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Research Article

Confluence Dynamics in an Ephemeral Gully Basin (A Case Study at Rangamati, Paschim Medinipur, West Bengal, India)

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Abstract: Despite many efforts over the last decades to understand confluence angles of rill or gully, they remain unclear. This paper presents the results of gully confluence angles developed at Rangamati ephemeral gully basin of Paschim Medinipur District, West Bengal in India. The confluence angles are monitored for 3 years (2007-2009) and gradient, discharge and stream power of both parent and tributary stream are measured at each junction. Calibrating the data to existing models shows that Optimal Confluence model (Roy, 1983) is better applicable to the present study where average value of symmetry ratio becomes, 0.300 and the value of exponent ‘x’ becomes -0.20. The plot experiment at laboratory under simulated rain shows the tendency of Tran’s link development and downward migration of the lower most junctions due to availability of maximum discharge under constant slope condition. In the situation of homogeneous soil resistance, equal distributed rain and general gradient, local variation of energy is observed due to localized erosion or deposition and associated local variation of gradient in micro scale. Angles of junction are changed in response to the variation of gradient (S), discharge (Q) and Sediment Yield (SY). These changes are episodic in nature and so no average rate can be estimated. The junction migrates both upstream and downstream depending on the relative importance of deposition, erosion and associated change in junction angle.

Keywords: Confluence angle, confluence migration, discharge, gradient, symmetry ratio, sediment yield

INTRODUCTION

Confluences are very complex fluvial networks where the combination of matter (water and sediment) and energy (flow strength) from two different channels take place (Roy, 2008). Stream junction angles are important morphometric and geometric property of channel networks as it regulates the flow from a tributary to the receiving stream. The angles of junction are controlled by erosion and sedimentation at the confluence with time (Schumm, 1956) and by the gradient of the receiving and the tributary stream (Horton, 1945). The influence of the gradient of the two merging streams is reflected by relative importance of either erosion or deposition at or near the junction. The angle of junction varies inversely with the relief. Moreover, the angle of junction increases as the order of the receiving stream increases (Lubowe, 1964). It is related to discharge of the two tributary streams (Howard, 1971c) and discharge per unit width (Mosley, 1976). The discharge, gully width, gully depth, runoff contributing area and gradient are the important factors of gully network system. The river confluences are critical nodes in river systems where tributary fluxes of water and sediment can elicit adjustments in the geomorphology, hydraulics, sedimentology and ecology of the recipient channel (Abrahams, 1984; Rhoads, 1987; Paola *et al.*, 2006; Biron and Lane, 2008).

The present work monitors the drainage network dynamics through field study and Laboratory experiment by assessing the gradient, discharge, width and depth along both tributary and mainstream both upstream and downstream of the junctions. The confluence angles are also linked with the influence of varied condition of the catchment area. The major aim of the present research is to have cognition of the inter-working of processes leading to the development and variation of junction angles and the migration of confluences. In this process, the collected data are calibrated to the recognized models to make a comparative suitability test for understanding the association of factors working at confluences. Plot experiment with simulation rainfall is made to assess the mechanism of network development through the change in links and nodes (junctions).

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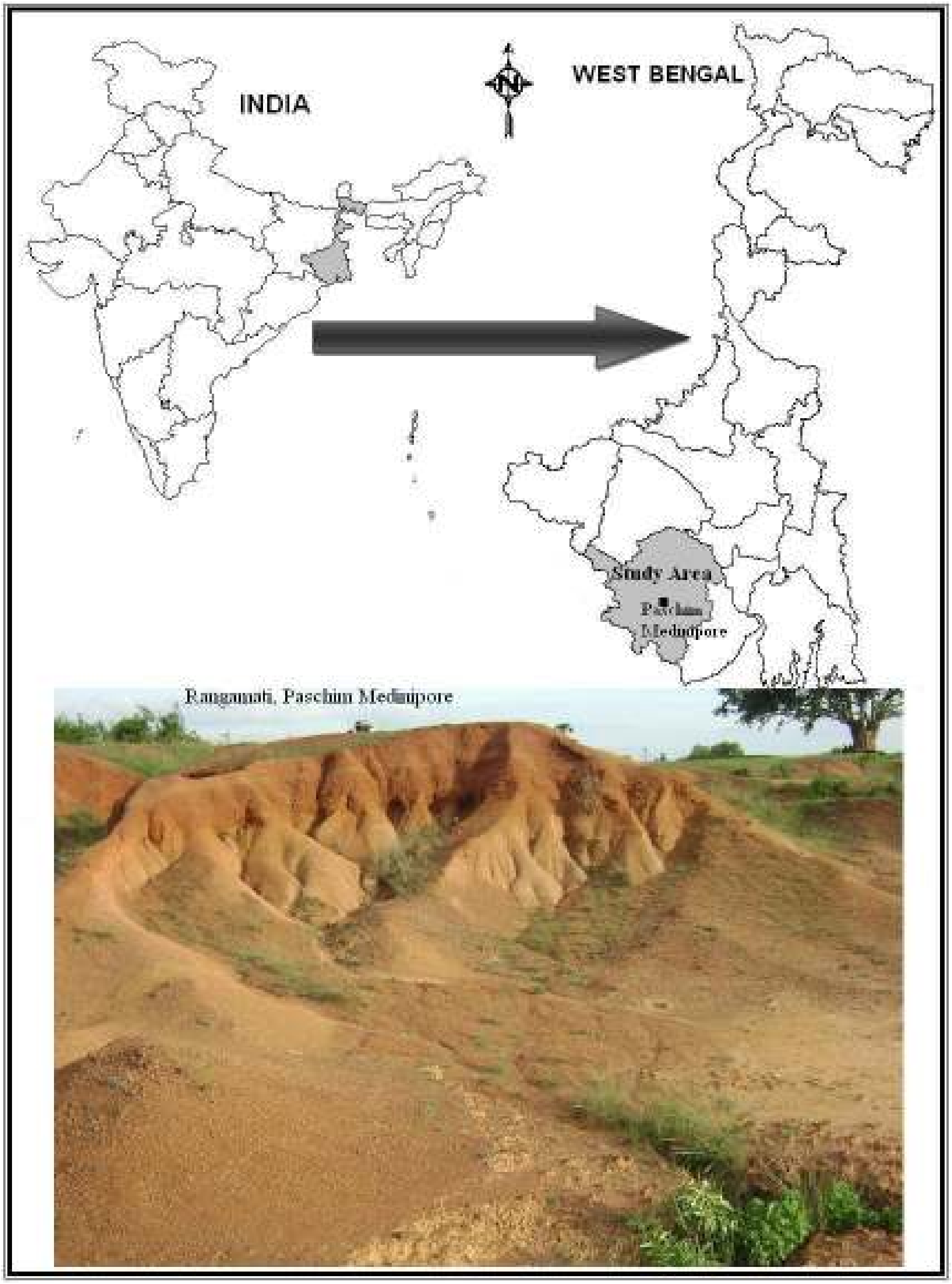

Fig. 1: The study area of 256 sq m encompasses an ephemeral discontinuous basin developed on lateritic soil; the upper catchment with steep slope shows more erosion and associated headward extension of gully heads with toppling failure; the channels are partially filled at lower catchment by sediments brought from upslope; channel network is frequently changed by adjustment with the continuously changing distribution and redistribution of mass (sediments) with variation in availability of energy (power) within the basin

GEOGRAPHIC AND GEOMORPHIC SETTINGS

The current research has been carried out in the lateritic western part of West Bengal, India, on the bank of river Kossi. A representative Rangamati Gully catchment of 256 sq m (22° 24' 42.0 "N to 22° 24' 43.2 "N and 87°17'48. 1" E to 87°17'48. 09" E) from this region was selected for present study (Fig. 1). A tropical, monsoonal climate prevails in with mean annual temperature of around 28.4°C and the average summer (May) and winter (December) temperatures of 40.9° and 7.5°C respectively. The mean annual rainfall is about 1850 mm. Rainfall distribution is irregular, experiencing high-intensity rainstorms during June to September (i.e., >125 mm/h over short periods), with high erosive potential (the rainfall erosive factor *R* varies between 1200 and 1500 MJ mm/ha/h year). The major part of soil profiles has been truncated by hydraulic erosion and underlying horizons constitute, at present, the top layers (Shit and Maiti, 2008). One of the main characteristics of the area is the dissection of the landscape by a dense and deep network of rill and gullies. Inter-gully areas are usually undulating and rolling. The average slope of this area is between 25 and 35%. The most frequent landforms are complex slopes and gullies. The rills are characterized by vertical sidewalls of 7 -13cm and are 90 cm wide. Rill has a high degree of lateral as well as head retreat. The nick points, developed at the vertical head near the source, sometimes show the tension cracks for toppling, where centre of gravity overlies the centre of mass (Shit and Maiti, 2008). Sediment mobilized from the walls and vertical heads is usually removed by flowing water during high intensity rainstorms. In other cases, the sediments are deposited on the walls or on the gully bottom, which may lead to some degree of stabilization. Major part of the destabilized sediment is deposited at the lower catchment that makes the gully discontinuous. Major shift of the channels and junctions are observed on these deposits in response to the variation of discharge and load.

BACKGROUND AND MATHEMATICAL DEVELOPMENT

The regularity of the angular relations at stream junctions was recognized early in the development of geomorphology by Playfair (1802) who noted that "….. this law is in general observed, that where a higher (steeper) valley joins a lower (gentler) one, of the two angled which it makes with the latter, that which is obtuse is always on the descending side; a law that is the same with that which regulates the confluence of streams running on a surface nearly of uniform inclination" (Howard, 1971). Horton (1932, 1945) proposed, for the first time, that the junction angle (Ø) depends solely on the ratio of main stream gradient to that of the tributary Eq. (1).

$$Cos\varnothing = S_m / S_t \tag{1}$$

where, S_m and S_t are the gradients of the main and tributary streams, respectively.

Lubowe (1964), after testing Horton's model concluded that it is predictive of the junction angles close to actual 'except for the junction of streams of the same order' with same gradient.

Howard (1971c) modified Horton's model and divided the junction angle (T) into two by extending the receiving link up slope and are named as E_1 & E_2 in correspondence to the joining link 1 and 2, respectively. The receiving stream is marked as link 3. The angle E_1 and E_2 are calculated following Horton's rule:

$$T = E_1 + E_2 \tag{2}$$

where,

$$CosE_1 = S_3 / S_1 \tag{3}$$

$$CosE_2 = S_3 / S_2 \tag{4}$$

The entrance angle E_1 *and* E_2, measured in the horizontal plane, lie between the prolongation of the receiving stream at each junction and the smaller and larger tributaries, respectively and S_1, S_2 and S_3 are the gradients of the smaller and larger tributaries and the receiving stream, respectively.

Howard (1971) suggested for minimum power function in connection to the flow geometry in transport network. These links will join at a point where the total power cost (Ω) is minimum and is calculated by the sum of the costs per unit length (C_i) over three links multiplied by the segment length (L_i):

$$\Omega = \sum_{i=1}^{3} CiLi \tag{5}$$

$$CiLi = \rho g Q_i S_i \tag{6}$$

where,

ρ = Fluid density

g = Gravitational acceleration

Q_i = discharge flowing through the channel segment

S_i = Channel gradient

Mosley (1976) proposed that the junction angle responds to the velocities of incoming links to conserve lateral momentum of the incoming flows:

$$Q_1 V_1 \sin E_1 = Q_2 V_2 \sin E_2 \tag{7}$$

where, Q_1 and Q_2 are the discharge of tributary 1and 2; E_1 and E_2 are the angles (Howard, 1971c).

Roy (1983) and Woldenberg and Horsfield (1983, 1986) linked minimum power with the junction angles being independent of the lengths *(Li)*.

$$CosE_1 = \frac{(C_3^2 + C_1^2 - C_2^2)}{2C_1C_3} \tag{8}$$

$$CosE_2 = \frac{(C_3^2 + C_2^2 - C_1^2)}{2C_2C_3} \tag{9}$$

where, C_1, C_2 and C_3 are the weights per unit length assigned to the smaller and larger tributaries and the receiving stream, respectively.

The discharge from the tributaries is considered to be collected along the receiving link through continuity equation:

$$Q_3 = Q_1 + Q_2 \tag{10}$$

A symmetry ratio is thus proposed for determining the variable hydro-geomorphic conditions along the tributary links.

$$\alpha = Q_1 / Q_2 (where, Q_1 \leq Q_2) \tag{11}$$

and Eq. (8), (9), (10) and (11) are combined to obtain:

$$CosE_1 = \frac{(1+\alpha)^{2X} + \alpha^{2X} - 1}{2\alpha^{X}(1+\alpha)^{X}} \tag{12}$$

$$CosE_2 = \frac{(1+\alpha)^{2X} + 1 - \alpha^{2X}}{2(1+\alpha)^{X}} \tag{13}$$

where,
X = The exponent

Following Eq. (2), the combination of E_1 and E_2 gives rise to the junction angle (T).

MATERIALS AND METHODS

The initial drainage network as on March, 2007 was mapped in details, by Total Station, tape, compass and level. The links and their junctions were numbered and given the permanent identity for keeping the records and monitoring the changes over time. The additional and decayed links and junctions were also recorded. The repetitive field surveys since 2007 were made to monitor the changes and to assess the mechanism involved in such changes. Major changes were recorded during the surveys on 2nd September, 2007, 26th June, 2009 and 12th September, 2009. The junction angles were measured in the field following Jarvis (1976) and Flarity (1978) to monitor the angular components of the drainage network. The angle of junction was studied following Schumm (1956) to understand the nature of association among the factors operating at or near the junctions, responsible for spatio-temporal change in junction angle and its position. The gradient of each link above each junction was monitored prior and after the high intensity rains and were recorded to monitor any change in response to relative erosion and deposition within the channels. The

Fig. 2: (a) Monitoring junction angle and gradient of the merging links in field, (b) measurement of infiltration in field through a plot of 1×1 feet area with regulated supply of water for duration of 5 h. until a constant rate is reached following (Goudie, 1990), (c) collection of water and sediment discharge at the gully mouth during a rain, recorded by rain gauge. The infiltrated water was also collected simultaneously from the base of a representative plot (1 m × 1 m) set the field with an average gradient for comparison with the former. Only little variation is observed between these two methods, (d) Monitoring discharge by setting 'V' notch at each junction connected with the bottles for collection of entire flow of water and sediment; the rain input is recorded in the field with recording type rain gauge

gradient (S) and discharge (Q) of the incoming links above each junction are measured in the field respectively by clinometers and 'V' notch set with impermeable clay (Fig. 2). The discharge from the prominent rains (quantified at the field by rain gauge, Fig. 2 was collected at each confluence and it's recorded. The rate of infiltration was measured in the field following Goudie (1990) (Fig. 2B). The collected discharge was analyzed to quantify the water and sediment component, in relation to rain intensity, contributing area, gradient and stream power (Torri *et al*., 2006). The shifting of the confluences was monitored by pegging techniques and associated change in junction angles were recorded and linked with relative importance of erosion and deposition at confluences. The mechanism of change in junction angle and shift of the confluence was studied through plot experiment under simulated rain condition (Gomez and Mullen, 1992; Berger *et al*., 2010) (Fig. 7). The plot of 1m x 1m is prepared with the soil collected from concerned study area and is exposed in open air for nearly six months for sufficient compaction in an attempt to prepare a situation similar to that of field area. The rain is dropped from 5 m distance over head at the constant intensity that is observed during last five years on an average. The plot was set at 20° initial gradient, the average of the field area. The experiment was continued for seven hours. The changes in the network as well as junctions were recorded at 1 h interval and mapped accordingly. The prediction of angles of junction are made following Horton (1932, 1945), Lubowe (1964), Howard (1971, 1971c) and Roy (1983). The observed data were used for calculating expected confluence angles after Horton (1945), Howard (1971, 1971c) and Roy (1983). The comparative validity testing of the models were made by comparing the expected angels to that of observed using SPSS software.

THE RESULTS AND DISCUSSION

Network dynamics: The gully basin under study showed remarkable change in the network that were revealed during field survey. These changes were episodic in nature and occurred in response to threshold conditions and were observed after catastrophic rains. The spatial variation in the network dynamics was linked with watershed zones. Maximum rate of lengthening of the links by headward extension were observed in sediment source zone (Laity and Malin, 1985). Minor channels were developed by concentration of overland flow that developed fresh bifurcation and branching during monitoring period. The sediment and water transfer zone depicted the change in confluence angle as well as width and depth of the channels. The depth was increased at the upper catchment but decreased at the lower section due to partial filling. The channel network showed constant adjustment to the changing conditions brought by the high intensity rains (Bruno *et al*., 2008). The angular component of the network, the confluence angle, was changed in response to the intensity of erosion and deposition near the confluence and surrounding region. Except for few junctions most of the angles registered a positive growth during the rains in 2007 and these were decreased by June, 2009 and subsequently increased in the rainy days of 2009. Additional links the mainly shoe-string gullies were developed from gully wall and some of the minor links were obliterated by cross grading also (Shit and Maiti, 2009). The link OP was obliterated due to cross grading of GB along its right bank during June- September, 2009 (Fig. 6A, B).

Fig. 3: The gully basin under survey, as on 09.03.2007 showed the orientation of links and distribution of junctions

The sediment sink zone, the lower reach, being characterized with low gradient, showed huge sedimentation and resultant closure of earlier channels and subsequent re-excavation during intensified rain. The prominent braiding was observed during post monsoon (September) of 2007 and after wards more sediment was deposited to cover the entire architecture. Two prominent channels were re-established leaving the debris at the centre thus the deposits are getting larger and higher by both lateral and upward growth (Fig. 3).

Confluence hydrology: All the confluences were monitored for a quite long duration. The result of recent survey on 12th September, 2009 is presented in Table 1. Discharge at the junction point largely depends on the contributing area of the merging streams, gradient and permeability of the catchment. The hour wise rain fall data was not available and so the arrangement was made to record the rain intensity at field by recording type rain gauge (Fig. 2C, D) Simultaneous measurement of infiltration and runoff (Fig. 2B, C) were taken to correlate with rain input. The records of the results at each junction point was arranged

Table 1: Hydro geomorphic characters of the confluences during a catastrophic rain (17.64 mm/h) on 12th September, 2009 with initial infiltration rate of 11 mm/h, and terminal rate of 1.2 mm/h; confluence ‘I’ and ‘K’ received huge water discharge as a result of larger contributing area; inspite of smaller catchment area, sediment yield is high at ‘C’ junction

Junctions name	Receiving stream		Tributary stream		Gradient (along the joined flow)	Contributing area m^2(during natural flow)	Channel width (cm)	Channel depth (cm)	Junction angle in degree	Water discharge (cm^3/sec)	Sediment Yield (kg m^2)
	Links	Gradient	Links	Gradient							
C_{20}	C_{20} J	11	$C_{20}N_{20}$	25	8	11.813	22	4.5	72	9.793	0.029543723
C_{21}	C_{21} J	8	C_{21} N_{21}	28	16	5.310	30	5.6	62	2.916	0.064971751
C_{25}	C_{25}J	20	C_{25} N_{25}	48	22	4.350	14	2.2	62	2.302	0.056469433
C_1	C_1 J	18	C_1 N_1	35	20	4.073	17	4.2	58	1.854	0.049908925
C_2	C_2 J	24	C_2 N_2	44	23	2.745	16	2.8	62	1.614	0.415308642
C_{26}	C_{26}J	24	C_{26} N_{26}	42	28	2.104	17	2.2	56	1.375	0.072222222
C_3	C_3 J	20	C_3 N_3	47	24	2.025	12	4.0	70	0.949	0.000517129
C_4	C_4 J	29	C_4 N_4	35	24	1.800	18	4.6	69	0.625	0.009284776
I	I B	7	I J	9	6	243.653	22	4.5	65	63.122	0.006791778
G	G B	10	GH	14	6	54.067	28	13.4	53	44.219	0.021668397
C_{23}	C_{23}H	14	C_{23} N_{23}	16	8	16.785	32	3.4	65	14.584	0.111689351
C_6	C_6H	12	C_6 N_6	18	13	14.445	26	9.6	72	10.937	0.162145242
C_7	C_7 N_6	29	C_6 N_6	30	25	2.498	20	6.0	56	3.333	0.014347079
C_5	C_5H	35	C_5 N_5	40	34	4.792	14	3.0	36	3.021	0.001360456
C_8	C_8 B	10	C_8 N_8	15	15	34.920	17	4.0	62	21.875	0.006500389
E	E B	40	EF	53	30	28.306	9	7.4	25	2.917	0.327868852
C_{24}	C_{24} F	22	C_{24} N_{24}	30	25	4.478	33	3.2	-	5.253	0.063161663
C_9	C_9 F		C_9 N_9			2.745			75	1.979	0.028070175
E_1	E_1 B	10	E_1 F_1	35	8	19.553	25	3.8	55	11.458	0.101017861
C	C B	10	CD	14	20	12.825	35	2.0	75	9.031	1.108651087
C_1	C_1 B	25	C_1 D_1	32	22	5.207	21	4.7	45	5.313	0.001245724
C_{10}	C_{10}B	20	C_{10} N_{10}	42	22	2.439	14	1.2	65	3.385	0.007870507
K_1	K_1 B		K_1L			246.443			-	16.412	0.017638656
K	K B	6	KL	8	2	152.595	14	3.9	56	115.938	0.040502931
C_{22}	C_{22}L	6	C_{22} N_{22}	9	4.5	80.505	30	4.0	50	27.605	0.037690747
V	V L	14	VU	18	10	35.977	15	4.0	60	10.833	0.314336918
C_{13}	C_{13}U	12	C_{13} N_{13}	17	14	8.370	11	1.8	36	0.73	0.155824508
C_{19}	C_{19} U	22	C_{19} N_{19}	23	12	5.288	105	2.9	70	0.391	0.065418227
C_{11}	C_{11} U	22	C_{11} N_{11}	26	12	4.005	105	3.0	65	0.260	0.191423002
C_{12}	C_{12} U	36	C_{12} N_{12}	45	21	2.565	12	1.8	52	0.167	0.010107015
M	ML	14	MN	17	7	70.785	16	3.4	62	25.00	0.614965986
T	TL	10	TS	19	10	13.456	11	2.8	60	10.105	0.147311828
C_{14}	C_{14}S	20	C_{14} N_{14}	35	22	2.205	18	3.0	72	1.395	0.642374789
C_{15}	C_{15}L	11	C_{15} N_{15}	26	22	5.580	16	3.0	50	4.583	0.034023464
X_1	X_1L		X_1Y_1			3.554			-	2.670	0.045766289
C_{16}	C_{16}N	11	$C_{16}N_{16}$	22	8	14.490	20	3.0	-	5.209	0.123279817
O_2	O_2N	22	O_2 O_1	26	18	7.582	14	4.0	50	3.646	0.184182015
C_{18}	C_{18} N	32	C_{18} N_{18}	42	42	3.488	9	6.0	55	1.667	0.185185185
C_{17}	$C_{17}O_1$		C_{17} N_{17}			1.846			48	1.651	0.178837556

and linked with other hydro-geomorphic elements like contributing area, channel width, channel depth at junction, gradient, water discharge from the particular rain, sediment yield etc following Roy and Sinha (2007) (Table 1).

The tributary following steep gradient supplied more sediment at junction (Vanwalleghem *et al*., 2005). The monitoring at each junction through tapping the water and sediment yield did not allow measuring the contributions from upslope junctions and thus the contribution of the concerned tributary and limited part of the receiving stream just below the tapped junction was responsible for the results recorded at each junction (Table 2). The gradient and discharge along the tributary thus played important role in sediment yield at each junction. But during natural flow, successive downstream junctions experience discharge from additional larger cumulative contributing area. The deposition or erosion at the junction were controlled by the amount of sediment yield and associated conditions for removal power guided by the discharge and gradient (Best, 1986; Rice *et al*., 2001, 2006). The possibility of confluence migration depends on the intensity of sediment yield and cross section area that accommodates this sediment and the power of the stream for removing this sediment (Howard, 1971; Mosley, 1976). Inspite of receiving greater discharge, the junction E, I and K showed huge deposition (Table 1) as the sediments could not be removed due to low gradient and so, these experienced considerable migration (Table 1).

Although the junctions like M, O_2, C_6 and T received considerable sediment discharge, efficient removal due to sufficient gradient developed erosion environment near the junction (Table 2) (Benda, 2008). Junction M, inspite of having low gradient, sufficient discharge helped to remove the sediment coming from large contributing area.

Confluence migration: Confluence point showed remarkable migration both up and down slope depending on the relative rate of erosion and deposition as well as orientation of incoming streams (Sanchis *et al*., 2009) (Fig. 10). Junction ‘V’ registered an upstream migration after the rainy season of 2009 as some catastrophic rain capacitated ‘VT’ link to

Table 2: Confluence dynamics: change in confluence angle and associated migration as a response to the change in length, width, depth, gradient and contributing area of the merging links; the junction 'E' showed considerable downstream migration due to huge deposition (up stream of junction) and associated shortening of links, reduction of width, depth, contributing area and confluence angle; a gradual downstream migration is also recorded at 'M' Upstream shifting of 'K' was recorded during 02.09.2007-26.06.2009 due to deposition and associated increase in mean length, width and contributing area of the links; gradient drastically decreased during that period; subsequently revamped energy started erosion with an increase of gradient, as a result, width and depth of the links; confluence angle decreased by three degree and the junction was shifted downstream

			Characteristics of confluence points in fluvial network (ephemeral gully)							Migration (cm)		
Confluences Points	Period (DD/MM/YY)	Max. rainfall intensity	Length Change (cm)	Mean width change (cm)	Mean depth change (cm)	Micro relief change (m)	Contributing area(m2)	Slope (degree)	Confluencesangle (deg)	Up stream	Down stream	Causes of confluence migration
I	09/03/07-02/09/07		30.19	29.73	4.94	3.79	95.177	6.5	35	x		
	02/09/07-26/06/09		43.51	63.0	4.67	3.67	241.259	3.0	69			
	26/06/09-12/09/09		26.05	20.5	4.50	3.32	243.653	10.5	51	x	15	deposition
C16	09/03/07-02/09/07		-	-	-	-	-	-	-	-	-	-
	02/09/07-26/06/09		6.45	12.5	3.5	1.93	14.917	19	60			
	26/06/09-12/09/09		5.75	15.5	3.0	1.78	7.582	20.5	50	40	x	Straightening of MN
V	09/03/07-02/09/07		20.43	27.12	5.34	3.46	68.330	15.0	30			
	02/09/07-26/06/09		17.40	15.00	4.53	3.43	48.645	12.5	56			
	26/06/09-12/09/09		13.94	17.50	4.00	3.35	35.977	13.5	30	57	x	Straightening of VL and deposition
E	09/03/07-02/09/07		8.79	30.90	9.45	1.20	24.230	13.5	45			
	02/09/07-26/06/09		8.71	37.00	7.64	1.18	25.852	15.5	60			
	26/06/09-12/09/09		7.30	39.50	7.4	1.08	28.306	14.5	56	x	210	deposition and subsequent erosion
G	09/03/07-02/09/07		16.70	25.07	14.86	3.12	55.575	11.0	58			
	02/09/07-26/06/09		16.74	30.50	19.42	3.07	55.117	19.0	47			
	26/06/09-12/09/09		14.50	36.50	13.40	2.94	54.067	19.0	49	x	23	erosion
C7	09/03/07-02/09/07		1.50	17.53	6.81	0.55	2.317	25.5	40			
	02/09/07-26/06/09		3.22	21.5	6.45	0.52	2.385	27.0	30			
	26/06/09-12/09/09		2.32	10.5	6.00	0.50	2.498	30.5	25	x	10	erosion
M	09/03/07-02/09/07		15.88	18.07	4.95	2.85	39.982	12.0	32			
	02/09/07-26/06/09		21.67	24.00	3.91	2.74	40.365	16.5	65	x	125	erosion
	26/06/09-12/09/09		18.05	29.00	3.40	2.65	70.785	8.5	55	x	30	erosion
O2	09/03/07-02/09/07		6.35	26.6	3.43	1.14	10.169	21.5	55			
	02/09/07-26/06/09		5.43	10.00	3.91	1.07	8.077	18.5	55			
	26/06/09-12/09/09		9.0	12.5	4.00	0.94	7.582	25.5	60	6.4	x	erosion
C6	09/03/07-02/09/07		6.46	21.05	7.25	2.95	15.119	20.0	45			
	02/09/07-26/06/09		7.88	18.50	11.21	2.64	11.270	21.5	60	13	x	erosion
	26/06/09-12/09/09		7.85	18.00	9.60	2.47	14.445	23.5	45	x	10	erosion
K	09/03/07-02/09/07		38.48	31.5	4.35	4.12	207.924	9.0	40			
	02/09/07-26/06/09		42.92	95.0	4.12	4.03	238.996	1.5	45	22	x	deposition
	26/06/09-12/09/09		39.35	49.5	3.90	3.90	246.443	2.5	42	x	60	erosion
T	09/03/07-02/09/07		9.30	25.76	3.20	2.65	12.734	17.5	36			
	02/09/07-26/06/09		9.73	18.00	2.98	2.55	12.286	15.5	50	x	12	erosion
	26/06/09-12/09/09		9.00	15.5	2.80	2.21	13.456	15.0	65	x	23	Erosion

straighten its flow. The angle at 'V' registered a growth of 100% from earlier 30°. The junction angle C_{16} showed up-slope migration due to straightening of link 'MN' (Fig. 9). The junction 'I' showed a remarkable variation due to huge deposition and subsequent re-excavation (Fig. 6A, B). The deposits covered the entire region during monsoon of 2007 and new shallow channels were developed on the deposits. The link IJ took a further downstream journey avoiding the deposits to join the mainstream at a downstream location. During June, 2009 it was observed that the link GI took a straight course to join IJ at I_1. After the rain in 2009, in September, all the minor channels were obscured and former orientation, as observed on 09.02.2007, that conveyed the entire contribution of IB segment to JK section, was reestablished. Migration of the junction angles, I, set remarkable variation in confluence hydrology also. Huge deposition and associated avulsion of 'IJ' link during Sept., 07 to June, 2009 led to huge braiding and thus 'I' junction was shifted downstream and received the drainage from a huge additional area and as a response, its confluence angle was increased by almost 100%. The confluence angle 'I' registered a considerable reduction after wards.

The downstream migration of the junction angle was due to the lowering of confluence angles that creates a flow separation (Best and Reid, 1984) developing a condition of deposition near the confluence region. This raised the geomorphic surface between the two rivers and thus the confluence point moved and downstream migration of the junction was possible (Roy and Sinha, 2007). The junction 'I' revealed downstream migration associated to deposition above the junction, that caused the elevation of the inter-stream area during September, 2007 to June, 2009. The junction 'K' was pushed down ward by a huge deposit during monsoon, 2009 that obscured all the minor links. The earlier channel network was re-established causing a separation of IJ and KL to avoid the huge inter-stream deposition. In the present study, most of the upstream migrations of the junction points were observed in association to active deposition at the sediment sink zone. Huge deposition below the junction pushed the junction angle upstream (K) that indicated the inability of the flow to remove the deposits downstream on low gradient. The junction M registered remarkable migration due to active lateral erosion on the left bank of MN and thus a considerable change (>100%) in the junction angle was recorded. MN link became straight in this process during the monitoring period. Some of the other junctions registered downstream migration also. The junction E showed a remarkable downstream shift (210 cm) during monsoon, 2009. Channel EF shifted right ward by reexcavating its channel along the margin of the huge deposits that once covered the junction (Fig. 8). In this process, instead of joining AB directly, EF now contributes via a smaller tributary C_8N_8. The junction C_1 and C_7 migrated down slope by active erosion at confluence.

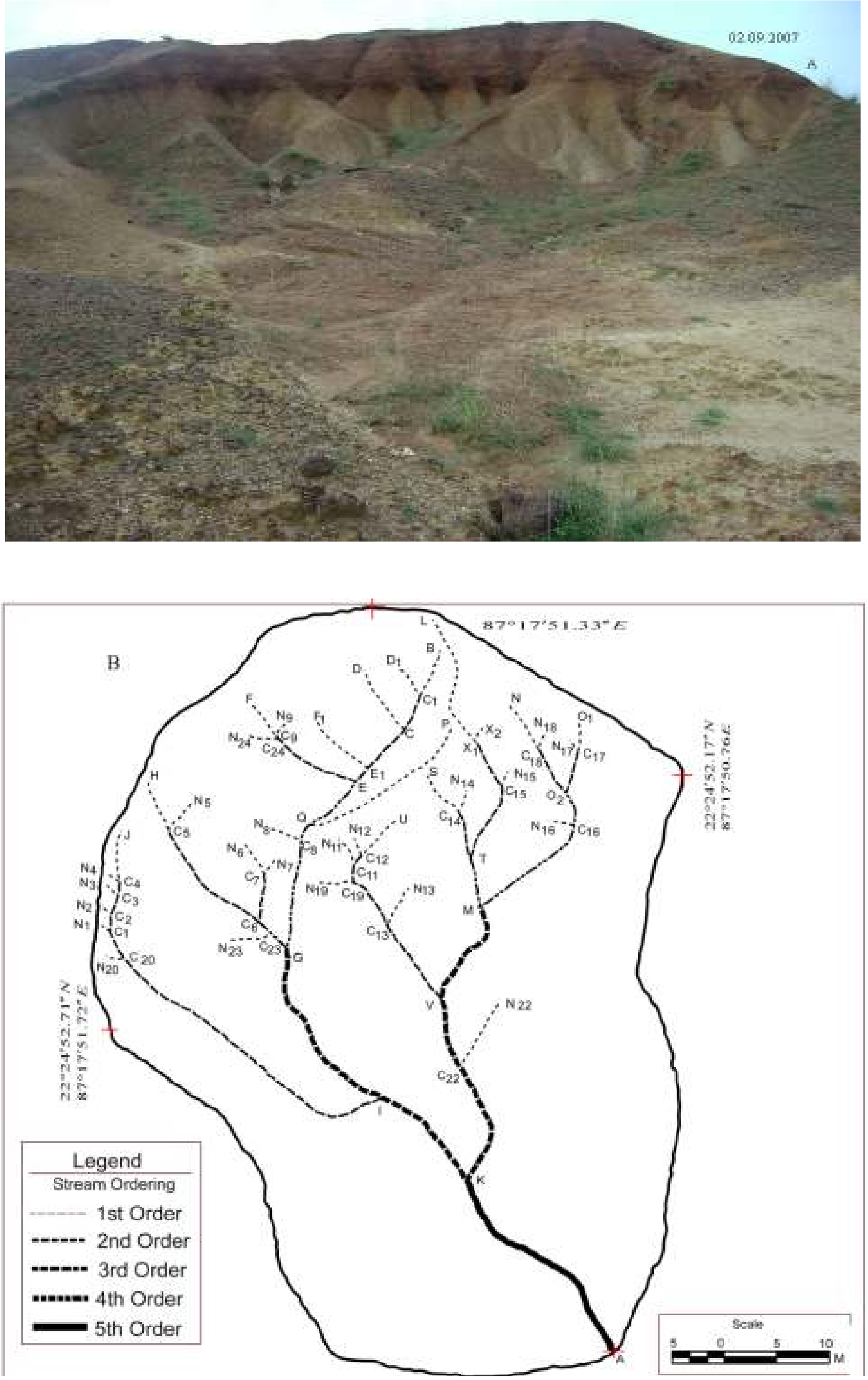

Fig. 4: (a) The gully basin as on 02.09.2007 showed remarkable change both at upper and lower catchments, (b)The additional branches were developed during the monsoon rain of 2007. Some of the links extended headward. The deposit led to braiding and the junctions at the sediment sink zone shifted downward.

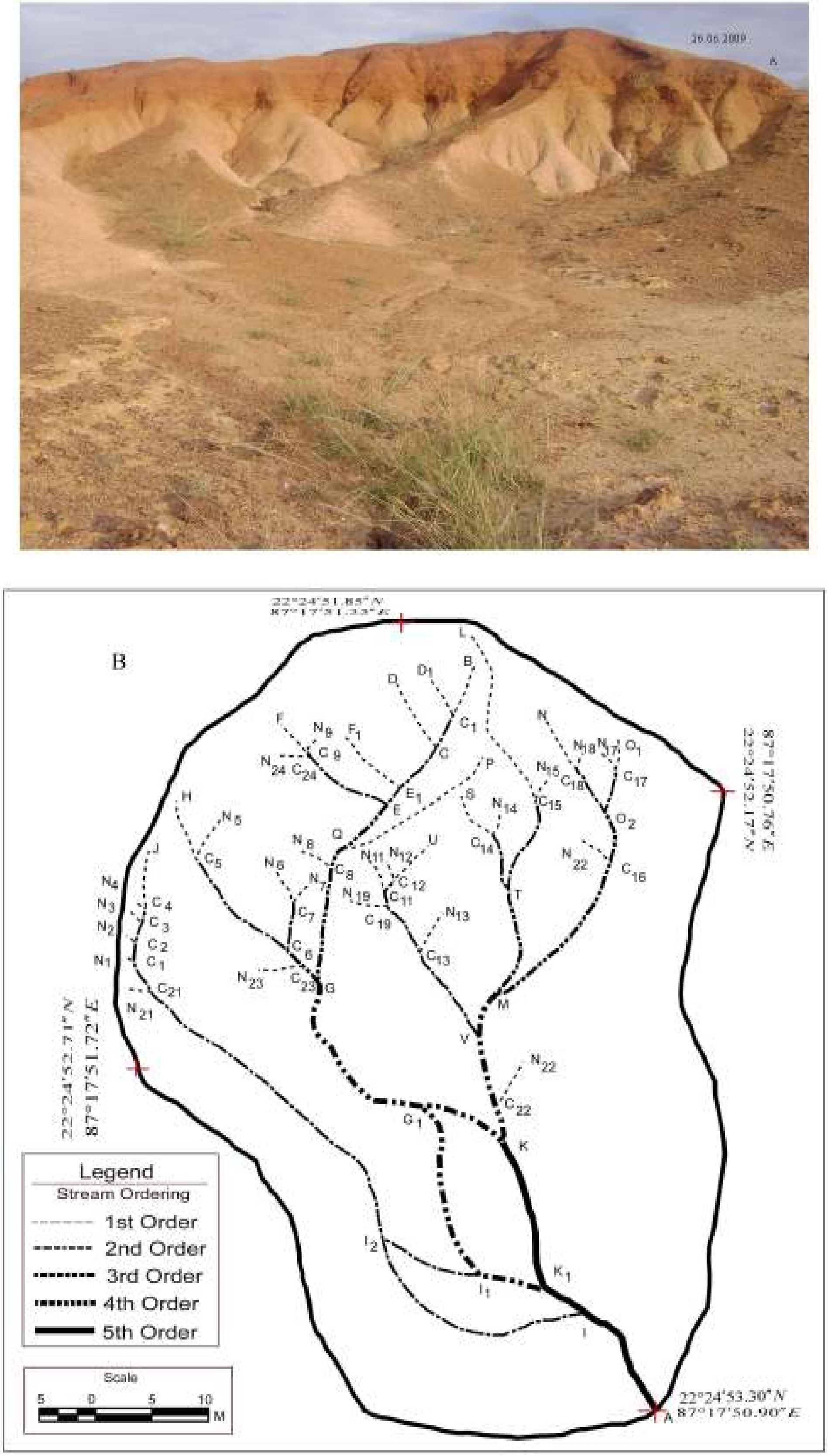

Fig. 5: By 26.06.2009 the basin experienced further braiding due to additional sedimentation at lower catchment

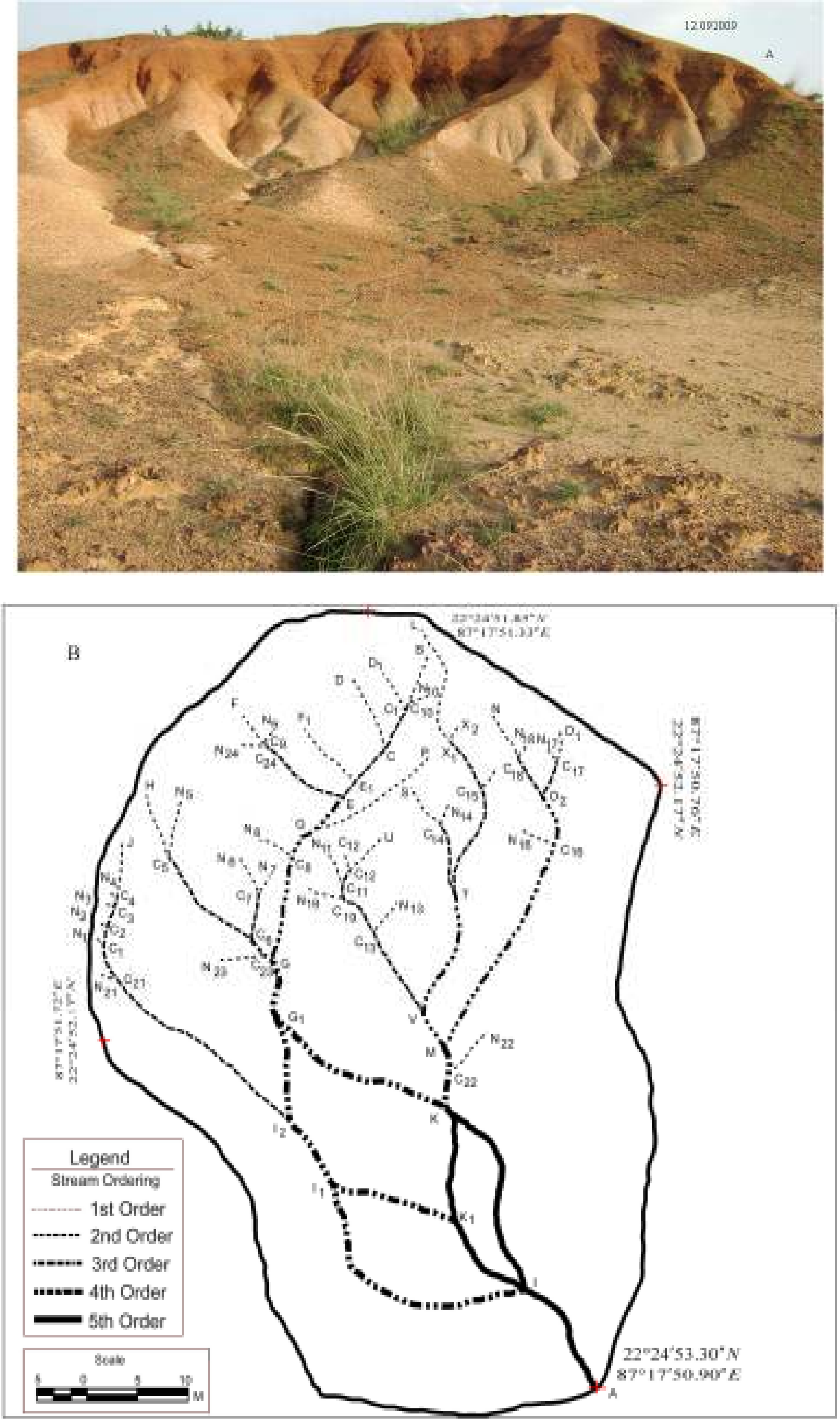

Fig. 6: Re-establishment of the earlier drainage orientation

In the present study the junction angles showed huge variation from time to time (Fig. 6A, B and Table 3). Any change in the relative gradient of tributary and mainstream and that of the discharge by flow intervention along both the streams might cause a change in the confluence angle. This in turn, might regulate the intensity of either deposition or erosion ultimately leading to the change of confluence angle. The variable intensity of rain might be responsible for such variation. Thus the shifting of junctions and associated change in the confluence angles are the results of variety of causes resulting from the association of relief, gradient, runoff contributing area and orientation of links that vary both spatially according to the location within a basin as well as temporally due to variation in rain intensity (Sanchis *et al*., 2009) (Fig. 3, 4, 5 and 6).

Plot experiment to monitor confluence angles: A plot experiment was done under simulated rain 16.5 mm/h on 1 m×1 m plot set at 20° gradient (Fig. 7 and Table 4). The soil from the concerned study area was collected and compacted for sufficient time to get the resistance comparable to that of the study area. During initial period, the sheet wash with laminar flow was dominant. The drainage links started developing by the concentration of runoff from upslope area at lower reach. Steady increases in the length of the links were

Table 3: Comparison of the accepted models for effective prediction of junction angle in the area under study shows that optimum junction model of Roy (1983) is better applicable for the present study area; the value of exponent (k) may be -0.20 to get better result; prediction with other models shows wide deviation from measured angle; analysis shows that for the smaller angles Horton's model is better predictive and Howard's model is better applicable for the larger angles

	09/03/07		02/09/07		26/06/09	
Junction Points	Actual Angle (ø)	Horton (1932, 1945)	Actual Angle (ø)	Horton (1932, 1945)	Actual Angle (ø)	Horton (1932, 1945)
C_{20}	40	64°07'	45	62°44'	55	63°26'
C_{21}	35	26°47'	75	61°29'	56	75°47'
C_{25}	-	-	-	-	-	-
C_1	45	71°02'	60	40°03'	35	52°36'
C_2	52	59°25'	70	34°35'	65	71°02'
C_{26}	-	-	-	-	-	-
C_3	70	68°38'	85	51°22'	75	61°01'
C_4	60	52°41'	70	47°35'	52	40°35'
I	35	51°30'	69	60°	51	60°29'
G	58	55°41'	47	70°37'	49	60°19'
C_{23}	62	75°54'	75	60°	50	56°40'
C_6	45	54°55'	60	66°25'	45	44°24'
C_7	40	43°12'	30	39°32'	25	45°50'
C_5	35	50°40'	55	48°39'	28	46°31'
C_8	40	81°22'	70	64°24'	55	66°40'
Q	56	63°14'	35	68°39'	50	54°55'
E	45	54°46'	60	51°52'	56	53°15'
C_{24}	55	63°33'	40	59°57'	50	56°14'
C_9	52	48°14'	85	53°48'	55	56°14'
E_1	70	84°00'	65	70°19'	70	56°22'
C	50	74°22'	60	67°24'	75	33°36'
C_1	60	46°48'	57	50°55'	50	40°35'
C_{10}	45	57°20'	60	51°46'	52	39°59'
K_1	-	-	45	48°11'	60	54°42'
K	40	37°9'	50	44°33'	42	48°12'
C_{22}	46	45°51'	48	51°30'	54	44°33'
V	30	61°1'	56	54°16'	30	54°46'
C_{13}	45	58°15'	68	53°01'	65	32°51'
C_{19}	70	54°55'	65	56°20'	52	40°32'
C_{11}	62	64°17'	68	66°10'	61	57°34'
C_{12}	47	50°54'	50	48°39'	42	36°53'
M	32	32°39'	65	69°09'	55	45°51'
T	36	67°46'	50	57°43'	65	60°00'
C_{14}	65	33°26'	65	63°30'	56	42°34'
C_{15}	52	48°22'	56	51°19'	66	33°35'
X_1	-	-	42	46°03'	40	38°37'
C_{16}	-	-	60	60°19'	50	64°15'
O_2	55	59°44'	55	48°27'	60	43°12'
C_{18}	55	60°16'	50	45°28'	42	38°29'
C_{17}	22	21°23'	40	36°20'	30	37°22'

Table 3 (Continue)

12/09/09

					Roy (1983) OJM X = 1+K				
Junction Points	Actual Angle (ø)	Horton (1932, 1945) GM	Howard (1971) GM	Howard (1971c) MPLM	Symmetry ratio	K = -0.15	K = -0.20	K = -0.25	K = -0.4
C_{20}	72	65°21'	124°12'	-	0.033	60.78	67.93	73.52	84.85
C_{21}	62	57°21'	55°09'	63°41'	0.216	53.85	61.36	67.69	82.38
C_{25}	62	-	-	157°11'	0.105	56.30	63.69	69.77	83.28
C_1	58	58°40'	84°53'	133°39'	0.047	59.38	66.62	74.37	84.38
C_2	62	62°32'	75°04'	77°11'	0.107	57.85	64.62	69.71	83.25
C_{26}	56	-	-	122°56'	0.100	56.48	63.86	69.92	83.33
C_3	70	70°09'	93°18'	94°58'	0.138	55.43	62.76	68.74	82.93
C_4	69	37°39'	80°50'	98°35'	0.199	54.12	61.50	67.90	82.47
I	65	39°10'	78°11'	79°15'	0.500	51.85	59.48	66.00	64.38
G	53	33°56'	113°07'	116°40'	0.516	51.90	59.43	65.96	81.62
C_{23}	65	29°35'	115°09'	180°56'	0.167	54.67	62.14	68.38	82.68
C_6	72	49°08'	101°24'	103°56'	0.750	51.43	59.04	65.61	81.48
C_7	56	16°14'	64°00'	65°21'	0.600	51.65	59.24	73.27	81.55
C_5	36	33°26'	44°30'	46°29'	0.611	51.62	59.22	65.77	81.53
C_8	62	48°50'	94°38'	112°29'	0.167	54.67	62.14	68.38	82.68
Q	75	45°35'	100°00'	-	-	-	-	-	-
E	25	50°46'	96°55'	-	0.037	60.33	67.50	73.15	84.70
C_{24}	-	-	-	-	-	-	-	-	-
C_9	75	45°35'	100°00'	100°03'	0.652	51.70	59.15	65.71	81.52
E_1	55	75°24'	113°39'	114°38'	0.222	53.77	61.28	67.62	82.35
C	75	62°41'	79°57'	80°33'	0.405	52.28	59.84	66.32	81.78
C_1	45	48°39'	110°42'	126°00'	0.275	53.18	60.71	67.10	82.11
C_{10}	65	46°48'	96°18'	103°38'	0.230	53.67	61.18	67.53	82.30
K_1	-	-	-	-	-	-	-	-	-
K	56	41°35'	108°11'	109°49'	0.484	51.95	59.53	66.05	81.67
C_{22}	50	35°25'	89°48'	-	0.060	58.43	65.71	71.57	84.05
V	60	22°11'	84°06'	159°44'	0.130	55.53	62.96	69.11	83.00
C_{13}	36	19°19'	81°28'	81°46'	0.751	51.43	59.04	65.61	81.21
C_{19}	70	17°51'	115°29'	-	0.249	53.45	61.00	67.33	82.23
C_{11}	65	34°04'	119°26'	-	0.250	53.43	60.95	67.32	82.21
C_{12}	52	43°24'	116°28'	117°21'	0.605	51.63	59.24	65.78	81.55
M	62	35°21'	125°41'	125°54'	0.714	51.46	59.08	65.64	81.48
T	60	44°47'	114°16'	129°8'	0.293	53.00	60.55	66.96	82.05
C_{14}	72	37°39'	91°42'	99°30'	0.489	51.91	59.51	66.03	81.65
C_{15}	50	42°21'	122°51'	-	0.047	56.58	66.62	72.37	84.38
X_1	-	-	-	-	-	-	-	-	-
C_{16}	-	-	-	115°02'	-	-	-	-	-
O_2	50	34°04'	81°16'	81°24'	0.750	51.43	59.04	65.61	81.48
C_{18}	55	21°15'	62°30'	63°27'	0.560	51.74	59.32	65.86	81.58
C_{17}	48	16°14'	64°00'	-	0.250	53.43	60.95	67.32	82.22

observed by mainly headward growth (Bryan and Poesen, 1989). Bifurcation at source and branching along the valley side maintained the law of Tran's link development that is expected on homogeneous slope and materials. The network development at an interval of one hour were recorded and mapped accordingly to monitor the position and angular value of the confluences. The study showed that lower most junctions like A and C experienced downstream migration at a rate of 0.2-0.5 cm/h (Fig. 7). As the other factors remained constant, the duration of exposure to stress (rainfall) of certain intensity seemed to be important in the variation of network. Through the plot was set at a constant angle (20°), the local variation in the redistribution of materials according to availability of power was responsible for micro scale difference in the gradient. This distribution pattern also varied with time. The materials once deposited at one confluence, started shifting after attaining critical power and so no confluence showed a constant situation of either erosion or deposition. Thus within constant slope, lithology and rain, local variation in the gradient led to the variation in the distribution of energy (Wirtz *et al*., 2012). This spatio-temporal variation in energy distribution was responsible for the change in the confluence angle (Torri *et al*., 2006).

Prediction of junction angle: There is an increasing need for predicting drainage network characters, specially the angular component, that regulates the flow

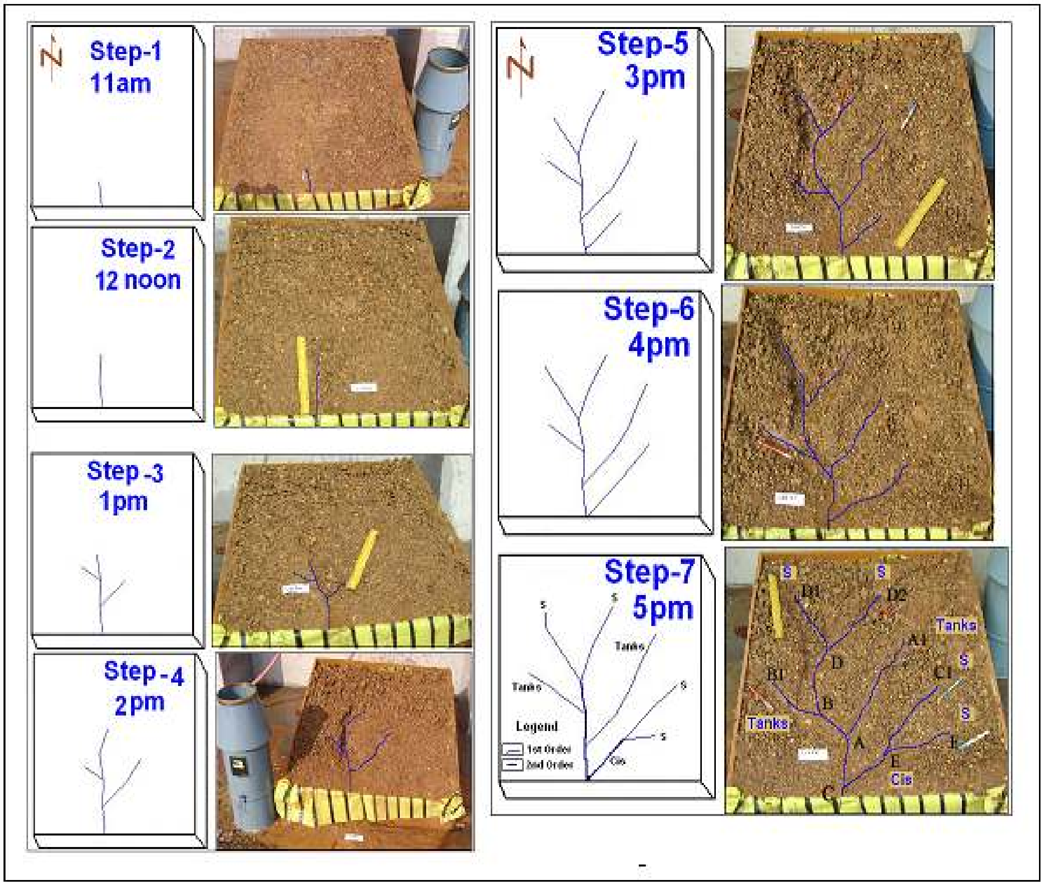

Fig. 7: The plot experiment for monitoring the mechanism of channel development under constant rain on homogeneous gradient and soil; channelization starts after 2 h of sheet wash; branching started after another one and half hours after initiation of channels. Branches are developed from both sides of main channel showing the mode of 'Trans links' development due to homogeneous lithology and gradient. Network extends over entire plots in a manner to have equal catchment per unit length of link

Table 4: Plot experiment on a 1 m x 1m plot set at 20° slope gradient, under simulated rain of 16.45 mm/h showed uniform sheet wash for initial 2 h. Since then gradual extension of channels by head ward erosion and branching were observed. In order to adjust with variable situation of either erosion or deposition junction angle changes; confluence points gradually shifts downstream to get adjusted with dynamic discharge and gradient; infiltration rate ranging from 5.8-1.2 mm/h

		Receiving stream			Tributary stream				
Period (Time)	Confluence points	Name	Length (cm)	Gradient (deg)	Name	Length (cm)	Gradient (deg)	Junction of angle (deg.)	Down stream migration during 1 h.
10- 11am		Sheet wash							
11 12noon		Sheet wash							
12-1 pm	A	AB_2	21	10	AA_1	15	12	45	
	B	BB_2	10.5	11	BB_1	10	13	54	
1-2 pm	A	AB_2	31.7	10	AA_1	25	12	40	1.0 cm
	B	BB_2	18.7	11	BB_1	8.3	13	56	
2-3pm	C	CD_2	67.48	10	CC_1	20.8	12	52	
	A	AD_2	55	12	AA_1	41.6	14	45	0.5 cm
	B	BD_2	42	14	BB_1	18.72	17	51	
	D	DD_2	29	15	DD_1	10	19	56	
3-4 pm	C	CD_2	71.04	09	CC_1	41.6	11	42	0.4 cm
	A	AD_2	58.56	12	AA_1	52	13	41	0.5 cm
	B	BD_2	44	13	BB_1	22.88	15	43	
	D	DD_2	30	16	DD_1	29.12	18	58	0.3 cm
4-5pm	C	CD_2	83	09	CC_1	60	10	50	0.2 cm
	A	AD_2	68	10	AA_1	62	11	45	
	B	BD_2	53	13	BB_1	32	14	50	
	D	DD_2	38	16	DD_1	37	17	55	
	E	EC_1	35	13	EF	15	14	40	

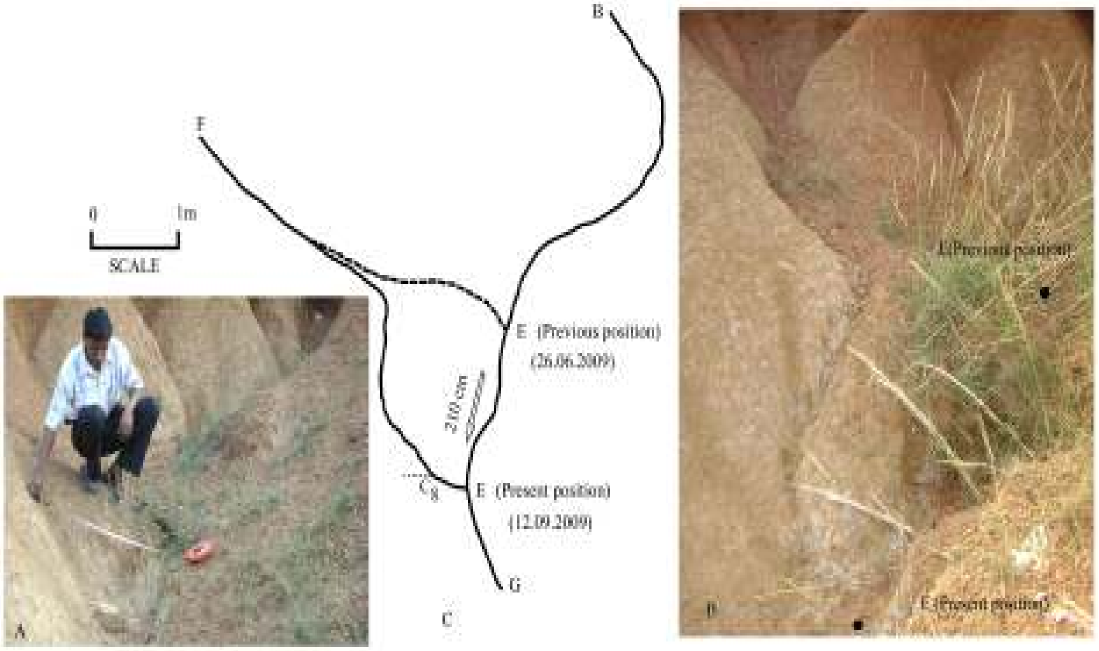

Fig. 8: (a) Earlier junction of EF with parent stream AB as surveyed on 26.06.2009, (b) huge deposits covered the earlier junction E, (c) in response to the catastrophic rain of 12th Sept. 2009. A huge deposit was observed at the confluence. Channel was with forced to shift right ward, to avoid the deposit. Avulsion of EF thus shifted the confluence downward by 210 cm. Instead of direct contribution to the parent stream AB, EF was observed to join C_8M_8 on 12.09.2009

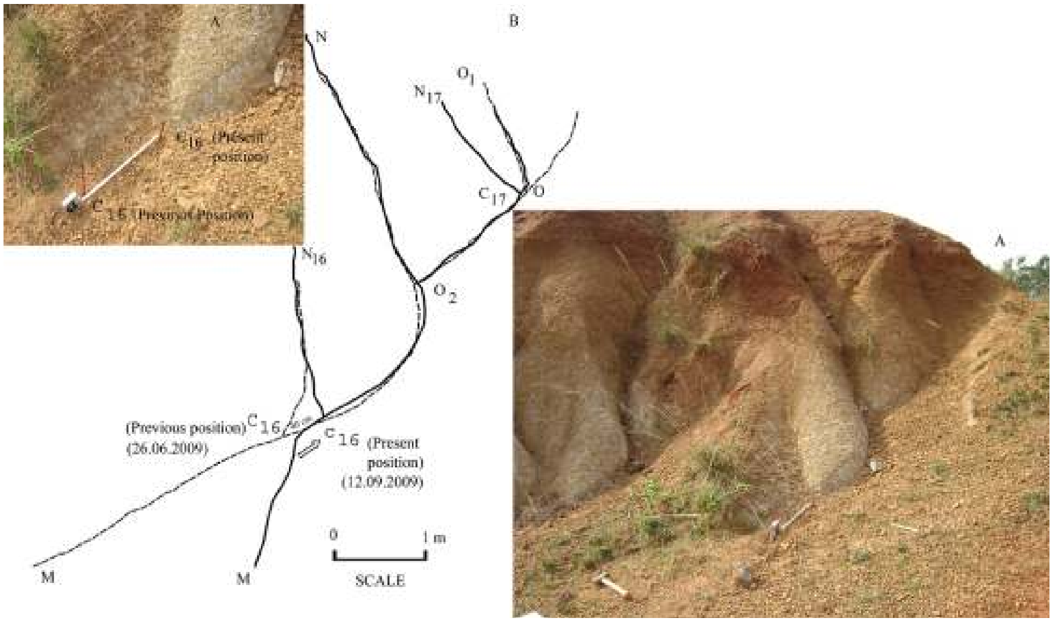

Fig. 9: (a) Huge rain on 12th Sept. 2009 capacitates the link C_{16} N_6 to straighten its course, (b) the confluence C_{16} is shifted upstream by 40 cm in this process of straightening of course

of mass and energy from upper to lower catchment as well as the confluence character (Poesen *et al*., 2003). Confluence angles largely depend on the gradient and discharge of the tributary and those of the main streams. Following Horton (1945) and Howard (1971) wider angle is related to steeper tributaries where as lower angle is associated to the incoming links of equal gradient. The confluences with wider angles are more dynamic and susceptible to migration and flooding, where as the confluence with low junction angles are more stable (Roy and Sinha, 2007). The flow characters and morphology of a junction is controlled by the

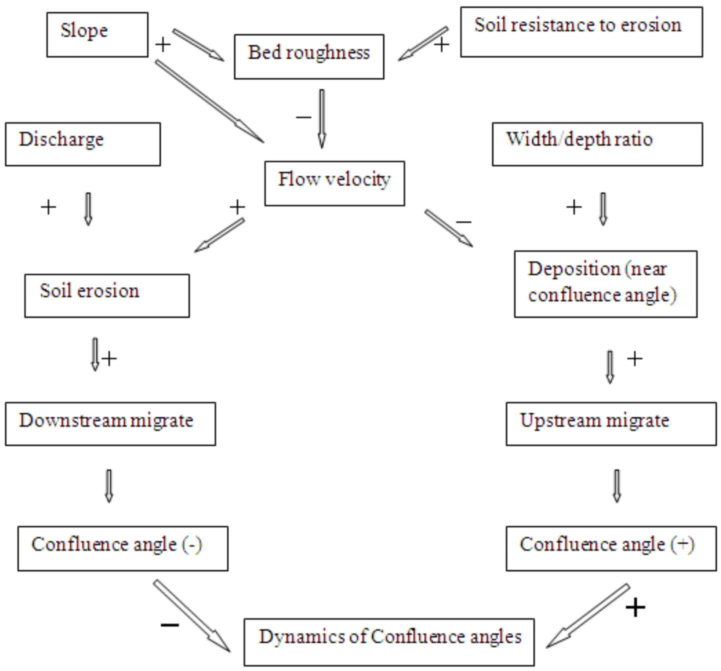

Fig. 10: Conceptual model of the factors influencing Confluence angle in rills or gullies; the increase in gradient leads to greater flow velocity along the links; being assisted with greater discharge, the streams are capacitated with greater power to carry on active erosion at the confluence that leads to lowering of confluence angle and downstream migration; the deposition at confluence, on the other hand, is facilitated by reduction in gradient and resultant reduction in velocity; this favours in increasing confluence angle and associated upstream migration

symmetry ratio, junction angle, gradient of the incoming streams, discharge ratio, zone of flow separation and bank stability (Mosley, 1976; Roy, 1983, 1985; Best, 1988; Bristow *et al*., 1993; Roy and Sinha, 2007).

The observed data collected on 09-03-2007; 02-09-2007; 26-06-2009 and 12-09-2009 are calibrated to the model proposed by Horton (1945), Howard (1971, 1971c) and Roy (1983) and expected angles are calculated. The analysis of validity of models, efficient to predict junction angles for the present study area shows that optimum junction model Roy (1983) is more valid considering the value of exponent (k) of -0.20. The discharge is considered as the product of a number of hydro-geomorphic factors. The ratio between the discharge of minor (Q_2) and major tributary (Q_1), the “symmetry ratio” proposed by Roy (1983) is thus taken as an important criteria to determine the confluence angle (Roy, 1983; Best, 1988; Benda, 2008). Roy (1983) experimented his model on large drainage network from Devon and the value of ‘k’ was estimated to be -0.4 and for the smaller basin, the value of ‘k’ was proposed to be -0.30 (Roy, 1985). However, in the present study on smaller ephemeral gully basin the values of ‘k’ become -0.20, (Table 3). Horton (1945) seems to be efficient for the angles of lower value where as Howard (1971) model is efficient to predict those of higher values.

CONCLUSION

The confluence may be considered as a comprehensive environment rather than a mare junction of links. The temporal variability of influx of sediment and water supply from the tributary basin to the main river essentially affect the environment and that is managed by the internal systematic interaction of rain intensity, gradient, channel width and depth that ultimately lead to either deposition or erosion (Fig. 10). This erosion and deposition changes the junction angles guided by the mechanism of flow separation. The present study reveals that erosion or deposition at the confluence also regulates its migration by changing in junction angles. The dynamic nature of confluence environment is associated to the threshold conditions which are episodic in nature. The change in confluence angles and related shift in the position of junctions associated to some catastrophic rainfall. During the study period (09-03-2007 to 12-09 2009) four catastrophic rains occurred on 7th July, 2007, 14th August, 2009, 6th September, 2009 and 12th September, 2009 with rain intensity of 10.53, 12.72, 7.70 and 17.64 mm/h, respectively. Close observation and continuous monitoring of the dynamic nature of drainage links and the confluence angles revealed that all the noticeable changes are occurred during these catastrophic events being separated by a long period of relative stability. Thus no average rate of change can be proposed.

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