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A Comparative Investigation of Infiltration and Channel Roughness of Ephemeral and Perennial Streams in a Mountainous Catchment

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ABSTRACT

Infiltration and channel roughness, two major factors that govern stream discharge, were studied in similar-sized ephemeral and perennial streams in a mountainous tropical catchment. Seasons were defined based on two ephemeral flow conditions, i.e., with (wet season) and without (dry season) surface flow. A stream was divided transversely into low-flow areas (close to the thalweg) and high-flow areas (close to the channel margin). The highest average infiltration (~50 mm/h) was observed in the low flow areas around the thalweg of ephemeral streams in the dry season and was significantly higher than for any other spatial scale or temporal period. The infiltration in high-flow areas did not show a statistically significant difference between the two stream types, and surprisingly, perennial streams in the dry season showed higher infiltration than ephemeral streams. Since sediment moisture and organic content showed negative and positive correlations with infiltration, respectively, for both stream types and ephemeral streams showed statistically significant negative correlations between litter and infiltration during the dry season, the low infiltration in ephemeral high flow areas was attributed to stream-type dependent litter processing. The litter of ephemeral stream high-flow areas was subject to partial decomposition due to rapid drying and had residue of previously buried litter. Ephemeral channels were two to three times rougher than perennial channels. Standing crop biomass and mean particle size increased stream roughness in both stream types but were less prominent in ephemeral streams due to the presence of litter. The study demonstrated that litter has a special role in defining the infiltration pattern, channel roughness, and flood control potential of ephemeral streams.

1 | Introduction

Headwater streams are usually defined with a Strahlers stream order of less than three and may have a perennial or non-perennial flow regime (Fritz, Johnson, and Walters 2006; Datry, Arscott, and Sabater 2011; Gomes et al. 2014). They are essential not only to headwater mountainous environments but also to downstream waters as they are physically, biologically, and chemically connected and where water and other materials are concentrated, mixed, transformed, and transported (Gomes, Wai, and Yan 2017; Arendt et al. 2023). Non-perennial streams can be further divided into intermittent (connects to the groundwater table at specific flow regimes) and ephemeral (stream bed is well above the groundwater level) streams and are often interchangeable due to difficulty in identification (Gomes, Wai, and Yan 2017). Also, some studies (e.g., Larned et al. 2010) have differentiated the ephemeral and intermittent streams based on the flow duration. Ephemeral streams account for more than half of the total length of rivers worldwide (Datry, Arscott, and Sabater 2011). They are noted for their role in flood control of downstream environments (Gomes, Wai, and Yan 2017) and aquifer recharge (Shanafield and Cook 2014) through infiltration. Ephemeral stream beds lie above the groundwater table and due to the large hydraulic gradient between the stream bed and the regional groundwater table, facilitate more infiltration than perennial stream beds, which are below the groundwater table (Shanafield et al. 2021). Therefore, compared to ephemeral streams that infiltrate water from their banks and beds, perennial streams can only infiltrate from part of their banks that lie above the groundwater table (Ghobadian and Fathi-Moghadam 2013). Schilling et al. (2021) showed that ephemeral streams have 2–20 times higher infiltration than perennial streams and that the infiltration rate increased with the impending dry phase of the stream.

Even though transmission losses are one of the better-studied aspects in non-perennial streams (Leopold and Miller 1956), there are research gaps to be filled (see reviews by Shanafield and Cook 2014, and McMahon and Nathan 2021 for recent synthesis on infiltration). One such aspect is the lack of quantification of infiltration through integrated studies (Schilling et al. 2021). Transmission losses are quantified by analyzing streamflow reductions, including infiltration through the sediment layer of the stream bed, evapotranspiration back to the atmosphere, loss to terrestrial lands, and losses to stream banks (Ghobadian and Fathi-Moghadam 2013; Shanafield et al. 2021; Perera and Gomes 2022). Because of the difficulty in measuring evapotranspiration and other losses during the lotic phase, especially in upstream areas, and also because evaporation and transpiration losses are several orders of magnitude less (see Schilling et al. 2021 observed at least two folds) than the infiltration, transmission losses are surrogated or solely represented by the infiltration in practical applications (Shanafield and Cook 2014).

Water infiltration through sediment of stream channels and its floodplain can be a complex hydrodynamic phenomenon. It could be affected by several ecosystem attributes such as sediment properties and its composition (including sediment surface characteristics) (Shanafield and Cook 2014), biological activities in the soil (Assouline 2013), sediment moisture (Shanafield et al. 2021), terrain factors such as slope (Morbidelli et al. 2018), degree of compaction (Chen et al. 2013), and vegetation (Subramanya 2013). Studies such as Gomes, Wai, and Dehini (2020) observed that the vegetation composition of the same catchment differed between ephemeral and perennial stream ecosystems. Because vegetation is an important factor that defines many surface and subsurface bio-physical factors, we hypothesized that these two stream types have different infiltration rates. The quantitative variation of infiltration considering different spatiotemporal scales was one research gap we aimed to address.

Knowledge of stream flow generation and contributing factors is vital in flood control. In cases where human intervention is needed, stream roughness is the parameter that is usually manipulated (Dorn, Vetter, and Höfle 2014). Stream roughness is a critical parameter for open channel flow calculations and influences hydrographic and engineering practices. Stream roughness is commonly expressed by Manning's roughness coefficient (Subramanya 2013). Different methods are practiced in determining the stream roughness, 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), and application of empirical equations under field conditions (Lang, Ladson, and Anderson 2004). Channel roughness is an important attribute in open channel studies, and some studies of ephemeral stream roughness exist (e.g., Aldridge and Garrett 1973; Gillen 1996), but are rarer compared to perennial streams (e.g., Gillen 1996). Scamardo et al. (2022) noted the increase in roughness with vegetation in ephemeral channels leading to sediment deposition, and Graeme and Dunkerley (1993) attempted to quantify this effect, stating that just under half of the total channel roughness may be contributed by in-channel vegetation, the remainder coming from boundary friction effects. However, careful review suggests that none of the studies have attended the roughness on a comparative basis between ephemeral and perennial streams.

This study worked on three objectives with fieldwork covering equal-sized ephemeral and perennial streams. The first objective was to investigate the hypothesis that infiltration of ephemeral streams would show significantly higher values spatially (i.e., at different transverse positions) and temporally (i.e., in different seasons) than perennial streams. The second objective was to test the hypothesis that there is a significant difference of the channel roughness between ephemeral and perennial streams. The third and final objective was to quantify the discharges of both stream types through a combination of field and analytical methods to identify the contribution of ephemeral streams' flood control potential.

2 | Materials and Methods

2.1 | Study Area, an Overview of Streams, and Sampling Schedule

The study was conducted in ephemeral and perennial streams of stream order 1 or 2, located in Kalthota, Ratnapura district, Sri Lanka (Figure 1). All streams were located within a few kilometers and had the same geological, climatic, and weather conditions. The study area is in the intermediate climatic zone, one of three major climatic zones in Sri Lanka (Meteorological Department of Sri Lanka, 2023). Generally, rainfall commences in mid-March to April (the first inter-monsoon) and gradually decreases after May. Rainfall increases after August due to the latter stage of the southwestern monsoon and second inter-monsoon. The second inter-monsoon brings high-intensity rainfall until November. A sudden decrease in rainfall is observed in January, and the decrement continues until February. January to February and July to August are the periods with low rainfall, which was the case during the study period. The total annual precipitation in 2017, 2018, and 2021 was about 2800, 2500, and 2700 mm, respectively (Meteorological Department of Sri Lanka, 2023). Kalthota is located on the Highland soil complex, one of the four main soil complexes in Sri Lanka

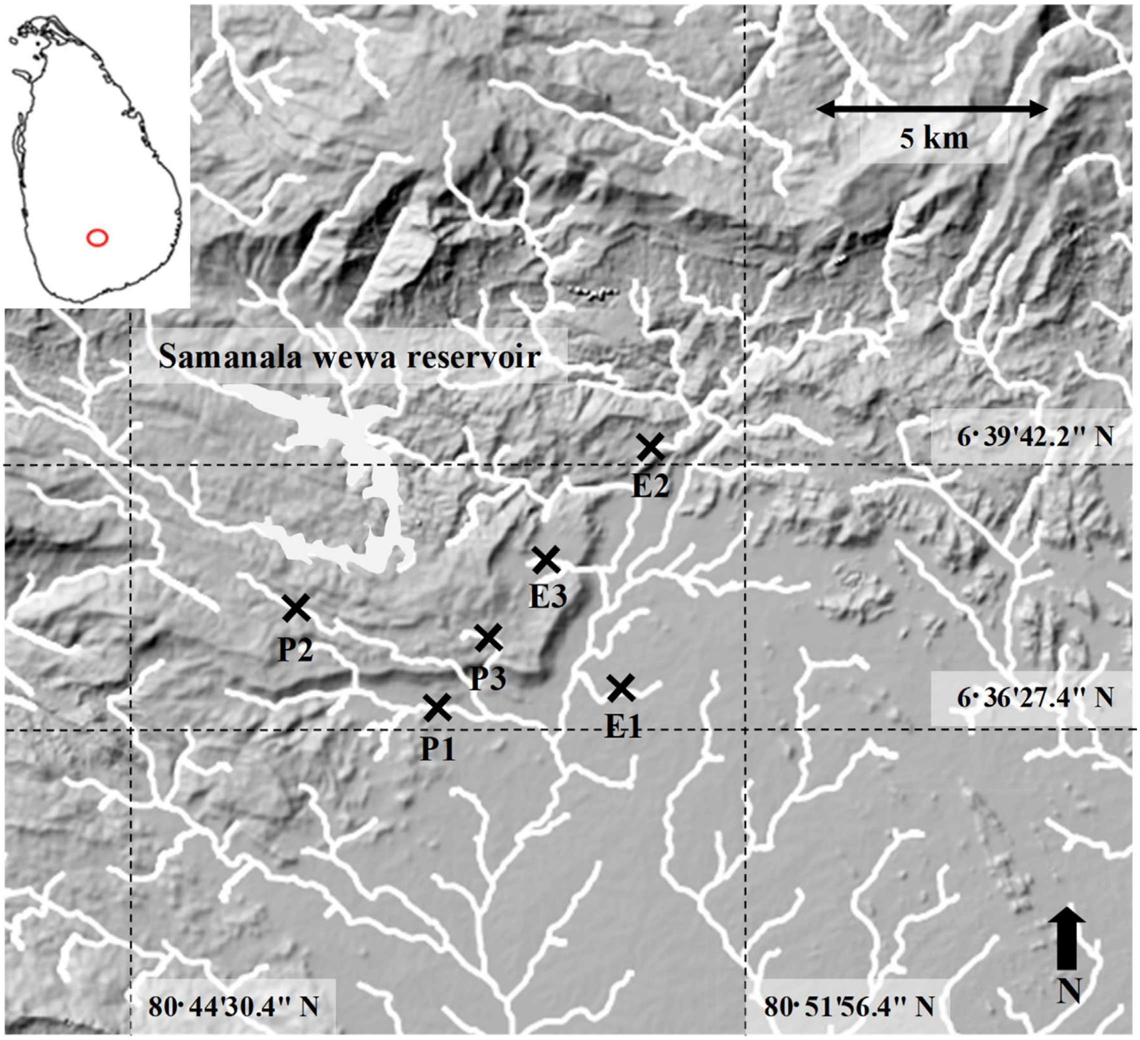

FIGURE 1 | (a) Sri Lankan map with the encircled study area of Kalthota. (b) Stream locations marked on the drainage network derived from a DEM model (P and E are perennial and ephemeral streams considered for sampling). [Color figure can be viewed at wileyonlinelibrary.com]

(others are Wanni, Vijayan, and Kadugannawa), divided based on the lithology, isotope geochemistry, and tectonic–metamorphic history. All the sites consist of reddish brown earth and immature brown loam soils with rolling hills and steep terrains (source: Soil Map of Sri-Lanka.—ESDAC—European Commission 2024).

Three ephemeral streams (E1, 2, and 3) and three perennial streams (P1, 2, and 3) were studied (Table 1 indicates the locations and the general hydro-ecological descriptions, including the contributing catchment areas). All perennial streams had typical perennial characteristics and were gaining streams. Fieldwork for detailed sampling in 2017 (Figure 2) was conducted during the third week of November (wet season), and the first week of July (dry season). For 2018, detailed sampling was conducted during the second week of October, the fourth week of November (wet season), and the second week of July in the dry season. The last sampling session (to validate the observations of 2017 and 2018) was conducted in 2021 for E3 and P3 during the second week of July (dry season) and the third week of November (wet season). Detailed sampling included observations of all hydro-ecological parameters, such as infiltration and vegetation surrogates, and stream observations, such as wetted depth, wetted width, depth, and stream discharge.

In the wet season, ephemeral streams showed surface flow, whereas in the dry season, they were either characterized by disconnected pools or were completely dry. We did not observe high flow conditions during the wet seasons. The 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, Johnson, and Walters 2006)). During the dry season sampling, perennial streams showed a flow very close to low flow conditions (12% reduced depth compared to the maximum low flow depth), and groundwater is likely to have been the main source of the water.

2.2 | Details of Sampling Locations Within the Stream System

Three 20–30 m representative longitudinal reaches were selected from each stream (Figure 3). There were no sudden

TABLE 1 | Key hydro-ecological details of the sampled streams (parentheses show standard deviation).

Stream type	GPS coordinates	Catchment area (m^2)	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	9737	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	9985	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	10,701	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	6655	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	6681	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	6791	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)

changes in the channel bed or sediment profile within the reach (i.e., no channel transition). 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). This region always had a flow in perennial streams, whereas in ephemeral streams, water was seen only at specific periods, varying between observable surface flows and disconnected pools. 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). The high flow hydrologic floodplain boundary was often closer to the channel margin or valley (bankfull level).

To allow a clear comparison between ephemeral and perennial streams, the low flow areas were sampled close to the thalweg but at least 0.3 m from surface water. High flow area sampling was carried out approximately within the mid area between the low-flow boundary and channel margins or close to the channel margin, but never went beyond it. The selection of sampling locations within these two regions was entirely random unless special conditions would make sampling biased (e.g., locations with outcrops). During the sampling years, perennial streams showed high flow conditions for about 3 months each year, and they were rare in ephemeral streams. The number of days in a year with high flow conditions in ephemeral streams was about 30.

2.3 | Infiltration Tests

A single ring infiltrometer with an internal diameter of 35 cm and a height of 55 cm, made of polyvinyl chloride and driven 7–10 cm beneath the ground, was used for infiltration tests. Each test was conducted for 20–30 min, and in about 90% of the cases, the steady state was reached without showing any bias to the stream type, its transverse location or season. Long-duration and double-ring infiltrometer tests were infeasible, due to logistic issues and the size of the streams, respectively. Therefore, we had two options: either to exclude the tests that did not reach the steady state in line with the common practise of using only comparable results (Artiola, Pepper, and Brusseau 2004) or to derive the steady state for all tests using an infiltration model such as Horton's equation (Subramanya 2013). The use of infiltration models (physical, semi-empirical, or empirical) is not rare and in some cases was found to have the best matches (e.g., Gifford 1976 noted for Horton's equation). However, in some cases there were concerns about their representation for different types of soils (Mishra, Tyagi, and Singh 2003). In our case, the representative comparisons made between Horton's equation and graphical expression of field data for the steady state infiltration showed a good match (see Figure 4 and Figure S1). f_t is the infiltration at any given time t, f_c is the steady state infiltration, and f_0 is the initial infiltration. k is a soil-specific constant (Horton's decay coefficient). Because whether the steady state reached or not was independent of stream type or season, and with the assumption that any errors are random, it was decided to use Horton's equation.

$$f_t = f_c + (f_0 - f_c)e^{-kt} \quad (1)$$

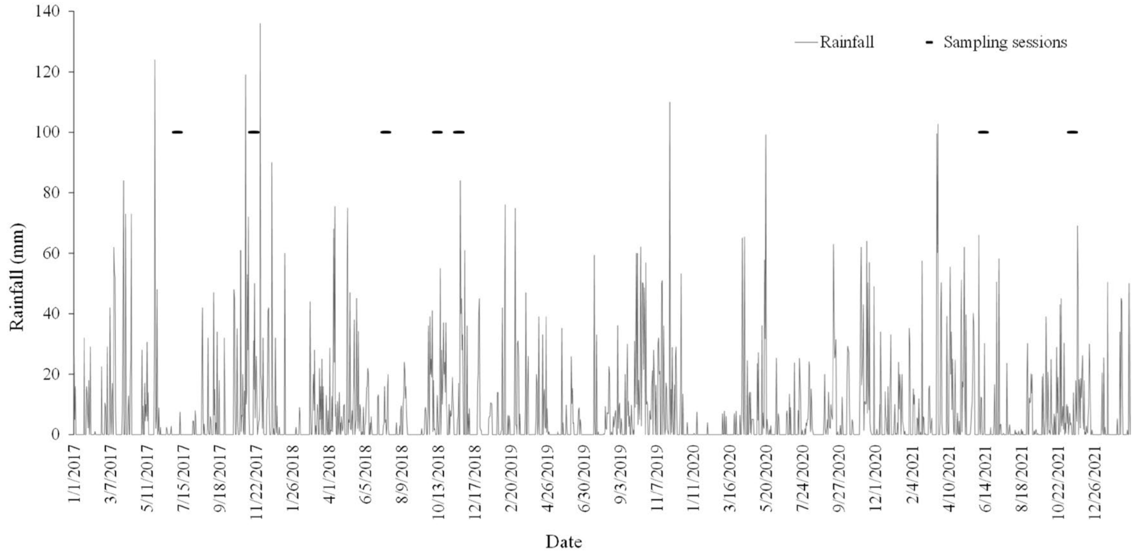

FIGURE 2 | Rainfall of the study area from 2017 to 2021 with marked sampling periods.

The ponding height is usually maintained at 40 cm for undisturbed soils (Assouline 2013) and was followed in our study. 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; in sensu Liu et al. 2020). In addition, comparative tests until the steady state were conducted using a double-ring infiltrometer as specified by ASTM (2002) D3385-09 (one of the most widely referred infiltration standards). The steady-state rates of the single ring infiltrometer showed values about 5-fold more than the double ring. This study will only report the steady-state infiltration values adjusted to the ASTM D3386-09 specified double-ring infiltrometer.

2.4 | Hydraulic Parameters, Stage-Discharge Relationships, and Channel Roughness

Three cross-sections were considered in each stream to observe flow velocity and cross-section dimensions. The velocity was measured at 0.6 of the water depth using a velocity meter (Flowatch Switzerland) or the float method (Herschy 1995) when the water level was less than 5 cm. We used small oranges (*Citrus crenatifolia*) with a diameter of ~10 mm as the floats such that they were buoyant enough not to be affected by the wind. The channel slope of each reach was computed by measuring the vertical elevation difference and dividing it by the longitudinal distance using an Auto level (Sokkia Auto Level B40 Japan) and a measuring tape. Depths and widths were measured by a steel ruler and a measuring tape, respectively. For discharge, the area × velocity method (Subramanya 2013) or the bucket method as appropriate (Gomes et al. 2014) was used. The bucket method was used by constructing a weir from boulders and gravel at a cross-section where flow could easily be converged and collected in a bucket with a known volume, and the time to fill was measured with a stopwatch. The filling time was always kept more than 30 s.

Discharge was analytically derived 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). Without a bankfull stage during sampling, bankfull discharges had to be analytically derived also considering the compound nature of the channel cross-section. This was attended through Lotter's method (Lambert and Sellin, 1996). Based on Lotter's method, each section was divided by a vertical line, and discharges of each were calculated separately using Manning's equation and summed up to the total.

$$Q = \frac{A^{5/3} S^{1/2}}{n P^{2/3}} \quad (2)$$

Manning's roughness coefficient was derived through two approaches. First, the roughness of low flow areas was derived by Equation (2) using field-observed discharges (will be referred to as experimental Manning's roughness). Second, Manning's coefficients were estimated based on a general quantitative approach (Equation (3)) as described in Gillen (1996) (will be referred to as analytical Manning's roughness) for different regions (low flow and high flow up to the bankfull level of the compound section). n_b is a base value for Manning's roughness (n) for a straight, uniform, and smooth channel with natural materials. n_1 is a correction factor for the effect of surface irregularities. n_2, n_3, and n_4 are values for variations in shape and size of the cross-section, obstructions, and amount of vegetation and flow conditions, respectively. m is a correction factor for the meandering of the channel. The selection of values for these variables is comprehensively explained in Gillen (1996). This general quantitative approach was preferred over methods such as Strickler's method where roughness is expressed as a function of mean particle size (McGahey, Knight, and Samuels 2009) due to the incorporation of many factors that differentiate these two stream types. Channel roughness was calculated at two places of each selected reach.

$$n = \left(n_b + n_1 + n_2 + n_3 + n_4\right) m \quad (3)$$

2.5 | 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

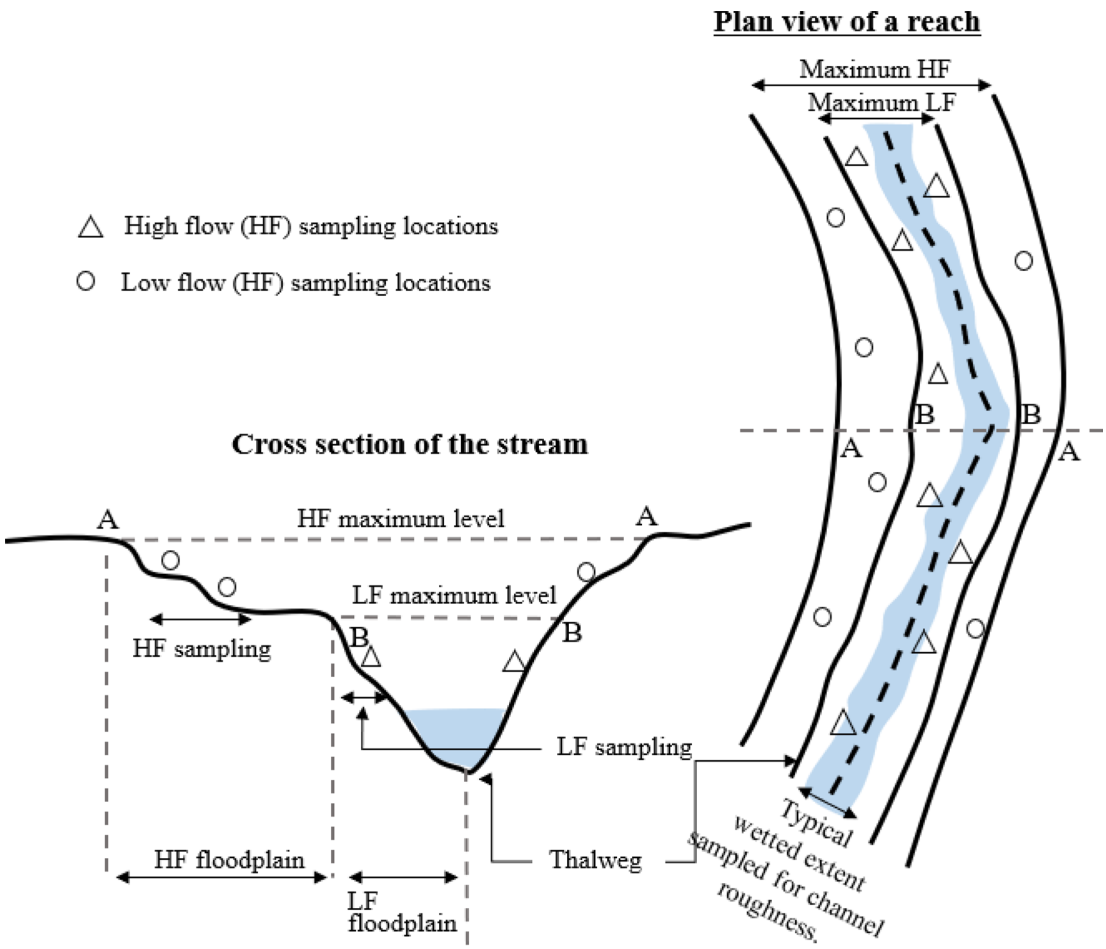

FIGURE 3 | An illustration of the sampling regime referring to a hypothetical cross-section and a reach under flowing conditions. [Color figure can be viewed at wileyonlinelibrary.com]

vegetation (herbs, forbs, graminoids, vines, and tree saplings shorter than 0.5 m) was considered for the biomass. The role of trees (or tree saplings) less than 0.5 m tall (about a year old) on infiltration and channel roughness was assumed to be similar to herbs, forbs, graminoids, and vines. Also, trees over 2 years old were rare up to the channel margin. In all cases, the standing crop biomass included the summation of above and below-ground components other than for observations related to channel roughness, where only the aboveground biomass was considered. The below-ground biomass of ephemeral streams was relatively more than the perennial streams (60% vs. 45% of total biomass). Samples were thoroughly washed to remove sediment and other foreign matter. Each sample was oven-dried at 100°C until no weight loss was observed. The diversity of herbs was realized by the Shannon–Wiener index (SWI) (Equation (4)) (Gomes et al. 2014). P_i is the proportion of cover by the *i*th species.

$$\mathrm{SWI} = -\sum_{i=1}^{n} P_i ln P_i \quad (4)$$

2.6 | Sediment Sampling

Sediment samples were collected up to a depth of 10 cm close to the infiltration test locations. The sediment samples were collected in airtight plastic Ziploc bags to preserve moisture during transportation to the laboratory. Sediment moisture content was water's weight relative to the sediment's dry weight (ASTM 1998 D2216). Particle size distribution was determined by a sieve analysis (ASTM D422-632007), and the particle size corresponding to 16% finer in the cumulative distribution (D16), and particle size corresponding to 50% finer in the cumulative distribution (D50; mean particle size) were recorded. The organic content of the sediment was determined by the loss of mass on the ignition test (ASTM D2974, 2014). The particle size distribution of soil samples with cobbles and boulders was realized via photographic analyses. The AUTO-CAD 2015 version was used to scale and digitize.

2.7 | Data Analysis

All data is presented as mean ± standard deviation unless otherwise stated. The assumption of normal distribution and the homogeneity of variances were checked using the 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. Multiple comparisons in one-way ANOVA were done using the Tukey Post Hoc test. This post hoc test would adjust the *p* value in multiple *t*-test comparisons (Midway et al. 2020). Most of the comparisons,

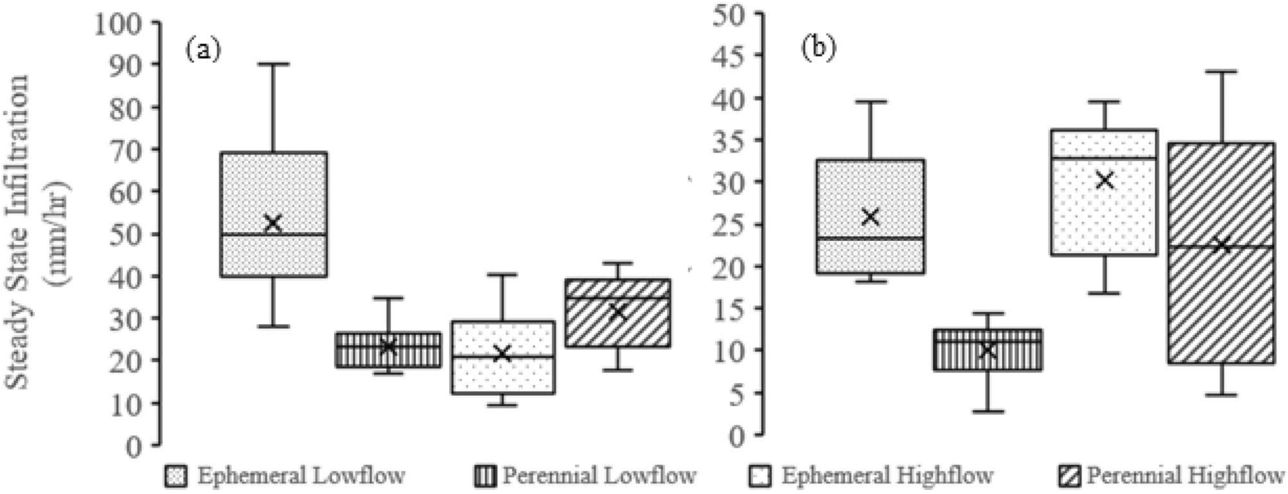

FIGURE 4 | Box plot view of infiltration (a) dry, (b) wet seasons.

including all that involved infiltration had more than two groups.

In addition, Pearson's correlation analysis was carried out to check the relationship between two variables, and Pearson's correlation coefficient (*r*) was used to identify the strength of the correlation. Multiple linear regression was used to observe the relationship between two or more eco-hydrologic variables and infiltration. Infiltration was always the response variable. Organic content, moisture, organic litter, mean particle size of sediment, Shannon–Weiner index, and standing crop biomass of herbs were considered as explanatory variables under different scenarios representing the season. The variance of inflation was observed to detect the multicollinearity and was avoided by removing one or more of the violating variables from the regression model. This ensured all the variables used had less than a 5% variation of inflation. The residuals of the models were checked for the normal distribution and homogeneous variance. Multiple linear regression was undertaken using the forward selection option where variables were added one at a time beginning with the variable with the highest correlation with the infiltration. The stepping method criteria for the forward selection was the probability of *F* (or *F* statistic), where 0.06 was used for entry and 0.1 for removal.

All statistical analyses were performed using IBM SPSS V.24. In all cases, other than specifically stated $p<0.05$ is considered significant, and depending on the circumstances the *p* value will be reported.

3 | Results

3.1 | Spatiotemporal Variation of Infiltration and Hydro-Ecological Variables

The ephemeral low-flow areas showed exceptionally high infiltration rates in the dry season that were significantly (one-way ANOVA; $p<0.05$) higher than the infiltration observed at any other spatiotemporal combination of these two stream types, defined by the transverse location and season (Table 2). It also showed a high variation, with some locations as high as 90 mm/h (Figure 4). However, no difference was observed at any other location for ephemeral streams in any season compared to another spatiotemporal scenario involving perennial streams. Two observations could explain this. First, the infiltration rates between these two stream types were not significantly different (one-way ANOVA; $p>0.05$) in high-flow areas for both seasons. Second, infiltration in the dry season for high-flow areas of ephemeral streams (21.7 ± 10.1 mm/h) was lesser than the equivalent involving perennial streams (31.6 ± 8.6 mm/h), and the differences were almost statistically significant (one-way ANOVA; $p=0.06$).

The sediment moisture content of ephemeral streams was significantly less than perennial streams in low-flow (one-way ANOVA; $p<0.001$) as well as high-flow (one-way ANOVA; $p<0.001$) areas in the dry season (Table 2). This was the case even during the wet season, but the differences were not significant (one-way ANOVA; $p>0.1$).

The organic content was higher in ephemeral streams in the low-flow region during the dry season but did not show any significant differences. In all other cases, perennial streams showed a higher sediment organic content, but only the high flow area in the wet season showed a statistically significant difference to ephemeral streams (one-way ANOVA; $p<0.001$).

Standing crop biomass observations revealed ephemeral streams had significantly lower biomass than perennial streams (one-way ANOVA; $p<0.001$ for low-flow and $p=0.007$ for high-flow). In contrast to biomass, litter content was always higher in ephemeral streams, but with a large variation around the average value, and the differences were significant between the two stream types in the low flow area (one-way ANOVA; $p=0.002$). A high vegetation diversity was observed in perennial streams with statistically significant differences (one-way ANOVA; $p=0.009$ in low flow and $p<0.001$ in high flow).

The particle size distribution curves revealed that the sediment of ephemeral low-flow areas were gap-graded (data not shown), which is a special case of poorly graded sediment. The low-flow areas of ephemeral streams were coarser, D50 was

TABLE 2 | Seasonal and transverse variation of infiltration and hydro-ecological variables.

Season	Dry season				Wet season			
Transverse location	Low flow		High flow		Low flow		High flow	
Stream type	ES	PS	ES	PS	ES	PS	ES	PS
Infiltration (mm/h)	52.5 (18.2)	23.5 (5.5)	21.7 (10.1)	31.6 (8.6)	25.8 (7.8)	10.1 (3.6)	30.2 (8.3)	22.5 (13.8)
Moisture content (%)	3.2 (1.6)	8.4 (1.3)	5.1 (2.2)	16.1 (3.4)	20.4 (6.1)	26.3 (5.7)	14.8 (8.9)	18.3 (10.3)
Organic content (%)	5.3 (3.3)	3.6 (1.4)	5.5 (1.6)	6.8 (4.1)	5.9 (2.3)	8.3 (2.8)	7.2 (2.4)	11.0 (1.2)
Standing crop biomass (including below ground) (g/m^2)	52.9 (21.8)	93.8 (25.5)	65.6 (21.0)	96.2 (15.0)	—	—	—	—
Litter (g/m^2)	115.1 (50.1)	65.4 (11.1)	96.4 (32.8)	85.1 (22.5)	76.1 (9.9)	62.0 (19.1)	102.3 (14.4)	51.2 (10.8)
Shannon–weiner index (SWI)	0.8 (0.2)	1.1 (0.2)	0.7 (0.2)	1.2 (0.4)	—	—	—	—
Mean particle size (D50) (mm)	103.7 (166)	64.5 (38.3)	1.0 (0.5)	1.0 (0.3)	—	—	—	—
Particle size where 16% of the particles are smaller (D16) (mm)	6.3 (7.7)	5.4 (7.8)	0.4 (0.1)	0.4 (0.1)	—	—	—	—

about 10 cm and was 1.5 times more than the perennial's mean particle size. However, the variation of D50 was also high in ephemeral streams indicating a nonsignificant difference (one-way ANOVA; $p > 0.05$) between stream types. D16 of ephemeral stream low-flow areas were slightly larger than that of perennial streams but not large enough to show a significant difference (one-way ANOVA; $p > 0.05$). Particle sizes of the high-flow areas were similar in both stream types.

3.2 | Bi-Variate and Multiple Linear Correlations Between Infiltration and Eco-Hydrologic Variables

Sediment moisture and litter showed negative correlations with infiltration. The correlations were stronger and more significant in the dry season (e.g., the moisture content in ephemeral stream low-flow areas: $r = -0.81$; $p < 0.001$ in the dry season (Figure 5a) vs. $r = -0.66$; $p = 0.07$ in the wet season (Figure 6a)) and for ephemeral streams (e.g., organic content in low-flow areas in the dry season (Figure 5b): $r = 0.75$; $p < 0.001$ in ephemeral streams vs. $r = 0.61$; $p = 0.03$ in perennial streams). Similar to the dry season (Figure 5b), only ephemeral streams displayed negative correlations in the wet season. Still, those also were weak to moderately strong with no statistical significance (Figure 6b). Litter showed a strong negative statistically significant correlation with infiltration in ephemeral streams in the dry season. The impact of litter on infiltration was weak and statistically insignificant for perennial streams ($r = -0.43$; $p = 0.16$ in the low-flow dry season was the strongest and most significant correlation, whereas in all other cases $p > 0.4$). Vegetation parameters (standing crop biomass and SWI) and D16 did not show even a weak correlation (all were $r < 0.2$ and $p > 0.2$) (data not shown).

On the other hand, D50 showed strong positive correlations with infiltration during the dry season (Figure 5d) for both stream types without showing any stream type dependency.

Multiple linear regression models predicted better relationships for ephemeral streams than perennial streams, and for both stream types, prediction was better in the dry season (Table 3). For the wet season, not a single model could be developed. Input scenario 1, or the scenario involving organic content, litter, and soil moisture, gave strong and significant models for ephemeral streams; however, the models did not include soil moisture. Litter showed a negative effect, whereas organic content had a positive effect. The statistically significant perennial stream models included only the organic content. Incorporation of D50 slightly improved or impaired the explanatory power of some models (data not shown).

3.3 | Variation of Manning's Coefficient in Low Flow Areas and Discharges

Ephemeral channels, in general, were two to three times rougher than perennial streams (0.088 ± 0.073 vs. 0.044 ± 0.022) under low flow conditions in the wet season, and the differences were statistically significant (*t*-test; $p < 0.001$). Standing crop biomass (Figure 7) and D50 for both streams resulted in more friction, with statistically significant correlations that were more prominent for perennial streams. For all cases, linear relationships gave the best explanatory power, other than the relationship between D50 and Manning's roughness in ephemeral streams. Litter in ephemeral streams resulted in a smooth channel, whereas the diverse vegetation produced a rougher perennial channel.

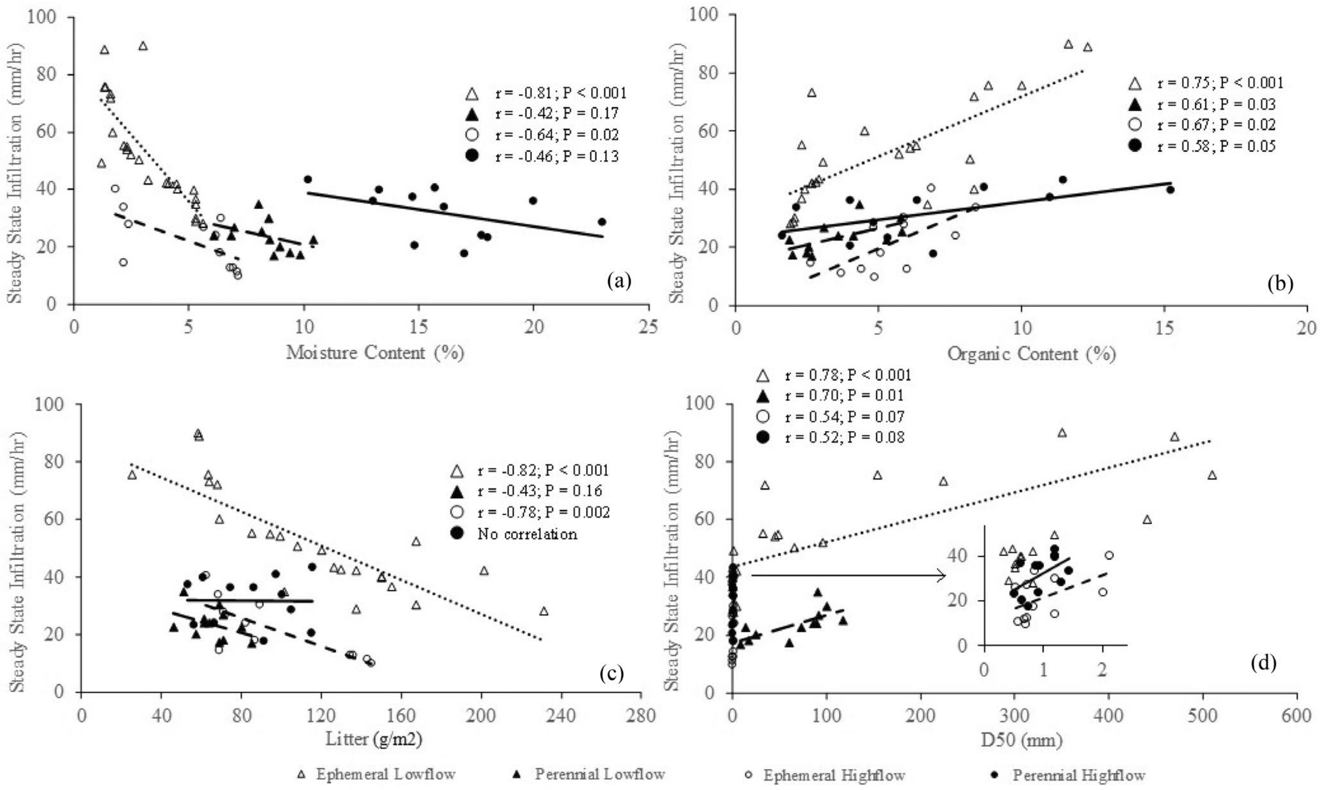

FIGURE 5 | Variation of infiltration with eco-hydrologic variables in the dry season (some of the statistically insignificant and/or weak correlations are not shown).

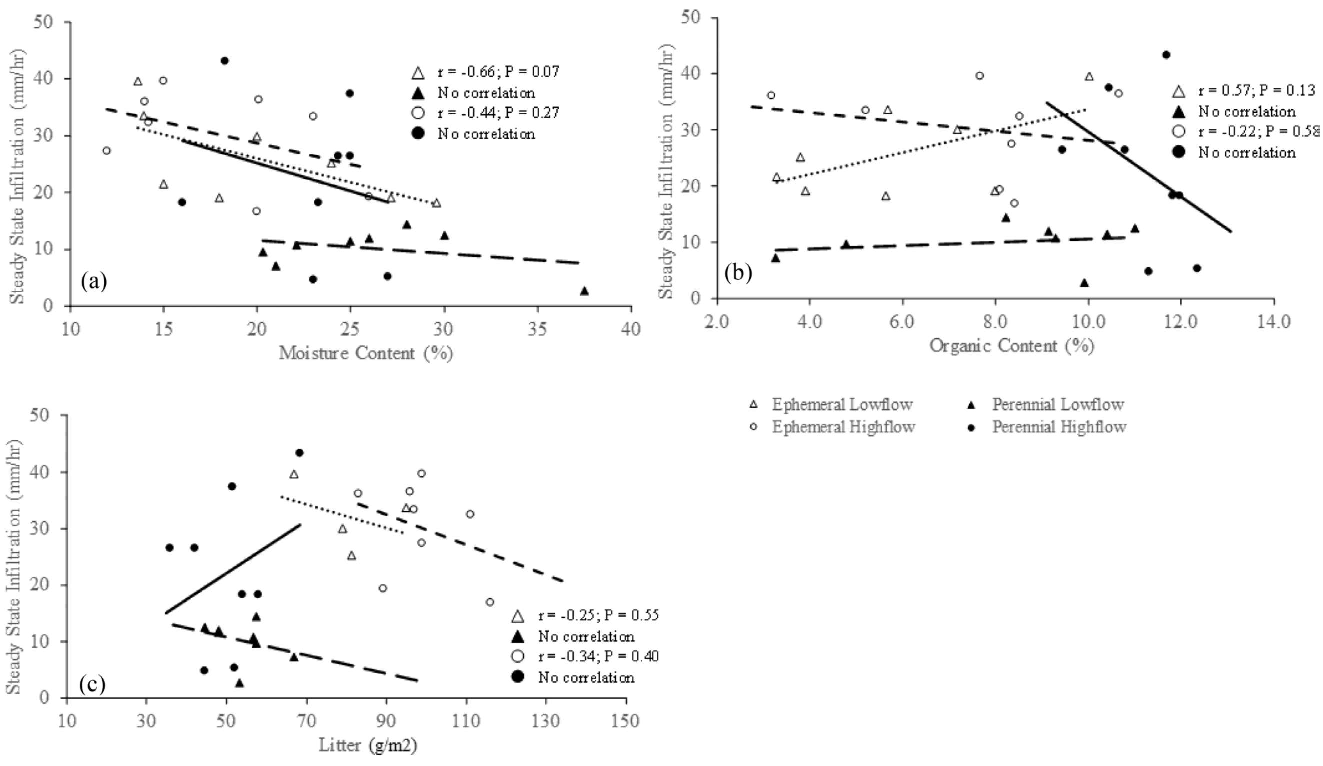

FIGURE 6 | Variation of infiltration with eco-hydrologic variables in the wet season (some of the statistically insignificant and/or weak correlations are not shown, and assumed D50 did not change from the dry season).

TABLE 3 | Simple linear multiple regression models.

Stream type/transverse location/season	Model	R^2	Highest *p* of a variable	Model's *p*	Input scenario
Ephemeral stream/low flow/ dry season	$I = 65.3 + 2.1(OC) + 0.2(L)$	0.66	0.01 (OC)	0.001	1
	$I = 58.6 + 0.04(D50) + 1.4(OC) - 0.1(L)$	0.82	0.05 (OC)	0.001	2
Ephemeral stream/low flow/wet season	None				1, 3
Perennial stream/low flow/ dry season	$I = 17.2 + 0.1(D50)$	0.50	0.01 (D50)	0.01	2
Perennial stream/low flow/ wet season	None				1, 3
Ephemeral stream/high flow/dry season	$I = 25.5 - 0.2\ (L) + 2.7(OC)$	0.80	0.02 (OC)	0.001	1, 2
Ephemeral stream/high flow/wet season	None				1, 3
Perennial stream/high flow/ dry season	$I = 23.3 + 1.2\ (OC)$	0.58	0.04 (OC)	0.04	1
	$I = 10.8 + 1.1\ (OC) + 13.6\ (D50)$	0.51	0.06 (D50)	0.02	2
Perennial stream/low flow/ wet season	None				1, 3

Note: Input scenarios: Scenario 1 included organic content (OC), moisture content (MC), and litter (L) only as input variables for both seasons; scenario 2, in addition to the variables of scenario 1, also included mean particle size (D50), standing crop biomass (summation of above and below ground), and shannon–wiener index (SWI) for only the dry season. Scenario 3 included all variables of scenario 1 for the wet season. However, D50, standing crop biomass (summation of above and below ground), and SWI were assumed to be the same as the dry season.

Observed and analytically derived discharges (Figure 8) showed a good match with strong positive relationships (Pearson's $R > 0.75$) for both ephemeral and perennial streams. Both the low flow and bankfull discharges remained higher in perennial streams, although without significant differences (*t*-test; $p > 0.05$).

4 | Discussion

4.1 | Hydro-Ecological Status Quo of Ephemeral Streams

In both stream types, the biomass was higher in the high-flow area close to the riparian zone due to nutrient-rich soil (Gomes et al. 2014), and especially in perennial streams due to higher soil moisture (Zalewski 2006). High litter content, especially in ephemeral stream low-flow areas, was due to primary production in the dry season by terrestrial vegetation within the channel and litter supply from riparian (channel bank) vegetation (Gomes, Wai, and Dehini 2020) accumulating until the flow recommences, when litter would be transported downstream by advancing wetting fronts (Datry, Arscott, and Sabater 2011).

High organic content in high-flow areas of perennial streams in the wet season was due to rapid soil hydrological processes controlling the release of the organic content that can be utilized by the plants (Heisler and Weltzin 2006); this process may be slower in ephemeral high-flow areas. The higher organic content in the low-flow areas of perennial streams in the wet season was due to the increased bio-geochemical cycling because of previous flood events that fuelled heterotrophic activities in sediments (Brooks, Haas, and Huth 2007; Shanafield et al. 2021).

4.2 | Can Infiltration in Ephemeral Streams Be Explained With Conventional Understanding?

Due to their high infiltration potential, ephemeral streams are known as losing streams (Chen et al. 2013; Subramanya 2013; Shanafield et al. 2021). Even though infiltration rates across the ephemeral stream floodplain are perceived to be high, rates are largely unquantified (Scamardo and Wohl 2023), stressing the importance of studying the variation through the ephemeral network. Infiltration rates reported in the literature vary for ephemeral streams (e.g., 0.02–0.075 cm/min (Chen et al. 2013); 0.16 cm/min (Schoener 2016); 0.02–0.13 cm/min (Batlle-Aguilar and Cook 2012)) and our observations varied from 0.05 to 0.15 cm/min, agreeing with the range observed by Batlle-Aguilar and Cook 2012. The hydrologic soil group A (classified by USDA soil classification and Unified Soil Classifications and characterized by a gap or well-graded gravel and/or coarse sand) has the highest infiltration of all soil classes starting from 2 cm/h (0.03 cm/min) (Minnesota Stormwater Manual 2023); interestingly, half of the dry ephemeral stream beds were observed to have twice that value.

Comparative field studies related to ephemeral and perennial streams are rare. However, Schilling et al. (2021) conducted simulations of infiltration with varying ephemerality defined based on the number of days without a flow varied from 0 days (i.e., perennial conditions) to 640 days. They observed infiltration about

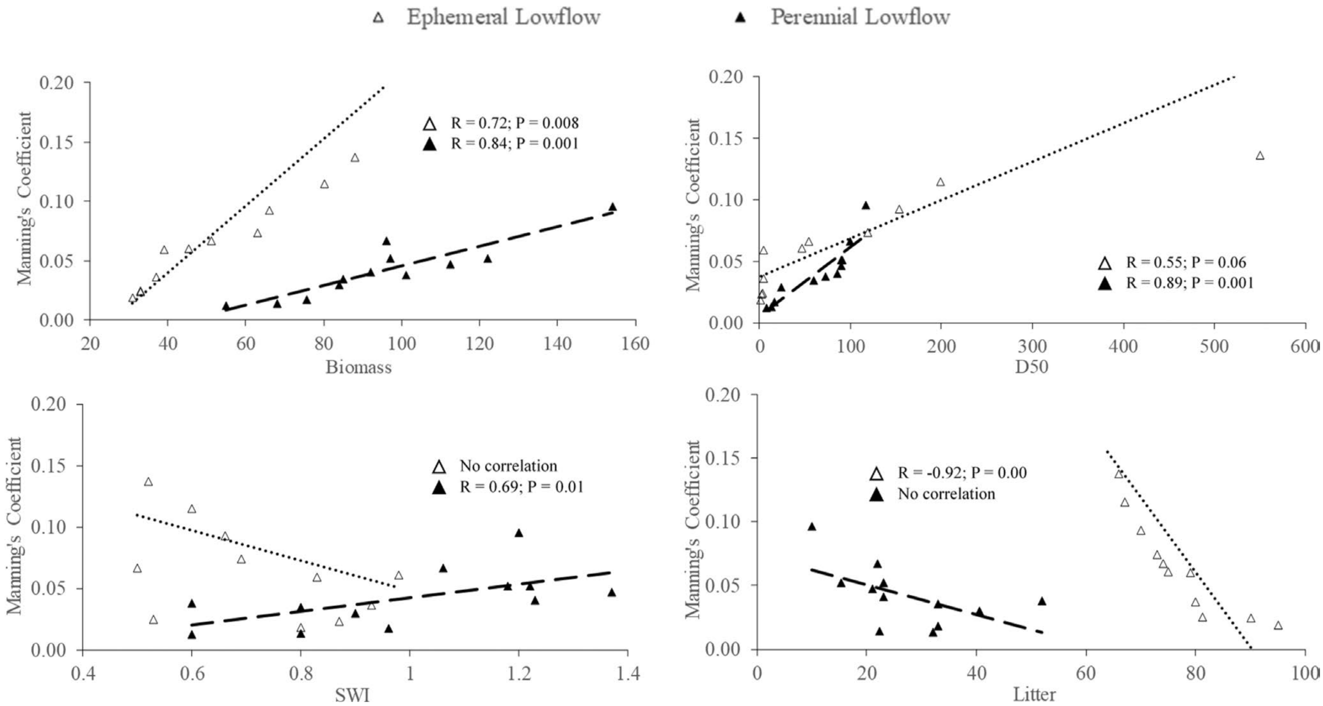

FIGURE 7 | Variation of manning's roughness with eco-hydrologic variables in the wet season (some of the statistically insignificant and/or weak correlations are not shown).

16 orders of magnitude higher under ephemeral conditions that persisted for 80 days, which agreed with our field observations when compared with the lowest and highest infiltration values of our perennial and ephemeral streams, respectively. Nevertheless, the 20-day ephemerality agreed with our results, displaying a two-fold difference in infiltration.

Some correlations agreed with the common understanding of infiltration and the factors influencing it. However, observations reported in the literature are not uniform. For example, Fischer et al. (2014) and Schoener (2016) established no correlation between particle size and infiltration existed. In contrast, Wang, François, and Lambert (2017) observed D10 (particle size where 10% of particles are finer) has a positive correlation with infiltration. In our case, we did not observe a correlation with fine particle size but a positive correlation with mean particle size. Mean particle size had only a marginal and limited effect on explaining infiltration in ephemeral stream ecosystems but was more influential in perennial streams.

Increased organic matter indirectly contributes to soil porosity via increased soil faunal activities, consequently increasing infiltration (Eusufzai and Fujii 2012). The fact that soil with high organic content is more infiltration-friendly (Olorunfemi, Ogunrinde, and Fasinmirin 2014) was also observed in our study, but only in the dry season. The wet season not displaying the expected relationships could be due to water filling the cracks and capillary forces (i.e., sorptivity) in moist soils (Batlle-Aguilar and Cook 2012). Also, in the wet season activation of perched water tables is possible (Shanafield et al. 2021) and would disrupt expected correlations.

Statistically similar infiltration rates in perennial and ephemeral streams in the high-flow areas were unexpected and opposed our hypothesis. In addition, perennial high-flow areas in the dry season displaying higher infiltration than their ephemeral counterpart was even more surprising, considering the drier surface and subsurface conditions due to the deep-water table in ephemeral streams (Fritz, Johnson, and Walters 2006; Gomes, Wai, and Dehini 2020). Under field conditions, several factors can govern infiltration, some of which could be more influential than sediment moisture or organic content. Therefore, it was surprising that the infiltration responses cannot be understood only with the hydrological permanence, and we attempted to answer this by including the vegetation and its surrogates, such as litter, into the analysis.

4.3 | Variation of Biological Factors and Infiltration

The observations of vegetation's impact on infiltration somewhat conflict between studies. Pingping et al. (2013) observed that the infiltration rate reduced with the increased vegetation cover due to the micro–biotic soil crust over the ground surface. However, Thompson et al. (2010) observed that infiltration increased as a power-law function of aboveground biomass in water-limited ecosystems. Similarly, Saco, Willgoose, and Hancock (2007), Subramanya (2013) and Newcomer et al. (2016) highlighted the enhancement of infiltration capacity with the presence of vegetation. Vegetation guarantees that soil is relatively less compacted as it intercepts direct rainfall (Subramanya 2013). In contrast to all the above relationships, which were either positive or negative, Thompson et al. (2010) found no significant correlation between vegetation biomass and infiltration capacity in a forest terrain (in Durham), and this was the case in our study. Even though biomass did not show a direct effect on the infiltration capacity, biomass after decaying can contribute to the organic

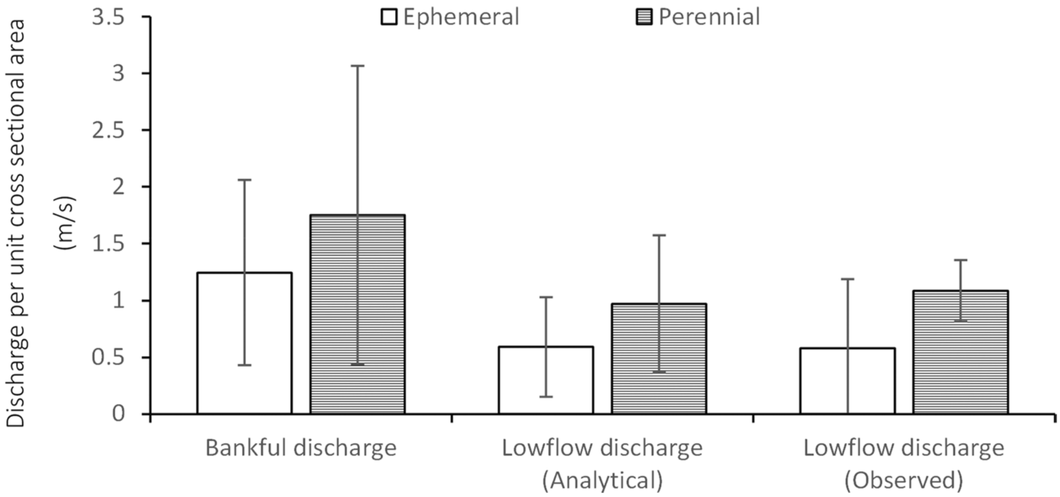

FIGURE 8 | Discharge per unit cross-sectional area corresponding to the low flow (observed in the wet season), and low-flow and bankfull flow (analytically derived).

content of the soil, enhancing infiltration by the formation of macro and meso pores (Eusufzai and Fujii 2012); therefore, playing an indirect or surrogated role.

The unexpected considerable drop of infiltration in ephemeral high-flow areas in the dry season can be attributed to the subsequent natural compaction of the sediment surface covered with litter with decreased moisture content (*in sensu* Pingping et al. 2013). This also explains the hydrological difference between ephemeral high-flow and low-flow areas concerning temporal moisture change. The decrease in sediment moisture could happen at a higher rate in the ephemeral high-flow areas due to the deep groundwater table, leading to the litter air drying faster than decomposition and decaying under a moist environment. In the case of ephemeral low-flow areas, the moisture content decrease will not be as fast as the high-flow areas, as low-flow areas are the last to lose water. This would mean that the leaf litter decomposition in low-flow areas of ephemeral streams happens in a moist environment and sometimes under submerged conditions (Hardwick, Fryirs, and Hose 2022). Therefore, litter can decompose into fine particulate organic matter with the help of macroinvertebrates such as shredders without forming a litter mat or a micro-biotic soil crust such as in high flow areas. It should be noted that these areas also had buried residues of previous litter, therefore, the impact of litter should also include sub-surface material.

4.4 | Channel Roughness of Ephemeral Streams

Standing crop biomass and D50 showed an increasing impact on channel roughness, and the correlations were strong in perennial streams. The more prominent increased roughness due to biomass in perennial streams has been reported in previous studies (e.g., Limerinos 1970; Plakane 2017). Limerinos (1970) highlighted that friction depends on the plant type. Nevertheless, past studies did not observe the impact of increased diversity on roughness, as we observed for perennial streams. The larger the D50, the more it contributes to flow resistance by creating irregularities on the stream bed, thus contributing to high roughness (Lau and Afshar 2013). The relatively weak relationship between roughness and D50 in ephemeral streams can be attributed to the formation of a slime layer (biofilm) and periphyton on the bed surface contributing to a smooth channel. This happens because of the high penetration of solar radiation during low-flow conditions in ephemeral streams than perennial streams due to shallower depths. Relatively well-covered litter on the stream bed of ephemeral streams also makes the influence of particles less important than in perennial streams. This was evident with D50 showing an exponentially reducing relationship over a linear relationship with Manning's roughness. The D16 particle size was 40-fold less than the corresponding D50, making the contribution from fine particles negligible.

5 | Conclusion and Recommendations

Our comparative study gave quantitative evidence of the infiltration signature of ephemeral streams. Ephemeral low-flow areas in the dry season showed at least twice the infiltration relative to perennial streams. However, it was revealed that high-flow areas of ephemeral streams do not have a significant advantage over perennial streams aiding infiltration in the dry season. This was due to the impact of litter and stream-type-dependent litter processing. For both stream types, sediment moisture and organic content showed negative and positive correlations, respectively, with ephemeral streams showing stronger and more significant associations. The eco-hydrologic variables incorporated in our study, and the bivariate and multivariate linear models developed to explore the relationships of infiltration were able to explain the variations satisfactorily only during the dry season. Explanatory power of such models was stronger in the low-flow areas. Therefore, more studies are recommended to identify variables that can explain the infiltration in the wet season.

Ephemeral streams were two to three times rougher than perennial streams, and for both streams, crop biomass and D50 contributed to a rougher channel and the impact was more prominent in perennial streams. Channel roughness is inversely proportional to the discharge through a stream channel; therefore, ephemeral streams would convey a lower discharge.

Hence, ephemeral streams have a better holding capacity than perennial streams, delaying the flow to the downstream perennial sections. This further supported the understanding that ephemeral streams have flood control potential, and obviously, these streams would play a major role in flood control in tropical regions. Further studies are recommended to identify the individual and combined influence of various hydro-ecological variables on infiltration and how field observations related to abstraction losses and channel roughness are reflected in discharge simulations in numerical models.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated during this study are available from the corresponding author upon reasonable request. A preprint of an early version of this article is available at DOI: 10.1002/essoar.10512030.1.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.