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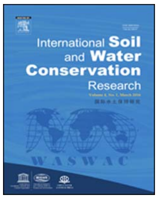

Original Research Article

Effect of land cover on channel form adjustment of headwater streams in a lateritic belt of West Bengal (India)☆

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ABSTRACT

Present work is exploring the influence of land cover on channel morphology in 34 headwater catchments of the lateritic belt of West Bengal. Non-parametric tests (Mann-Whitney U and Kruskal-Wallis) and multivariate analysis (Principal Component Analysis and Canonical Discriminant Function models) have successfully differentiated the performance of land cover on channel morphology adjustment among the three groups of headwater streams (forested, transitional, and agricultural) on the Kunur River Basin (KRB). Spatial Interpolation Techniques reveal that intense land-use change, particularly forest conversion to agricultural land, is significantly increasing channel widths (269%) and cross-section area (78%), whereas agricultural channels become shallower (40%) than would be predicted from forested streams. Catchments with the dominance of forest and agricultural land are classified as ‘C′ and ‘B′ types of streams respectively, as per Rosgen's Stream Classification Model. Finally, the work claimed that transitional stream group is the definitive area to exaggerate the river restoration plan to stabilize the anthropogenic deformation on channel morphology.

1. Introduction

Management of agricultural rivers, as well as forested rivers is a major research concern to the countries of southeast Asia, when about 94% of the areas suitable for agriculture have already been cultivated (Atapattu & Kodituwakku, 2009; FAO, 2002). To feeding the largest percentage of world population in the southeast area, the century-old practice (i.e. agriculture) is still expanding its coverage with significant deforestation for agricultural land (Atapattu & Kodituwakku, 2009). India lost nearly 7% of its forest cover in last two decades (1990–2010) due to a rapid transformation of land cover by anthropogenic activities (FAO, 2015). Thereby, river basins are considerably losing their canopy cover, and the immediate indirect and/or direct effects have been faced by headwater streams with the input of huge surface runoff and eroded soil. Apart from the deteriorating of river water quality and declining the biodiversity of a river (Alexander, Boyer, Smith, Schwarz, & Moore, 2007; Blann, Anderson, Sands, & Vondracek, 2009), expansion of agricultural land in the forested area may also significantly contribute to change the channel morphology of headwater streams (Lester & Boulton, 2008). From example, more than 98% of the North American prairie and vast areas of forest have been replaced with croplands under modern agricultural systems, which have been associated with extensive modifications to natural drainage networks (Blann et al., 2009).

Headwater streams (first order and second order streams, after Strahler, 1957) are generally recognized as major external links within the river system (Fritz, Johnson, & Walters, 2008) with contributing > 90% of catchment stream flow (Deschamps, Pinay, & Naiman, 1999; McIntosh & Laffan, 2005) and represents 50–70% of total stream length within a river basin (Leopold, Wolman, & Miller, 1964; Meyer & Wallace, 2001; Nadeau & Rains, 2007). According to McMahon and Finlayson (2003), headwater streams are more prone to natural drying than are downstream segments because they have smaller drainage areas with less recharge potential and higher topographic elevations. In addition due to drain over impermeable land with small source area than large rivers, headwater streams cannot maintain their base-flows for lower storage capacity (Burt, 1992). However, forested headwater streams are hydrologically as well as geomorphologically more stable than agricultural streams due to higher retention capacity, larger lag-time, lower discharge, less sediment and stable bank slope (Ruprecht & Schofield, 1991).

Since the expansion of human civilization, effect of land use – land covers change (especially deforestation for croplands) becomes a major research issue in fluvial geomorphology (Wang, Liu, Kubota, & Chen, 2007), due to significant influences on the alteration of chemical and biological characteristics of river water (Garman & Moring, 1991;

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Mullen & Moring, 1988; Schnitzler, 1997), basin hydrology (Harden, 2006; Hewlett & Helvey, 1970; Nagasaka & Nakamura, 1999; Zabaleta & Antiguedad, 2013), and sediment supply (Ausseil & Dymond, 2008; Dunne, 1979; Golosov, 2006; Restrepo & Syvitski, 2006; Vorosmartry et al., 2003). However, the effect of deforestation on the deformation in channel structure still needs more attention from fluvial geomorphologists.

Hack and Goodlett (1960) had reported the relationship between vegetation, topography and hydrological processes. Zimmerman, Goodlett, and Comer (1967) documented the influence of vegetation in the channel form of small streams. Wolman (1967) in a diagram represents a correlation between the land cover type, river channel condition and sediment yield within a river basin, wherein forested land cover makes channel stable but with the transformation of forest cover channel conditions have also altered significantly. The effects of land use – land cover change on the in-stream bar formation (Begueria et al., 2006; Hickin, 1984), channel planform (McKenney, Jacobson, & Wetheimer, 1995), channel side slope (Allan et al., 2002), migration rate of river meander (Begueria et al., 2006; Micheli, Kirchner, & Larsen, 2004), channel width (Gurnell, 1997; Harden, 2006; Sweeney et al., 2004), shape of the channel (Shepherd, Dixon, Davis, & Feinstein, 2011) have been well studied across the world.

The prime objective of our study is to explore how the catchment level variation in land cover may affect the channel morphology. The main comparison is among the forested, transitional, and agricultural headwater streams on the lateritic belt of Ajay-Damodar Interfluve or Kunur River Basin in particular. The study has hypothesized that forested headwater streams with the least amount of anthropogenic impact will generate a lower volume of discharge with greater sinuosity and width – depth ratio. As the land use shifts from dense forest to degraded forest to agricultural land with an associated increase of anthropogenic pressure, the volume of discharge will increase, width – depth ratio will decrease, and sinuosity will approach straightness.

2. Materials and methods

2.1. Description of study sites

A total 34 sub-basins (SBs) of the headwater streams have been studied throughout the lateritic belt of Ajay-Damodar Interfluve, which administratively comes under the Barddhaman District of West Bengal, India (Fig. 1). In Q-GIS, online mapping tool has been enabled to extract land cover characteristics of all 34 micro-watersheds after opening the recent view of Google Earth. Multilayer GIS analysis helps to delineate the boundaries of selected sub-basins using ASTER GDEM (30 m), Topographical Sheets of Survey of India (1: 50, 000), Google Earth View. In dense forest area, field mapping using GPS has been used to track the basin coverage. The area of sub-basins varies from 0.23 to 18.67 km^2 and the range does not follow the normal distribution with the Skewness of 1.84 (SE 0.41) and Kurtosis of 2.71 (SE 0.79). The sub-basins are intentionally selected from single geological lithotop to exclude the effect of varying geology among the study sites. Geologically, the focused area is covered by the Cenozoic laterite of Lalgarh formation, an oldest formation consists of reddish brown latosol with iron-nodules (disintegrated duricrust) underlain the lateritic hard pan and lithomarge clay parts having light pinkish white sandy clay with few quantities of iron nodules (Roy & Banerjee, 1990). Soil type is predominantly sandy-loam and facing the problem of severe soil erosion in the form of rills and gullies (Roy, 2013).

The climate of the region is typical humid subtropical and influenced by monsoon-fed rain. Annual average rainfall observed is 1380 mm and mean temperature is 25.8° C in the last 100 years, where about 70–80% rainfall is falling from June to September only (IMD, 2014). Studied streams are ephemeral in nature and contain water only during the rainy season and no woody debris has been observed in these streams. Sites are numbered randomly within the Kunur River Basin, a major right-bank sub-basin of the lower Ajay River Basin. The Kunur River originates in the western upland of the district at about 100 m of altitude, flowing latitudinally from west to east for a length of ~114 km. There, elevation ranges from 20 to 131 m throughout the basin. The drainage pattern is nearly dendritic and catchment extends over an area of about 915.60 km^2, having an elongated and asymmetrical shape.

The basin has a forest cover (mainly wet deciduous type with Sal species - *Shorea robusta*) spreading over almost 31.35% area, water body holds around 10.35% area, 13.82% area is for human settlement, 41.74% for agricultural land and 2.73% area comes under barren land or unsuitable areas for agriculture (Roy & Sahu, 2015). The region is also facing huge anthropogenic pressure due to very high population density about 1100 person/km^2, where nearly 58% of populations are still engaged in the agricultural sector (Census of India, 2011). Single cropping system is basically following over the district with 64.74% of net sown area and *Kharif* rice as the principal crop type (Neetu, Prashanani, Singh, Joshi, & Ray, 2014).

2.2. Procedures to collect the information of channel geometry

Several intrinsic channel parameters (i.e., w – channel width; d –

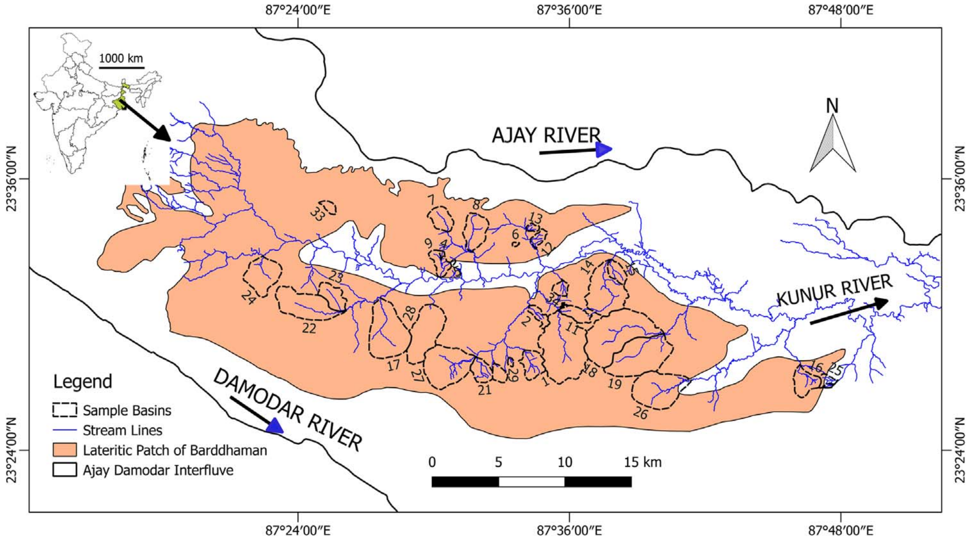


Fig. 1. Location of sample sub-basins (SBs) within the lateritic belt of Ajay-Damodar Interfluve and as a part of Kunur River Basin.

average depth; D – maximum depth; ER – entrenchment ratio; s – slope; a – cross-section area; w/d – width-depth ratio; Q – bankfull discharge capacity; SI – sinuosity index; τ_0 - shear stress and ω - unit stream power) have been computed from each sub-basin. All channel cross-sections and longitudinal profiles were surveyed using Auto level (Sokkia C410 ─ with 2.5 mm standard deviation for one km double run leveling) followed by the standard protocols of VDFW (2009). Bankfull indicators have been preferred for cross-section survey across the riffle area. A total 40X length of bankfull channel width has been selected for sinuosity index (SI) of all sample sub-basins. Visual to quasi-quantitative interpretation have been also done to analysis reach wise variation in channel conditions, such as bed materials, pool – riffle distances, area of the pool etc. Bankfull discharge, stream power and shear stress values have been estimated from the survey data to aid the analysis of stream form and processes. The Manning's equation (Eq. (1)) has been followed to calculate reach wise stream velocity (v) (m/s) and associated discharge (m^3/s). Reach wise shear stresses (τ_0) (N m^{-2}) and unit stream powers (ω) (W m^{-2}) are also estimated using the Eqs. (2) and (3), respectively (Shepherd et al., 2011).

$$v = (1/n)R^{2/3}s^{1/2} \text{ and } Q = (v \times a) \tag{1}$$

where, v is velocity, n is the roughness coefficient, R is the hydraulic radius, s is channel slope, Q is discharge and a is channel cross-section area.

$$\tau_0 = \gamma_w\, Rs \tag{2}$$

where, τ_0 is shear stress and γ_w is specific weight of water.

$$\omega = \gamma_w\, Q\, s/w \tag{3}$$

where, Q is discharge and w is channel width.

2.3. Data analysis

2.3.1. Grouping of sample sub-basins

To run non-parametric test and discriminant analysis (explained below), selected 34 sub-basins have been classified into three groups by the name of purely forested (PF), transitional (T), and agricultural (A) basins (Fig. 2), where (i) pure forested basins are characterized by > 80% of native forest (i.e. Sal Forest); (ii) transitional basins are dealing with 50 – 70% of forest cover and < 45% of agricultural land, and (iii) agricultural basin group is dominated by cultivated land (> 45%) with partly forest cover (10 – 20%) and notable percentage of settlement area (5 – 15%). However, for Spatial Interpolation Technique (explained below) selected basins have been re-classified into two groups; (i) forested streams with > 60% of forest cover (n =17), selected as unmodified catchment and (ii) agricultural streams (n =11) with maximum modification in catchment area by anthropogenic activities (as nominated in earlier classification).

2.3.2. Non-parametric test

Against the assumption of normality of collected data, Shapiro-Wilk's test ($p < 0.05$), visual inspection of the histograms, normal Q-Q plots and box plot have showed that the catchment areas of three basin groups are not following the normal distribution with the Skewness of 1.46 (SE 0.68), 2.43 (SE 0.62), and 0.76 (SE 0.66) for forested, transitional and agricultural basins respectively. Therefore, Mann-Whitney *U* test (for two groups separately) and Kruskal-Wallis test (for three groups in together) have been used to established the variability of channel morphology between three groups of sub-basin.

2.3.3. Multivariate analysis

Principal Component Analysis (PCA) has been applied to fifteen parameters for 34 sub-basins of the KRB, in order to group the parameters under different components based on significant correlations. According to Sharma (2002), a principal component conveys all essential information about the variables, ensuring economy in analysis and description while obtaining relatively accurate results. In addition, Canonical Discriminant Analysis (CDA) has been used to differentiate the pattern existed within the three basins groups (forested, transitional and agricultural) on the ten intrinsic variables of channel morphology (i.e. channel width, maximum depth, mean depth, width – depth ratio, cross-sectional area, channel slope, stream discharge, sinuosity, shear stress and unit stream power). CDA allows preparing a linear combination (canonical variable) that summarized between-group variation, thereby allowing the study groups to be successfully discriminated (Dunteman, 1984; Norusis, 1985; SAS, 1987). Wilks' Lambda (λ) and F statistics from squared Mahalanobis distances have been followed to describe the ability of the models to discriminate permanence categories. Wilks' λ can range from 0 (perfect discrimination) to 1 (no discrimination) among classes (Fritz, Johnson, & Walters, 2008).

2.3.4. Spatial interpolation technique

Spatial Interpolation Techniques (SIT) has been applied to identify and quantify the significant changes in channel geometry from the transformation of forested catchment to agricultural catchment. A convenient illustration of this approach has been provided by Gregory and Park (1976) and Gregory (1976). SIT is an applied technique in sub-basin scale analysis (Chin & Gregory, 2001; Hammer, 1972; Jeje & Ikeazota, 2001; Nanson & Young, 1981; Park, 1977; Wolman,

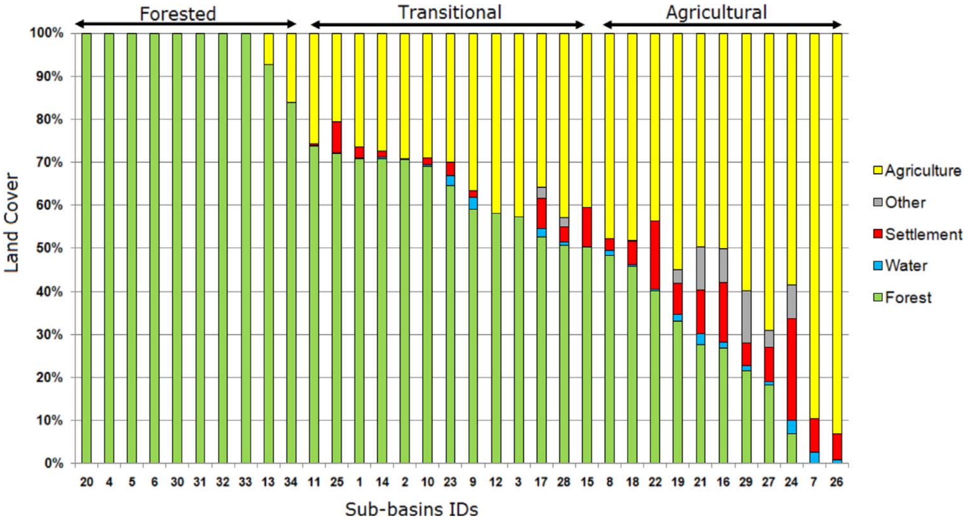


Fig. 2. Distribution of land cover types (five) in percentage among the sample sub-basins (basin ID ordered based on the descending values of forest cover).

1967), where channel-form properties are observed under modified conditions and compare them with the natural or unmodified condition at the same geographical area to detect the rate of changes and what should be in natural condition (Hammer, 1972; Park, 1977).

Channel cross-sections have been surveyed in the field at 17 sites on natural or unmodified channels within the forest cover area of Kunur River Basin. Cross-section area, channel width and mean depth at bankfull stage have been measured from each site. Power regression has been established between drainage area, as an independent factor, and three channel properties (w, d, & a) for the unmodified or natural channels. *T*-test also used to formulate significant relationship ($p < 0.05$, $n = 17$), which run to interpolate the channel properties under modification by land cover changes. The calculated ratio between the observed and predicted channel dimensions of the site also provides an 'enlargement ratio' (also may called 'reduction ratio') index (Gregory & Park, 1976; Hammer, 1972).

2.4. *Classification of stream reaches (after Rosgen, 1994)*

Level II stream classification method of Rosgen (1994) has been adopted to know the variation in stream type and nature of bank stability among the sample sub-basins. Since mid 1990s, this classification approach has been widely approved by governmental agencies, particularly those funding restoration projects (Malakoff, 2004). Simon et al. (2007) have identified some inconsistency in the Rosgen classification. However, this method can be used to combine channel morphological parameters to determine the present channel behavior in respect to the purpose of our study. In this model, Rosgen (1994) have introduced the term entrenchment ratio (ER) to make a quantitative relation between river channel and its valley and to know the level of channel incision and the condition of floodplain of study reaches.

3. Results

3.1. *Principal component analysis (PCA)*

Two broad types of variables are taken to run PCA with fifteen variables of 34 headwater streams – (i) intrinsic variables of channel (i.e. channel width, maximum depth, mean depth, width – depth ratio, cross-sectional area, channel slope, stream discharge, sinuosity, shear stress and unit stream power) and (ii) extrinsic variables of basin (i.e. forest area, water bodies, settlement area, agricultural area and other land use – land cover). As the system is functioned with multivariate components, PCA tries to identify the dominant components and variables which run the system positively or negatively in a defined direction of Eigen vector. To interpret the results of PCA, four principal components have been taken into consideration because the Eigen values of PC (Principal Component) 1, PC 2, PC 3 and PC 4 are greater than 1 and about 80% of the variance is explained in fourth PC (Table 1). Therefore, these four components have been interpreted separately in below to know the positive and negative dominance of variables in the system (Table 2).

Table 1
Explained variance and Eigen values of four principal components.

Component	Initial Eigen values		
	Total	% of Variance	Cumulative %
1	6.004	40.027	40.027
2	2.518	16.786	56.813
3	1.923	12.817	69.63
4	1.589	10.595	80.225

Table 2
Response of variables in four principal components and bold values are key dominance factors in the system.

Variables	PC 1	PC 2	PC 3	PC 4
w	**0.621**	0.494	−0.156	0.486
D	**0.783**	0.279	−0.06	−0.457
d	**0.846**	0.269	−0.086	−0.387
w/d	−0.472	0.15	−0.038	**0.735**
a	**0.842**	0.457	−0.033	0.059
s	−0.273	**−0.623**	−0.085	−0.156
F	**−0.876**	0.363	0.022	−0.105
W	0.590	**−0.542**	−0.118	0.371
S	**0.667**	−0.491	−0.158	0.2
O	0.391	**−0.704**	0.173	0.179
A	**0.863**	−0.235	−0.011	0.051
Q	**0.799**	0.079	−0.16	−0.05
SI	0.169	**0.510**	−0.247	0.425
τ_0	0.325	0.101	**0.910**	0.057
ω	0.225	0.107	**0.945**	0.131

[w= Channel Width; D = Channel Maximum Depth; d = Channel minimum depth; w/d = Width-Depth Ratio; a = Cross-Section Area; s = Slope; F = Forest Cover; W = Area of Water Body; S = Settlement; O = Other area, e.g. barren land, waste land, etc, A = Agricultural Land; Q = Bankfull Discharge (based on manning equation), SI = Sinuosity Index; τ_0= Shear Stress; ω= Unit Stream Power]

PC 1: With 40% of explained variance and Eigen value of 6.004, it is the most dominant and influential component in the relation between channel morphology and basin land use – land covers characteristics. This component signifies that this fluvial system is not influenced or affected by the isolated variables but the combined effect of all leading variables run the system. The result indicate that the dominant trend in the data set is positively associated with the variables w, D, d, a, S, A, and Q, and negatively associated with F. It reflects positively associated variables are functioned with the fluvial erosional processes, while forest cover adversely checks the system in this region.

PC 2: In the second important component, channel slope, water bodies and other land use – land cover variables are functioned negatively with key dominance (>0.50). But only sinuosity index gives a positive response (0.51) to the system with an important role to the system. This component has about 17% of explained variance with Eigen value of 2.518.

PC 3: With only 13% of explained variance and Eigen value of 1.923, PC 3 has only two positive intrinsic dominant factors – shear stress (τ_0) and unites stream power (ω) (>0.90).

PC 4: This component has only 11% of explained variance and Eigen value of 1.587, but it has only one positive leading variable, i.e. width – depth ratio (0.735) which has very low dominance in previous three components.

Based on above analysis, we can say that channel width, maximum channel depth, mean channel depth, cross-sectional area, channel discharge, forest cover, settlement area, water bodies and agricultural area, etc. variables are worked separately as well as combinedly with > 80% explained variance. Therefore, it is justified that multivariate factors have driven the inter-relationships between fluvial morphology of headwater streams and land use – land cover properties of the region.

3.2. *Non-parametric test for inter-group variability of channel properties*

Table 3 shows the absolute differences in variable means among the three basin groups and Fig. 3(a – i) is comparing the range of absolute values using quartiles of different channel parameters among the groups. In addition Kruskal-Wallis test shows from forested to agricultural streams via transitional stream group, channel width (w), maximum depth (D), mean depth (d), cross-sectional area (a), bankfull

Table 3
Descriptive statistic of ten channel properties for three different basin groups (Abbreviations are provided in Table 2).

Channel Properties	Forested		Transition		Agricultural		Total	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
w (m)	2.56	0.82	3.33	1.32	3.86	1.10	3.28	1.21
D (m)	0.33	0.18	0.63	0.28	0.68	0.18	0.56	0.27
d (m)	0.19	0.09	0.36	0.17	0.42	0.12	0.33	0.16
w/d	17.40	12.53	10.52	4.94	9.67	2.39	12.27	8.06
a (m^2)	0.48	0.21	1.24	0.79	1.75	0.91	1.18	0.87
s ($m\ m^{-1}$)	0.05	0.04	0.03	0.02	0.04	0.04	0.04	0.03
Q (m^3/s)	2.28	1.77	4.85	3.31	9.43	6.86	5.58	5.25
SI	1.16	0.13	1.22	0.17	1.19	0.16	1.19	0.15
τ_0 ($N\ m^{-2}$)	13.89	16.16	16.44	10.62	22.37	16.39	17.61	14.35
ω ($W\ m^{-2}$)	557.44	1057.97	537.61	398.35	999.89	1177.79	693.01	910.93

discharge (Q) are significantly ($p < 0.01$) increasing and width – depth ratio (w/d) is insignificantly ($p = 0.218$) decreased in agricultural streams than forested (Tables 3, 4). However, not significant ($p > 0.05$) differences in channel sinuosity index (SI), shear stress (τ_0), and unit stream power (ω) have been observed from forested to agricultural streams (Table 3).

To evaluate the inter-group differences in channel parameters, Mann-Whitney *U* test shows values of w, D, d, a, and Q in agricultural streams are significantly higher than forested stream, however no significant differences have been observed in w/d, channel slope (s), τ_0, and ω (Table 4). In comparison of forested vs. transitional streams only D and d are significantly changed, whereas no significant differences have been observed in all channel parameters between transitional and agricultural streams (Table 4).

3.3. Canonical discriminant analysis (CDA)

In CDA, two canonical discriminant functions have been fitted with ten intrinsic channel variables to separate intergroup variability (Table 5). The overall discriminant function is significant and it does a good job of classifying the three channel groups (Wilks'λ=0.38, $p < 0.01$). In the first discriminant function (f1) 68.50% of variance has

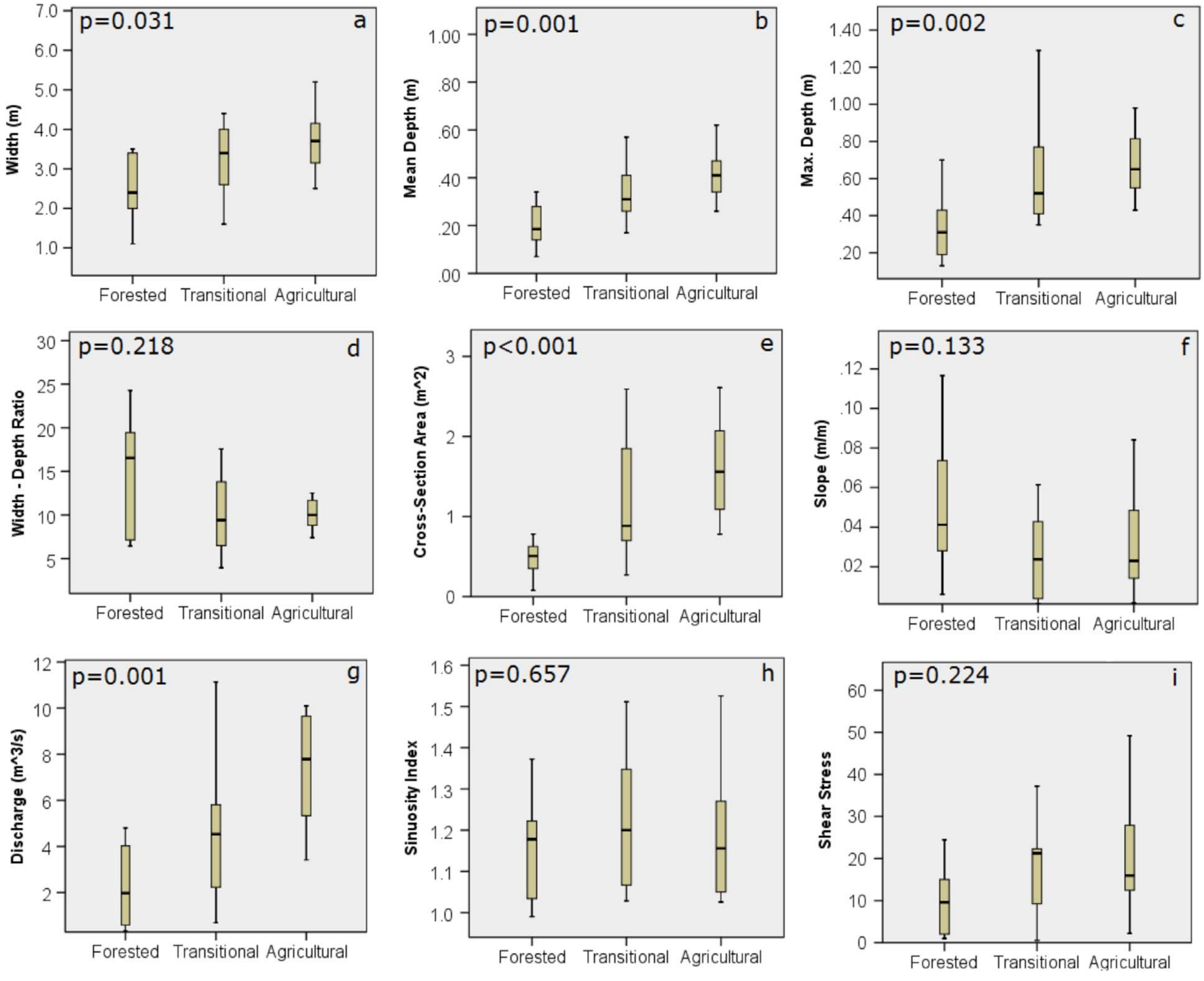


Fig. 3. (a – i): Box plots show the absolute differences of channel properties (in quartile format) among the three groups of sub-basins; p-value in the left corner of each diagram indicates the significant level as per Kruskal-Wallis Test.

Table 4
Test statistic for inter-group variability of channel properties using non-parametric techniques (Abbreviations are provided in Table 2).

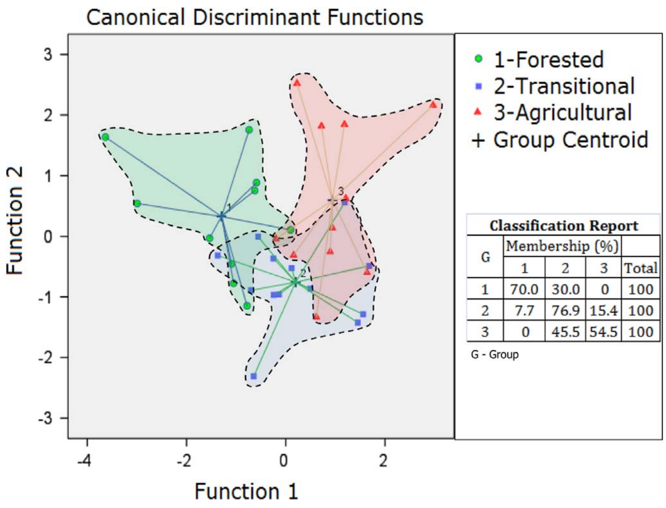
Group Variable	Non-Parametric Techniques	w	D	d	w/d	a	s	Q	SI	τ_0	ω
Forested vs. agricultural	Mann-Whitney U	16.50	8.50	6.00	34.00	1.00	37.00	7.00	48.00	32.00	29.00
	Sig. (2-tailed)	0.007	0.001	0.001	0.139	0.000	0.205	0.001	0.622	0.105	0.067
Forested vs. transitional	Mann-Whitney U	41.00	22.00	20.00	40.00	15.00	33.00	32.00	51.00	49.00	47.00
	Sig. (2-tailed)	0.135	0.008	0.005	0.121	0.002	0.047	0.041	0.385	0.321	0.264
Transitional vs. agricultural	Mann-Whitney U	53.00	54.50	48.00	68.00	42.00	60.00	34.00	63.00	57.00	61.00
	Sig. (2-tailed)	0.283	0.324	0.173	0.839	0.087	0.505	0.030	0.622	0.401	0.543
Among the groups	Kruskal-Wallis Test (Chi-Square)	6.96	12.32	14.11	3.04	17.63	4.03	13.33	0.84	2.82	3.22
	df	2	2	2	2	2	2	2	2	2	2
	Sig.	0.031	0.002	0.001	0.218	0.000	0.133	0.001	0.657	0.244	0.200

been explained and significantly correlated with cross-section area (0.76), mean depth (0.75), maximum depth (0.72), discharge (0.66), width (0.51), and width - depth ratio (– 0.48), whereas weakly correlated with shear stress, channel slope, unit stream power, and sinuosity. However, with explaining only 40.10% second discriminant function (f2) significantly correlated with channel slope (0.41), unit stream power (0.27) and sinuosity (– 0.20). Wilks' Lambda (λ) test shows the level of discriminant between the group means of ten variables (Table 5), where all variables are significantly ($p < 0.05$) discriminant between each group except channel slope (λ=0.88, p =0.131), sinuosity index (λ=0.97, p =0.625), shear stress (λ=0.94, p =0.385), and unit stream power (λ=0.92, p =0.409).

Fig. 4 and inserted classification report show 70% of forested streams are correctly classified (30% incorrectly classified as transitional streams), 76.9% of transitional streams are also correctly classified (7.7% and 15.4% incorrectly classified as forested and agricultural streams respectively), and only 54.5% of agricultural streams are classified correctly (with 45.5% streams are classified as transitional streams). A presence of clear discriminant between forested and agricultural streams has been observed with no significant overlapping in Fig. 4; however significant part of the transitional stream group has been overlapped over the zone of forested and agricultural streams. In particular, agricultural stream characteristics are more dominated in the group of transitional streams with > 16% overlapping area.

3.4. Spatial interpolation technique for forested vs. agricultural streams

Regression equations in Table 6 are showing that in forested streams, channel width (r =0.62), mean depth (r =0.76), and cross-section area (r =0.77) are positively increased with drainage area (Da)



Classification Report

G	Membership (%) 1	2	3	Total
1	70.0	30.0	0	100
2	7.7	76.9	15.4	100
3	0	45.5	54.5	100

Fig. 4. Plotting of canonical discriminant functions (f1 & f2) scores based on channel properties of three stream groups. Black dashed lines highlight the individual zones and level of their overlapping. Classification report has been inserted in right side.

Table 6
Functional relationships between channel parameters and catchment area of forested streams.

Power Regression Equations	n	df	R^2	r	T - values Calculated	Observed	'p'
$w = 3.287Da^{0.124}$	17	(n−2) = 15	0.383	0.62	3.03	2.13	0.001
$d = 0.259Da^{0.230}$			0.583	0.76	4.58		0.021
$c = 0.858Da^{0.350}$			0.594	0.77	4.36		0.007

Table 5
Tests of discriminant functions for classifying forested, transitional, and agricultural headwater streams (Abbreviations are provided in Table 2).

Eigenvalues

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation	Wilks' Lambda	Chi-square	df	p
1	0.871	68.5	68.50	0.682	0.381	25.540	20	0.01
2	0.401	31.5	100.0	0.535	0.714	8.938	9	> 0.05

Structure matrix

Function	a	d	D	Q	w	w/d	τ_0	s	ω	SI
1	0.775	0.752	0.72	0.663	0.511	−0.481	0.244	−0.291	0.184	0.128
2	0.092	−0.12	−0.24	0.387	0.071	0.180	0.172	0.406	0.273	−0.203

Wilks' Lambda Test

Variables	w	D	d	a	w/d	s	SI	Q	τ_0	ω
Wilks' λ	0.814	0.676	0.670	0.824	0.655	0.877	0.693	0.970	0.94	0.944
p	0.041	0.002	0.002	0.049	0.001	0.131	0.003	0.625	0.385	0.409

Table 7
Estimated changes in agricultural channel properties (w, d, & a) in comparison to the forested streams characters using Spatial Interpolation Techniques.

S.B.	Drainage area (km^2)	Width (m)				Mean depth (m)				Cross-sectional area (m^2)			
		Predicted	Observed	Change	%	Predicted	Observed	Change	%	Predicted	Observed	Change	%
22	8.27	1.55	5.20	−3.65	336.56	1.19	0.44	0.75	36.93	1.80	2.29	−0.49	127.30
8	4.95	1.44	4.50	−3.06	311.68	1.06	0.36	0.70	34.00	1.50	2.16	−0.66	143.83
18	15.06	1.67	2.50	−0.83	149.51	1.37	0.59	0.78	43.14	2.22	1.48	0.74	66.54
21	2.88	1.34	3.00	−1.66	223.19	0.93	0.26	0.67	27.81	1.24	0.78	0.46	62.78
16	2.00	1.28	2.90	−1.62	226.38	0.86	0.33	0.53	38.39	1.09	0.96	0.14	87.51
19	13.66	1.65	3.70	−2.05	224.13	1.34	0.50	0.84	37.39	2.14	1.85	0.29	86.35
24	7.02	1.51	3.80	−2.29	251.33	1.15	0.41	0.74	35.73	1.70	1.56	0.14	91.80
26	1.49	1.23	3.50	−2.27	284.05	0.80	0.35	0.45	43.57	0.99	1.23	−0.24	124.17
29	1.16	1.19	3.80	−2.61	318.76	0.76	0.43	0.33	56.70	0.90	1.63	−0.73	180.80
7	3.12	1.36	3.30	−1.94	242.92	0.95	0.28	0.67	29.41	1.28	0.92	0.35	72.32
27	9.58	1.58	6.30	−4.72	399.93	1.23	0.62	0.61	50.31	1.89	3.91	−2.01	206.43

at 95% level of significance. *T*-test derived significance level ($p < 0.05$, $n = 17$, $df = 15$) revels all three equations could be used to interpolate the channel parameters in the modification catchment land cover (Table 6). Table 7 indicates that channel widths in the agricultural streams are considerably greater than would be predicted from forested streams and the average enlargement ratio is 269%, although the range of ratio is from 150–400%. The mean depths of channels in agricultural streams are reduced than predicted values from forested streams, where the average reduction ratio is 40% and range varies from 27–57%. However, changes in the channel cross-sectional areas are relatively minor. Average 78% increase in cross-sectional area has been observed in six basins; whereas five basins are losing the cross-sectional area at an average 156% reduction ratio than predicted in forested basins (Table 7).

3.5. Differentiation of stream condition using Rosgen's channel classification model

As per Rosgen's model about 82% forested streams ($n = 17$) are slightly entrenched ($ER > 2.2$), whereas agricultural streams ($n = 15$) are moderate (47%) to highly (37%) incised ($ER < 2.2$) with accelerate channel erosion. Among the study reaches type of bed material varies from clay to gravel, where about 60% forested stream's beds are filled by coarse-sand to gravel with frequent presence of in-stream bedrock outcrop. However, size of bed materials is drastically decreased in agricultural streams where about 65% reaches are covered by sandy-clay to pure clay. In Level I classification, among the study streams 11%, 25%, 22%, 22%, 3%, and 17% of reaches are coming under A, B, C, E, F, and G types of streams respectively (Table 8). Level II classification shows the major concentration of forested streams is in C (C4, C5, C6) (48%) and E (E4, E5, E6) (30%) types and agricultural streams are in type B (B5, B6) (~54%). Four agricultural streams (SB – 3, 18, 19, and 26) are also come under G4 and G5 category due to the higher percentage of agricultural land cover as well as settlement area. Although previous sections show forested streams are in sustainable condition than agricultural, but the result derived from Rosgen classification indicates a threaten condition for each group of streams. Table 8 shows all study reaches come under very high to moderate disturbance zone in terms of their streamflow magnitude, sediment supply, and prone to bank instability. However, the column of recovery potentially suggests for starting an ad hoc planning for their restoration with good to excellent ability of channels to restore their own stability once the cause of instability is corrected.

4. Discussion

4.1. Control of land covers character on channel morphology

Channel morphology of the study reaches has been changed in response to the transformation of natural land cover (i.e. forest) to the agricultural land use. Significant interdependency between channel properties and land cover characteristics has been explained in PCA, where forest cover inversely influences to check the erosional processes within the KRB (Table 2). The channel morphology in forested,

Table 8
Sub-basin wise classified stream types and their potential management strategy (based on Rosgen Channel Classification Model).

Stream type	**Sample basin IDs**		**Sensitivity to disturbance**[a]	**Recovery potential**[b]	**Sediment supply**[c]	**Stream bank erosion potential**	**Vegetation controlling influence**[d]
	Forested	**Agricultural**					
A4	1		Extreme	Very poor	Very high	Very high	Negligible
A5	25		Extreme	Very poor	Very high	Very high	Negligible
A6		29	High	Poor	High	High	Negligible
B5	14	21	Moderate	Excellent	Moderate	Moderate	Moderate
B6		27, 7, 24, 8, 22, 15, 17	High	Excellent	Moderate	Low	Moderate
C4	31, 32		Very high	Good	High	Very high	Very high
C5	4, 34		Very high	Fair	Very high	Very high	Very high
C6	5, 11, 23, 30		Very high	Good	High	High	Very high
E4	13, 20		Very high	Good	Moderate	High	Very high
E5	6, 33	12	Very high	Good	Moderate	High	Very high
E6	2	16, 28	Very high	Good	Low	Moderate	Very high
F6	10		Very high	Fair	High	Very high	Moderate
G4*		3, 19	Extreme	Very poor	Very high	Very high	High
G5		18, 26	Extreme	Very poor	Very high	Very high	High

[a] Includes increases in streamflow magnitude and timing and/or sediments increase.
[b] Assumes natural recovery once caused of instability is corrected.
[c] Includes sωended and bedload from channel derived sources and/or from stream adjacent slope.
[d] Vegetation that influences width/depth ratio – stability

Table 9
Multivariate correlation matrix among the land cover types and channel properties.

	Da	**w**	**D**	**d**	**w/d**	**a**	**s**	**F**	**W**	**S**	**O**	**A**	**Q**	**SI**
Da	1													
w	0.540**	1												
D	0.564**	0.337*	1											
d	0.613**	0.398*	0.963**	1										
w/d	−0.211	0.169	−0.605**	−0.601**	1									
a	0.450**	0.622**	0.495**	0.551**	−0.186	1								
s	−0.313	−0.467**	−0.405*	−0.379*	0.000	−0.407*	1							
F	−0.423*	−0.395*	−0.480**	−0.509**	0.367*	−0.528*	0.114	1						
W	0.310	0.112	0.226	0.285	−0.265	0.191	−0.005	−0.673**	1					
S	0.239	0.238	0.194	0.236	−0.143	0.130	−0.032	−0.542**	0.333*	1				
O	0.023	−0.012	0.081	0.107	−0.160	−0.032	0.210	−0.478**	0.493**	0.091	1			
A	0.379*	0.355*	0.476**	0.482**	−0.352*	0.511*	−0.152	−0.860**	0.557**	0.048	0.414*	1		
Q	0.489**	0.652**	0.537**	0.610**	−0.286	0.596**	−0.015	−0.624**	0.262	0.255	0.165	0.611**	1	
SI	0.423*	0.299	0.145	0.173	0.003	0.213	−0.174	−0.232	0.248	0.630**	−0.186	−0.082	0.129	1

Da = Drainage Area; w= Channel Width; D = Channel Maximum Depth; d = Channel minimum depth; w/d = Width-Depth Ratio; a = Cross-Section Area; s = Slope; HG = Hydraulic Gradient; F = Forest Cover; W = Area of Water Body; S = Settlement; O = Other area, e.g. barren land, waste land, etc, A = Agricultural Land; Q = Bankfull Discharge (based on manning equation), SI = Sinuosity Index

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Fig. 5. (a) Typical agricultural stream reach with disconnected floodplain and facing problem of severe bank failure; (b) ideal forested stream reach with enriched floodplain ecosystem and stable bank slope.

transitional and agricultural streams are significantly differed from each other, as indicated by the width (w), mean depth (d), maximum depth (D), cross-section area (a), width – depth ratio (w/d), and bankfull discharge (Q), sinuosity (SI) of the channel (Tables 3, 4).

Changes in the catchment land cover can significantly modify the flow regime (discharge and sediment yield) and associated fluvial system (Chin et al., 2016; Clark & Wilcock, 2000). Table 9 shows that agricultural catchment ($r = 0.611$) generates significantly ($p < 0.01$) higher amount of discharge than forested catchment ($r = -0.624$). In particular, a two and four times more discharge has been observed in transitional (4.85 m^3/s) and agricultural (9.43 m^3/s) streams respectively followed by forested (2.28 m^3/s) streams (Table 3). Forested streams generate minimum discharge because the presence of Sal forest in these catchments has increased the rainwater retention capacity (~26%, Roy & Sahu, 2015) with higher infiltration rate (26 cm h^{-1}, NIH, 1996-97). Hewlett and Helvey (1970) and Dadhwal, Aggarwal, and Mishra (2010) have observed ~11% and ~5% more storm flow volumes due to clearance of forest cover in a southern Appalachian catchment and in Mahanadi River Basin respectively. In northern Japan, Nagasaka and Nakamura (1999) also shows agriculture-related deforestation has significantly altered the rainfall-runoff system and surface water retention capacity has reduced about 17%.

Large amount of discharge (9.43 m^3/s) in addition to higher shear stress (τ_0 – 22.37 N m^{-2}) and unit stream power (ω – 1000 W m^{-2}) of agricultural streams have induced to defer channel w, D, d, a, w/d, and SI from transitional (τ_0 – 16.44 N m^{-2}; ω – 537.61 W m^{-2}) and forested (τ_0 – 13.89 N m^{-2}; ω – 557.44 W m^{-2}) streams (Fig. 5a & b). Estimated channel cross-section areas (a) in forested streams are ranging from 0.07 to 2.39 m^2, which is nearly same to the previous studies (i.e. 2.4 m^2) on tropical forested basins (< 10 km^2) by Odemerho (1984). The cross-section area in agricultural streams varies from 0.27 to 3.90 m^2, with mean value of 1.75 m^2, which is significantly ($p < 0.001$) higher than transitional (1.24 m^2) and forested streams (0.48 m^2) (Table 3).

Width – depth ratio (w/d), an important indicator of river ecology (Rosgen, 1994, 1996; VDFW, 2009), suggests forested streams are ecologically rich with higher w/d (17.40) and stable bank side (Figs. 5b and 6a). However, lower w/d ratio in agricultural streams (9.67) indicates the presence of disconnected floodplain with the main channel (Bravard, Amoros, & Pautou, 1986; Ward & Stanford, 1995; Blanton & Marcus, 2009) and promotes steep bank slope and associated bank erosion (Hubble & Rutherfurd, 2010) (Fig. 5a). Smith (1976), Clifton (1986), Shepherd et al. (2011) have also supported that forested streams content better floodplain condition than non-forested streams due to higher w/d. For the study basins' restoration of channel width (w) is more important than depth (d) because d significantly correlated with w/d ($r = -0.605$, $p = 0.01$, $n = 36$), whereas no clear correlation ($r = 0.17$) has been observed between w and w/d (Table 9). Present study does not get any significant ($p = 0.657$) control of land cover on channel planform or sinuosity index, whereas Shepherd et al. (2011) showed anthropogenic influences make channel straight and shorter. Barasa, Kakembo, Waema, and Laban (2015) highlighted channel sinuosity has increased with the drastic change in land use - land cover. Jacobson and Pugh (1997) and Jacobson and Gran (1999) have also mentioned disturbed reaches having increased sinuosity than stable reaches.

In case of w, d, and a, spatial interpolation techniques (SIT) have estimated that streams in the agricultural land are about 269% wider

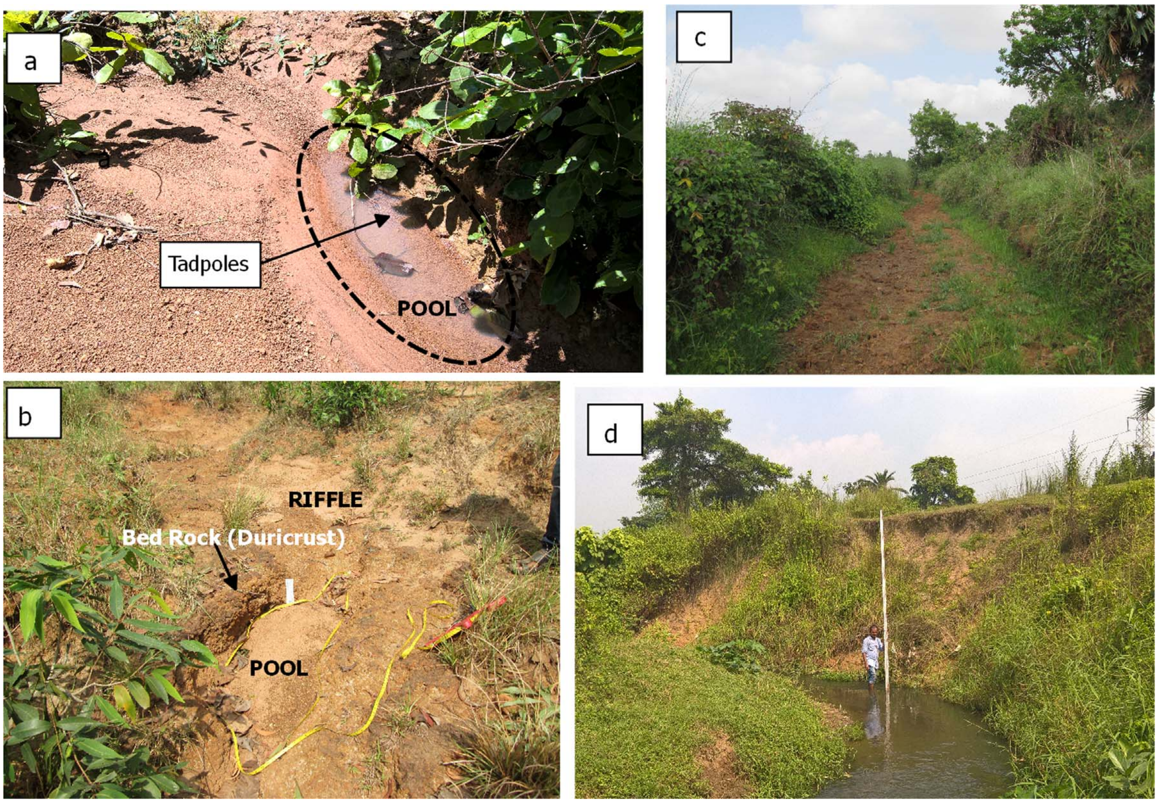


Fig. 6. (a) Existence of tadpoles in pool indicates healthy ecosystem of a forested stream; (b) presence of pool – riffle sequence and exposed bed rock (duricrust) in a forested stream; (c) flat sedimented agricultural stream and no evidence of pool – riffle geomorphology; (d) deep incision in a 'G′ type stream reach (leveling staff height is 3 m). In addition first three figures help to compare the size of bed materials.

and about 40% shallower than forested streams (Table 7). The result highlights significant alteration processes have been played in channel widening and deepening over the study region for land cover changes. Input of larger amount of fine sediments from agricultural land and bank collapsed materials may reduce the normal down cutting rate and make the channel shallower (> 40%) than predicted (Barasa et al., 2015; Walling & Fang, 2003). The dominant anthropogenic pressure such as de-vegetation of the catchments and/or banks (Brooks & Brierley, 2000) and instream sediment extraction (Erskine & Green, 2000) may also involve in mass failure of river banks (Hubble & Rutherfurd, 2010). Labbe, Hadley, Schipper, Leuven, & Gardiner (2011) reported that channel width directly depends on the cohesiveness of bank materials, which is also directly influenced by the alteration of land cover on channel bank. A drastic fall in bed material size in agricultural streams than forested also confirmed such explanation (Figs. 6a, b, and c).

Non-parametric tests and CDA show a clear discriminant between forested and agricultural streams. However, typical similarities have been observed between forested – transitional streams and transitional – agricultural streams (Fig. 4 and Table 4). Although, no characteristic of agricultural streams has been classified in forested group (see classification report in Fig. 4), but 30% of forested streams are classified as transitional streams. Hence, transitional group contents ~16% of agricultural stream character and only 7% of forested stream. However, about 45% of agricultural streams are classified as transitional streams and there is no indication of forested stream. Thereby, overall picture shows a significant transformation of land cover from agricultural basin group to transitional and from transitional to forested group due to gradual deforestation and expansion of agricultural land over the KRB. In particular, restoration of transitional streams can stabilize the anthropogenic influence on river deformation as a barrier to transforming the land use practices from agricultural to forested catchments.

4.2. Streams types and their functions

Forested streams with 48% of reaches in 'C′ category are developed good lateral connectivity between floodplain and channel (Rosgen, 1994), which helps to exchange energy and matter between these two platforms (Thoms, 2003) (Figs. 5b and 6a). However, agricultural streams have reduced the interplay between floodplain and channel with high bank height due to classified as 'B′ category (Fig. 5a). The lateral disconnection in agricultural streams may cause significant ecological damage, including loss of riparian forest, and losing richness and diversity for both terrestrial and aquatic species (Bravard et al., 1986; Ward & Stanford, 1995; Blanton & Marcus, 2009). In fluviogeomorphic aspect, 'C' category streams are containing meanders, point bars, sequence of pool-riffle and are partly controlled by bedrock (Rosgen, 1994), as observed in the forested headwater streams of KRB (Fig. 6b). However, 30% of forested streams are in 'E' group, which are standing in the edge of equilibrium stage and need an urgent restoration plan (Rosgen, 1994). Typical observation of land cover type shows all frosted streams in 'C' category are coming under native stacked forest with maximum preventing capacity of rainwater, whereas others streams in 'E' category are covered by partly native and/or partly with introduced eucalyptus forest. Thereby, result defined that type of forest cover is also a crucial factor in stream management. Agricultural streams in the 'B' and 'G' types are characterized with flat sedimented channel bed and deeply incised valley with severe bank erosion, respectively (Figs. 6c and d). Mechanical transformation of river types using geomorphic approach as initiated by Rosgen (1996) with four priorities is the best option for river restoration in the study area. The vulnerable stream types, i.e. 'G' and 'F' can be transformed into 'C′ or 'E′ types by re-establishing channel on previous floodplain using relic channel or construction of new bankfull discharge channel and may also by material filling in existing incised channel (Rosgen, 1996).

5. Conclusion

The study concludes that land cover types of a catchment play crucial role to adjust headwater stream geomorphology. Forested and agricultural streams contain significantly different channel character to each others. Transformation of forest cover to agricultural land has significantly increased the stream discharge in associate with make wider and shallow channel. Differences in channel sinuosity and width – depth ratio among the basin groups are not significant. Minor observations show agricultural stream fragments floodplain from its channel and minimized the in-stream micro – geomorphological features such as pool – riffle sequence, point-bars, etc. CDA successfully differentiates the studied stream categories, where streams in the transitional group deal combine characters of forested (~7%) and agricultural (~15%) streams due to rapid transformation of land cover. To stabilize the anthropogenic deformation of channel morphology, transitional stream group is an important area to exaggerate the river restoration plan.

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