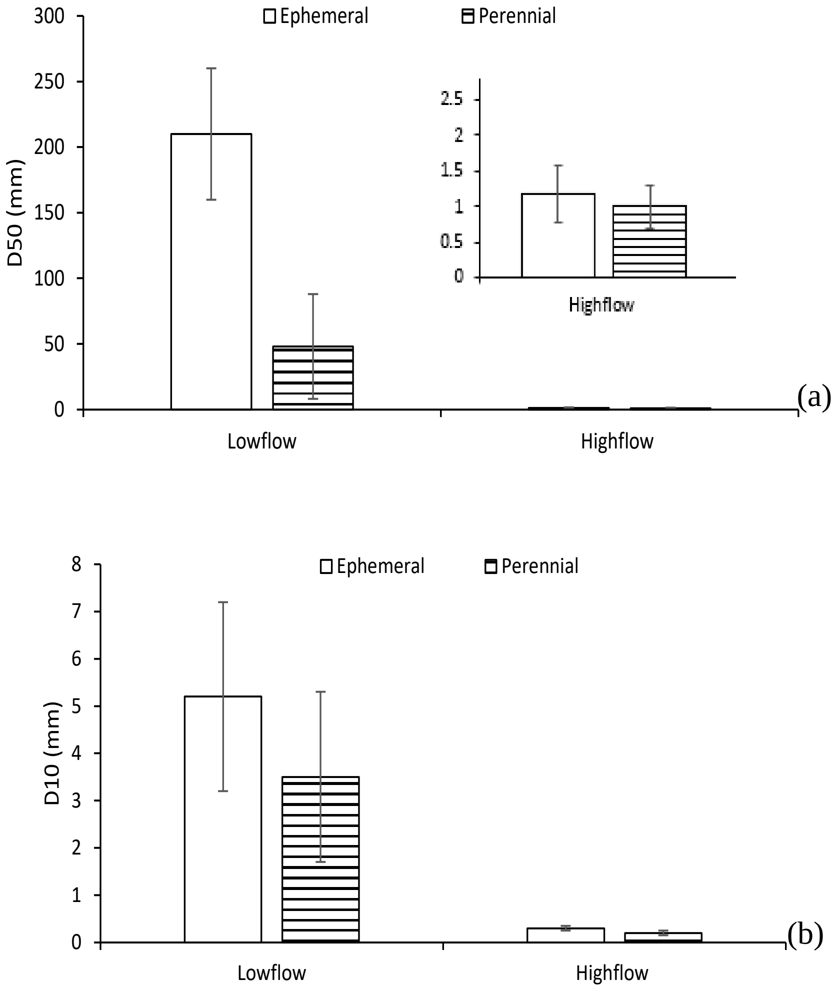

Ephemeral
Perennial
D50 (mm)
300
250
200
150
100
50
0
2.5
2
1.5
1
0.5
0
Highflow
Lowflow
Highflow
(a)
Ephemeral
Perennial
D10 (mm)
8
7
6
5
4
3
2
1
0
Lowflow
Highflow
(b)

Figure 5:

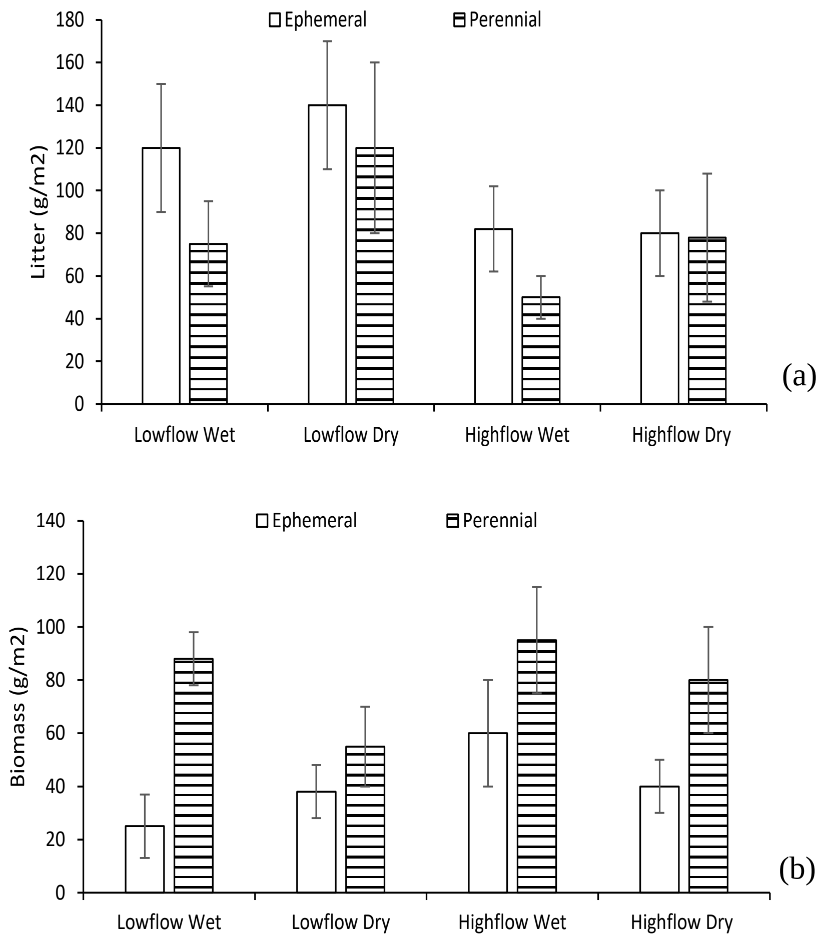

Ephemeral
Perennial
Litter (g/m2)
180
160
140
120
100
80
60
40
20
0
Lowflow Wet
Lowflow Dry
Highflow Wet
Highflow Dry
(a)
Ephemeral
Perennial
Biomass (g/m2)
140
120
100
80
60
40
20
0
Lowflow Wet
Lowflow Dry
Highflow Wet
Highflow Dry
(b)

Figure 6:

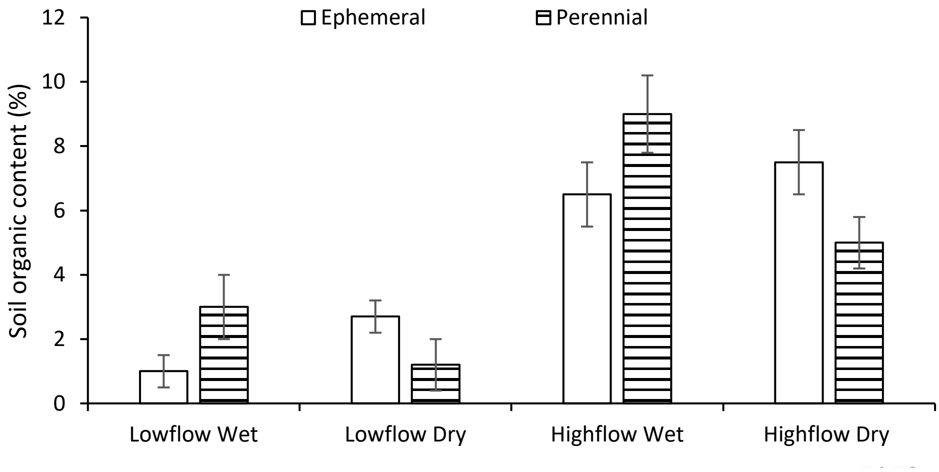

Ephemeral
Perennial
Soil organic content (%)
12
10
8
6
4
2
0
Lowflow Wet
Lowflow Dry
Highflow Wet
Highflow Dry

Figure 7:

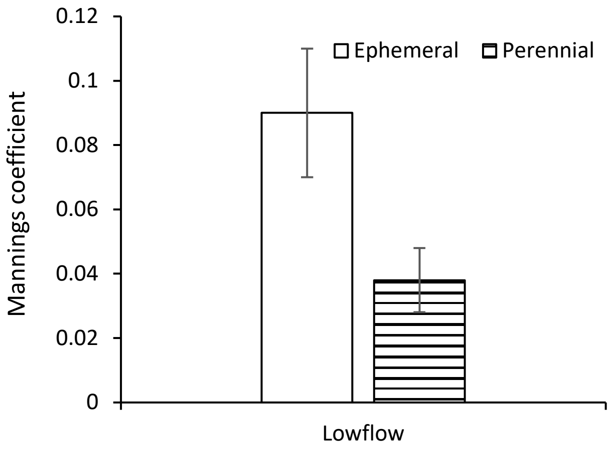
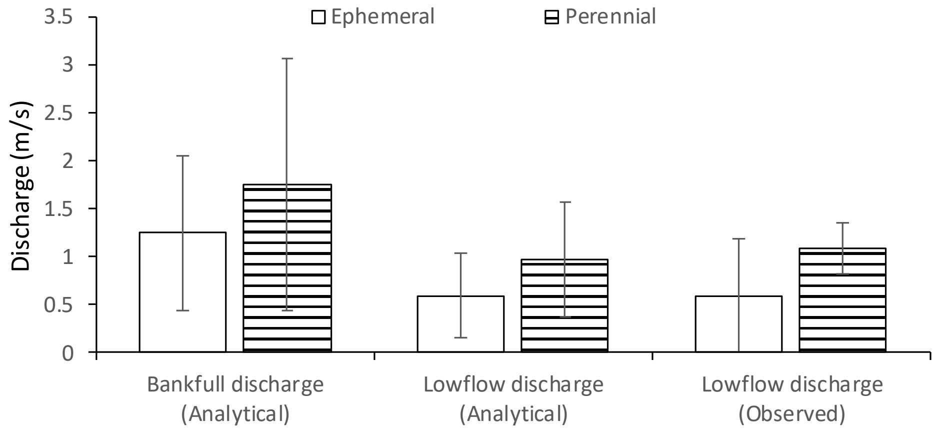

0.12
0.1
0.08
0.06
0.04
0.02
0
Mannings coefficient
Ephemeral
Perennial
Lowflow

Figure 8:



Ephemeral
Perennial
Discharge (m/s)
3.5
3
2.5
2
1.5
1
0.5
0
Bankfull discharge (Analytical)
Lowflow discharge (Analytical)
Lowflow discharge (Observed)

Figure 9:

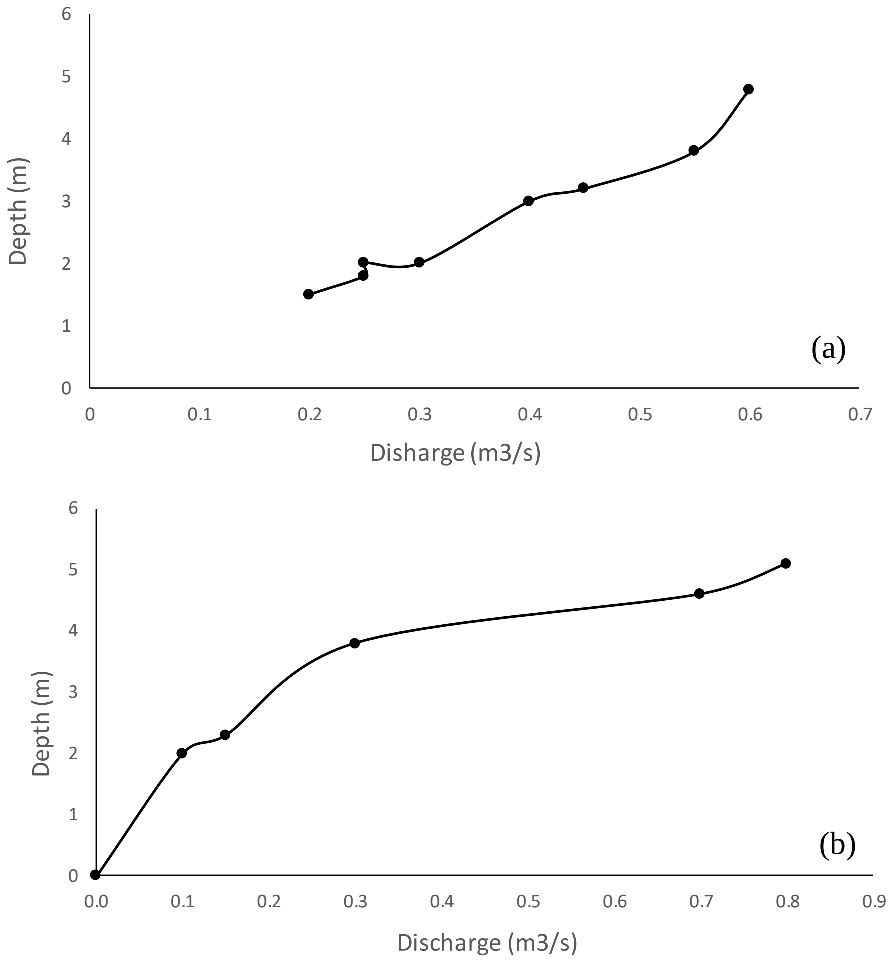


Figure 10:

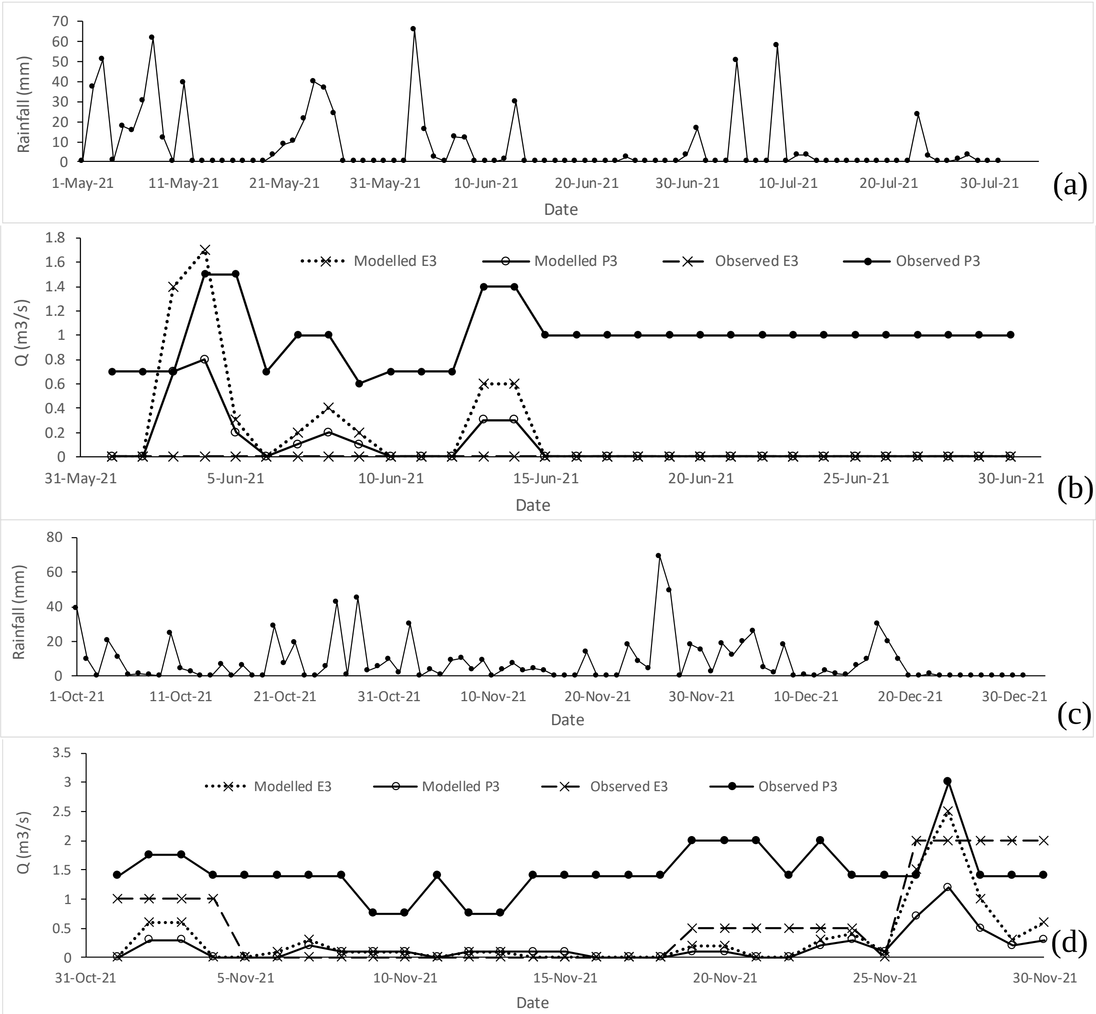

Rainfall (mm)
Date
(a)
Modelled E3
Modelled P3
Observed E3
Observed P3
Q (m3/s)
Date
(b)
Rainfall (mm)
Date
(c)
Modelled E3
Modelled P3
Observed E3
Observed P3
Q (m3/s)
Date
(d)

Table 1: Key eco-hydrologic details of the sampled streams (Parentheses show standard deviation)

Stream type	GPS coordinates	Slope (m/m)	Low flow			Bankfull		
			Flow area (m^2)	Top width (m)	Hydraulic radius (m)	Flow area (m^2)	Top width (m)	Hydraulic radius (m)
E1	6°39'42.37"N 80°51'56.43"E	0.039 (0.122)	0.38 (0.09)	1.41 (0.38)	0.04 (0.03)	6.09 (0.34)	6.19 (0.44)	0.62 (0.15)
E2	6°39'31.59"N 80°51'56.09"E	0.010 (0.003)	0.42 (0.05)	2.05 (0.93)	0.05 (0.01)	8.47 (3.15)	8.20 (0.86)	0.65 (0.06)
E3	6°37'20.35"N 80°50'57.47"E	0.02 (0.005)	0.22 (0.04)	1.66 (0.24)	0.03 (0.01)	10.36 (3.93)	8.36 (1.02)	0.87 (0.19)
P1	06° 36.658' N 80° 49.815' E	0.005 (0.002)	4.38 (0.88)	4.08 (1.13)	0.19 (0.18)	8.40 (1.5)	8.43 (0.55)	0.53 (0.13)
P2	06° 36.418' N 80° 49.084' E	0.01 (0.006)	0.70 (0.12)	3.08 (1.05)	0.05 (0.05)	7.01 (0.13)	7.01 (0.41)	0.65 (0.85)
P3	06°36'45.5"N 80°46'24.4"E	0.02 (0.002)	0.75 (0.05)	2.13 (0.22)	0.07 (0.02)	6.93 (1.65)	7.12 (0.91)	0.52 (0.22)

Table 2: Details of the catchments of the modelled streams

Stream	E3	P3
Number of contributing /number of Ephemeral sub catchments	10/10	5/2
Total /Ephemeral sub catchment area (km^2)	3.9/3.9	1.8/0.18
Total/Ephemeral stream length (km)	4.8/4.8	0.8/3.4

Note: If 50% or more of the stream length is ephemeral, the sub catchment is considered as an ephemeral sub catchment. All streams were checked for the hydrologic permanency.

Table 3: Pearson correlation between infiltration made with hydro-hydrologic parameters (Statistically significant data shown as ** for P<0.05 and * for P<0.1).

Location and season	Litters	Live biomass	SWI	Moisture Content	Organic Content	D50	D10
Ephemeral high flow areas-Wet season	0.04	-0.59*	0.54	0.5	0.73**	0.27	0.97*
Perennial high flow areas -Wet season	0.02	-0.54	0.31	-0.06	-0.78**	0.08	0.99**
Ephemeral low flow areas- Dry season	-0.51	-0.16	0.38	0.36	0.35	-0.3	-0.53
Ephemeral high flow areas- Dry season	-0.2	0.32	0.26	0.36	0.23	-0.25	0.32
Perennial high flow areas- Dry season	-0.04	0.03	-0.23	0.78**	0.59**	0.11	0.30

Table 4: Pearson correlation between Manning's roughness coefficient made with hydro-hydrologic parameters (Statistically significant data shown as ** for P<0.05 and * for P<0.1)

Location and season	Litters	Live biomass	Standing crop biomass	SWI	D50	D10
Ephemeral low flow areas- Wet season	0.53	-0.16	0.46	-0.92*	0.87	0.95**
Perennial low flow areas- Wet season	0.84	0.91*	0.94*	-0.89*	1**	-0.23
Ephemeral low flow areas- Dry season	-0.44	0.58	-0.31	0.25	—	—
Perennial low flow areas- Dry season	0.69*	0.92**	0.81**	-0.82**	—	—