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Study on Rock Characteristics for Assessing the Hydraulic Erodibility of Sandstones in the Manahari River Section, Sub-Himalaya, Central Nepal

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ABSTRACT

The long-term erosion of the bed rock is steered by the power of the stream of variable magnitude and frequency which would give us the idea about bed rock incision and its channel morphology. Large numbers of infrastructural development work such as roads, bridges are undergoing in the Manahari Area. Hence, hydraulic erosion of the rocks is always a topic of interest while carrying out these construction works. Therefore, the main aim of this study is to determine the hydraulic erodibility of the Siwalik rocks under the action of stream power. Erodibility of the rocks and the stream powers of the Manahari River were determined by extensive field survey and laboratory analysis of rock material properties. Rock mass strength, block particle size, discontinuity/inter-particle bond shear strength, the shape of materials units, and their orientation relative to the flow were assessed to determine erodibility of the rocks. The longitudinal and cross-sectional surveys were carried out to find out the hydraulic parameters to calculate the erosive power of the stream i.e., slope of the channel surface, hydraulic radius, and velocity. The erodibility index ranges from 22 to 198 on the basis of their rock mass properties whereas the stream power value ranges from 1 to 6 kW/m^2. The value of the stream power obtained at the bankfull condition at different flow time intervals i.e., 10, 25, 50, and 100 years ranges from 5 to 25 kW/m^2. With this range of stream power at different time interval flow, the Manahara River has the capacity to erode maximum of the sandstones present in the riverbed as all the values of the erodibility plot above the threshold line of erosion. However, the relation between the erodibility index and stream power at normal flow condition shows that the Siwalik sandstones of the study area are not erodible under the influence of the available stream power.

Keywords: Erodibility, Stream Power, sandstones, Hydraulic Erodibility Index, Siwalik

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INTRODUCTION

"Erodibility" term here sketches the remarkable erosion of the rock that transpires when the rock is submitted to hydraulic erosive power or in other word when water moves over the surface of the rocks, it exerts forces that dislodge and transport rock particles, leading to erosion. The various rock mass properties such as intact rock strength, block size, discontinuous conditions, bedding orientation, and groundwater condition have a major influence on the erosion of bedrock (Whipple et al. 2000). Kristen (1982) and Annandale (1995) have proposed a semi-empirical model known as Erodibility index method (EIM) that is based on field observations of scour threshold in various earth materials and is used for measuring the erosion resistance of earth materials and to relate the critical stream power (Kirsten 1982; Annandale and Smith 2001; Annandale 2005).

The erosional process is triggered by physical and chemical weathering, which coherently decreases rock strength and enhances susceptibility to abrasion, expanding fractures along which blocks are removed by plucking and pulverizing rock into small fragments (Hancock et al. 2011; Bizzi and Lerner 2015). The erodibility of rock is influenced by many interrelated geologic factors including material properties of the rock itself, as well as characteristics of the rock mass, particularly structural and stratigraphic discontinuities which determine the overall integrity of the rock mass. The erodibility of earth materials is determined by plotting the erodibility Index for a given earth material and the magnitude of the stream power. To elucidate stream power, it uses various geo-morphic parameters such as hydraulic radius, slope of channel, Bank full width, area, and velocity of stream. The fluctuation of stream power causes the jointed rock to be jacked out followed by dislodgement and finally displacement from its parent rock. A log-log plot of the erodibility index (K_h) and the rate of energy dissipation (P) of various

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materials are related to the critical threshold that can trigger the erosion of material. In cases, where the stream power exceeds the threshold line or point then the material will scour. The erodibility of the bedrock is also influenced by the shape of the river longitudinal profiles (Duvall et al. 2004). Shobe et al. (2017) have found that there is a great influence of weathering in the erodibility of the channel morphology. Sparacino (2012) has observed weathering is the dominant cause for the bedrock erodibility variation but the range and dominant form is highly variable, depending on climate conditions and rock type. The erosion was more rapid in the sandstone channel than in the limestone channel. Abundant coarse sediment can inhibit fluvial incision by armoring channel beds (Cook et al. 2012). High sediment transport rates can be more important than thresholds of coarse sediment motion for setting channel slope and limiting bedrock incision (Small et al. 2015). Pells (2016) have concluded that the main factor that triggers the erosion is the geological factors such as orientation, persistence, spacing, and nature of rock defects including bedding partings, joints, foliation, and shears.

A large number of developmental works are being carried out in the Siwalik area and also will be carried out in the forthcoming time. Large numbers of road alignments and bridges are under construction and will be constructed in the future in the Manahari-Chainpur area (Fig. 1). Bedrock erosion can be a severe threat to the river infrastructures in the Manahari River section that is mainly composed of weak sedimentary rocks. Hence, there has occurred a concern about hydraulic erosion of bedrock on the channel and near bridge pier foundation. The main aim to account this study was to see if this river could be able to scour river bed bringing instability in the structures such as bridge and embankment.

GEOLOGICAL SETTING

The Siwalik Groups sediments were deposited in a basin in the Himalayas by a major river system in the between the Middle Miocene and the Early Pleistocene period. Four stratigraphic units were mapped in the study area namely, the Midland Group, the Lower Siwalik Subgroup, the Middle Siwalik Subgroup and, the Recent Alluvial Deposits. The Lower Siwalik and the Middle Siwalik are too

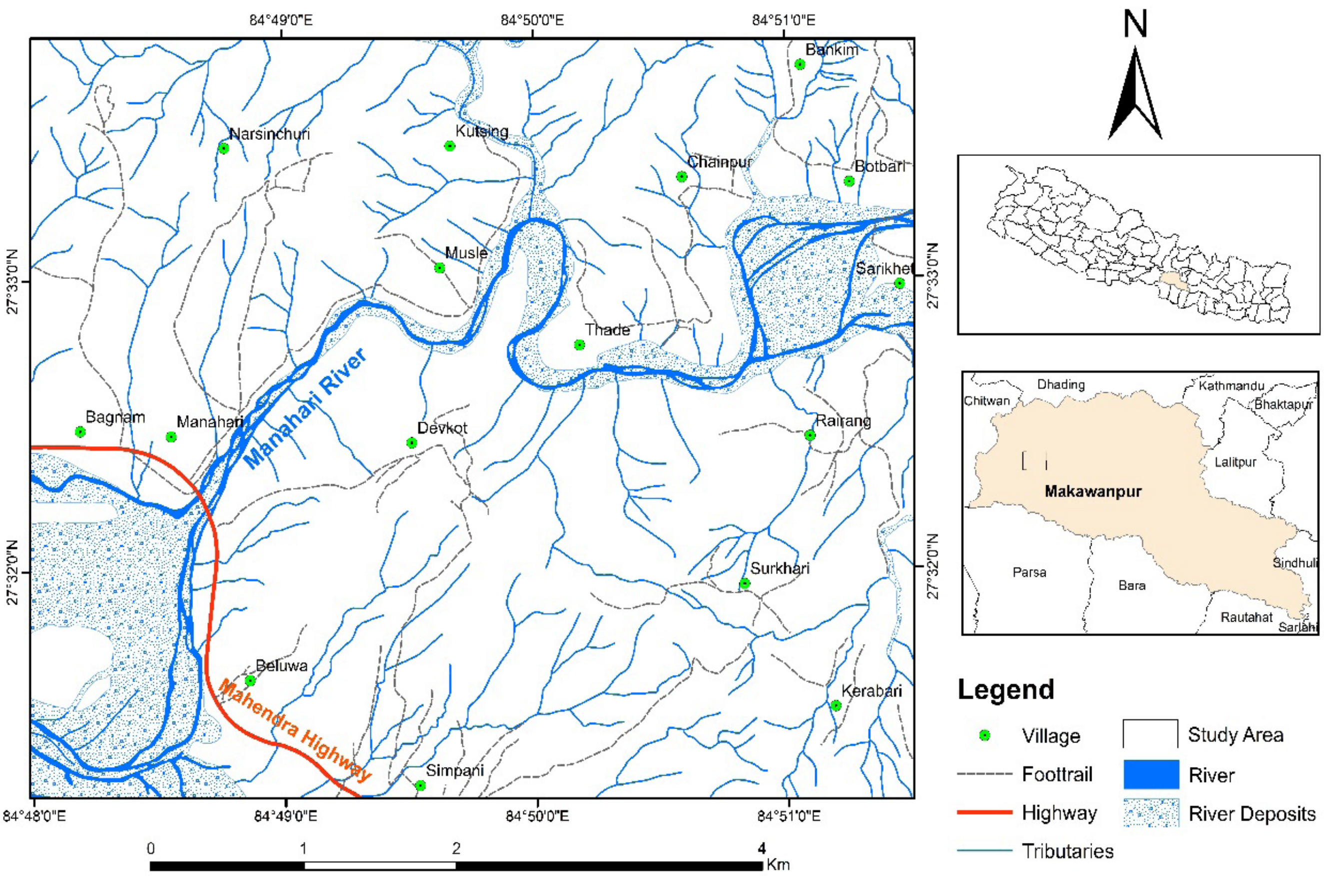

Fig. 1: Location Map of Study area

thick to assign them formation. Therefore, they have been considered Subgroup of the Siwalik Group, and the Subgroups nomenclature has been known for the Siwalik Group of India (Kumar et al. 2004; Kumar et al. 2007). The lithological changes between Siwaliks and Lesser Himalaya are due to the ongoing tectonic processes associated with the Himalayan orogeny, which is due to the collision between the Indian and Eurasian tectonic plates. The relief towards the southern part of Main Boundary Thrust (MBT) i.e., the Siwalik Hills is comparatively low with gentle slopes due to continuous erosion by rivers and other geological processes while that of the Lesser Himalaya which is towards the northern side of MBT has higher relief with steeper slopes and more rugged terrain because of more resistant to erosion.

The Midland Group mainly consists of light grey to greenish grey slate of the Benighat Slate which is observed on the Northern part of the study area (Fig. 2). The general lithological composition of the Lower Siwalik Subgroup is fine to medium-grained, greenish-grey to brown sandstones (Fig. 3), grey siltstones, and variegated mudstone and shale in some parts. The sandstone of the Lower Siwalik Subgroup becomes highly calcareous as the sequence goes up along with calcareous leaching. The grain size is coarse together with salt and pepper appearance brown sandstone having a very massive bed indicates the lithology of the Middle Siwalik Subgroup (Fig. 4). The coarse-grained micaceous sandstone is interbedded with purple to greyish siltstone which possesses a nodular weathering pattern and also with a thin bed of black mudstone in some sections. Pebbly sandstones were observed in the upper part of the Middle Siwalik Subgroup. Cross laminated sandstones of the Middle Siwalik Subgroup are also observed on the right bank of the Manahari River (Fig. 5). The Southern section represents the recent alluvium deposit, which is mainly comprised of loose alluvial materials along with gravel whose size ranges from, pebbles to boulders. The materials are mainly composed of quartzite, sandstone, granite, mudstones, etc. having sand, clay, and silt as supporting matrices. Stratigraphic section (Fig. 6) exposed along the Manahari River mainly comprises of the Lower and the Middle Siwalik Subgroups, and the Benighat Slate of the Lesser Himalaya (Shrestha 2019).

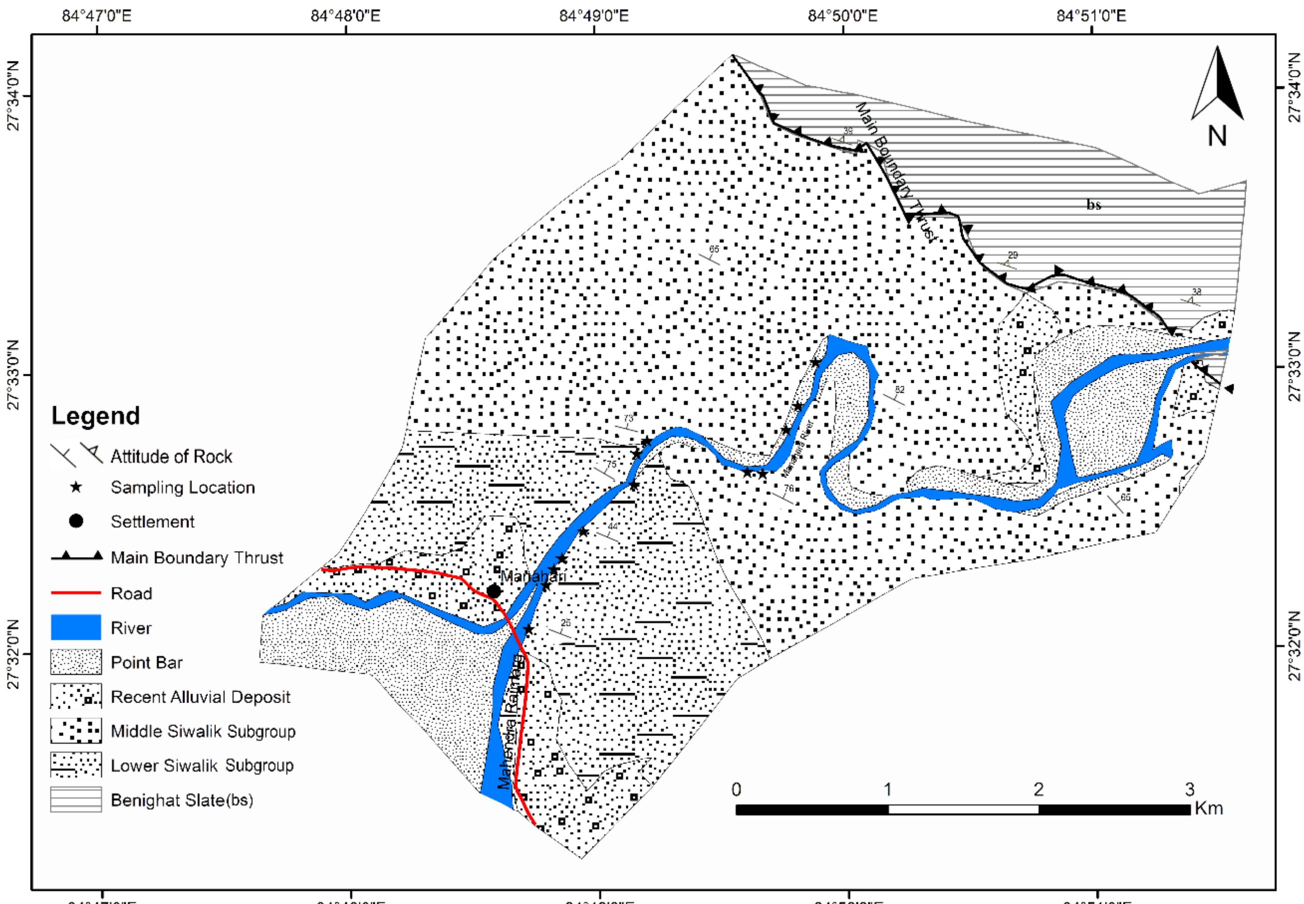

Fig. 2: Geological Map of the Study area

Fig. 3: Medium to thick bed of sandstone of the Lower Siwalik Subgroup on the left bank of the Manahari River

Fig. 4: Thick to massive bed of vertical sandstone interbedded with mudstone on the left bank of the Manahari River of the Middle Siwalik Subgroup

Fig. 5: Cross-laminated thick bed of sandstone of the Middle Siwalik Subgroup on the right bank of the Manahari River

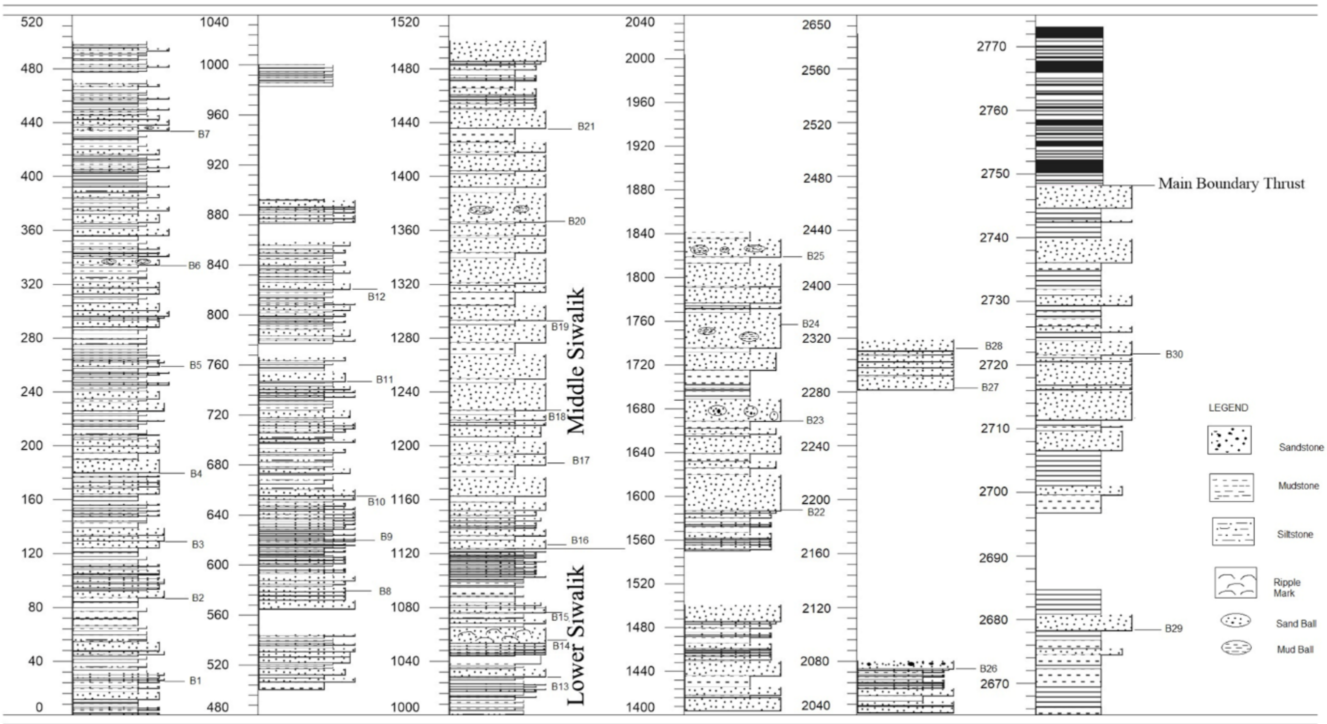

Fig. 6: Stratigraphic Section of the Lower and the Middle Siwalik Subgroups exposed along Manahari River (Shrestha 2019)

METHODOLOGY

Six locations were selected, of which three were from the Middle Siwalik area and three from the Lower Siwalik area to study erodibility and erosivity. Along with that, detailed information about rock type, lithology, orientations, weathering patterns, texture, and structures was also carried out in the fieldwork. Erodibility index parameters such as mass strength, joint roughness, and alternation, no. of Joints, joint orientation, river flow direction of every 13 locations were noted during the fieldwork. The total scores of the given parameter's values were calculated to find out the Erodibility index. The values for different parameters of erodibility index were assigned according to the criteria based on Kristen (1982). Therefore, the plot of the Erodibility Index and stream power as suggested by Annandale (1995) was followed to find out the erosivity of the sandstones.

Calculation of Erodibility Index (K_h)

The primary geological parameters like rock strength, block or particle size, discontinuity/inter-particle bond shear strength and shape of material units and their orientation relative to the flow were determined to figure out the Erodibility Index after Annandale (1995) as;

$$K_h = M_s . K_b . K_d . J_s \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, K_h -Erodibility index, M_s -Mass strength, K_b-Particle or fragment size of the rock blocks, K_d -Inter-block strength, and J_s-Relative shape and orientation of blocks.

The mass strength number (M_s), represents the relative ability of the rock mass to resist fracture and failure, is a function of the rock density and the rock unconfined compressive strength (UCS).

The block size number (K_b), represents the relative size of rock blocks, was estimated from the ratio of rock quality designation (RQD) and the joint set number (J_n).

$$K_b = RQD/J_n \ldots\ldots\ldots\ldots (2)$$

where, RQD= rock quality designation and J_n= Joint set number.

The shear strength number (K_d), represents the relative resistance offered by the rock discontinuities, was determined by the ratio of the joint roughness number (J_r) to the joint alteration number (J_a).

$$K_d = J_r/J_a \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where, J_r= joint roughness and J_a= joint surface alternation

The relative ground structure number (J_s), represents the ability of rock materials to resist erosion caused by the structure of the ground, was a function of the rock block shape and the least favorable joint orientation relative to the flow direction.

These four parameters of the erodibility index were taken to jointly represent the resistance of rock mass to the scour process of plucking.

Calculation of Stream Power (P)

Detail study on stream power parameters such as velocity, channel slope, the hydraulic radius was done in the Manahari River during the field study taking cross-section profile (Fig. 7) and longitudinal profile. Stream power (P) or erosive power is a parameter to ascertain the Hydraulic erodibility index. The erosive capacity of the Manahari River was determined from the equation derived by Bagnold (1966):

$$P = (\rho . g . Q . S_f)/w \quad ....(4)$$

Where, ρ = density of water (1000 kg/m^3), Q = discharge (m^3/s), g = acceleration due to gravity (9.8 m/s^2), S_f = slope, w = width of flow. The above obtained power is in W/m^2 and can be transferred to kW/m^2 after dividing by 10^3.

During high discharge exceeding the bank full discharge, the cross-sectional area, width of channel and velocity of flow increases, hence increasing the stream power. Density of water and slope are more or less constant whereas discharge may vary depending on velocity and cross-sectional area of stream.

Relation between Erodibility Index (K_h) and Stream Power (P)

Whether the rock will erode or not is represented by the correlation between stream power and the erodibility index of the materials by the below mentioned function after Annandale (1995).

$$P = K^{0.75} \quad ....(5)$$

At the erodibility threshold, if, $P>K^{0.75}$ the erodibility threshold is exceeded, scouring is expected (Annandale 1995; Annandale and Smith 2001). While, if $P<K^{0.75}$ the erodibility threshold is not exceeded, and scouring is not favorable. Combining both, the Erodibility index and stream power one can estimate scour potential as proposed by Annandale (1995) and Annandale and Smith (2001). Altogether, 150 field observation were reviewed in order to develop a curve illustrating the threshold of erosion. Concurrently, a best fit line for the line separating the erosion and non-erosion cases was also drawn from same sets of data. The correlation defined by Stream power (P) and the Erodibility index (K_h), forms a continuous curve for the whole range of earth materials which encompasses from silt to hard intact rock.

RESULTS

Erodibility Index Parameters

Based on field investigation and some of them in laboratory, the different parameters were calculated for measuring Erodibility index. With a sole aim of studying bedrock erosion, 13 locations were selected for the hand specimen collection, including the rocks of the Lower Siwalik Subgroups and the Middle Siwalik Subgroups so as to calculate the erodibility indices. The parameters include the mass strength number (M_s), rock block size (K_b), joint shear strength (K_b), a block's shape and orientation relative to the flow direction of river or stream (J_s), and the joint spacings.

Fig. 7: Cross-sectional survey of the Manahari River to calculate the Hydraulic parameters

Mass strength number (M_s)

The rating for M_s was specified according to the UCS value of the sandstones which was obtained from the lab work. The highest rating of the M_s value has been assigned to locations 2,5,8,9 and 13 i.e., 17.7 as it has the greater UCS value, and the lowest rating i.e., 8.39 to location1,3,4,6,7,10,11 and 12 because of the lower UCS value (Table 1). The value of UCS shows that the rock sample collected from the study area falls under the hard rock category. Kristen (1982) has suggested a table regarding the UCS value of the rock in which the UCS value is assigned with a rock strength number. The strength of sandstones can also be calculated in the field by calculating the different parameters as suggested by Bieniawski (1989). The variability in the rock mass strength in bedrock channels is due to the interactions between weathering erosion, and hence erodibility of rock, across bedrock channels. Weathering is one of the most convincing mechanisms for reducing rock tensile strength and thereby reducing the critical stress necessary to alter rock which makes rock more prone to erosion by abrasion.

Particle/Block size number (K_b)

For the calculation of block size number, two basic parameters are required i.e., Rock Quality Designation (RQD) value and no. of joint sets of the desired location. The value of RQD ranges from 5-100 whereas the values of J_n ranges from 1-5. Consequently, the value of K_b ranges from 1-100. Knowing the joint sets, the corresponding J_n rating is determined by following the Kristen's (1982) table. The joint sets normally observed in the field were of 3 sets whereas in some locations 4 types of joint sets were also observed along with the maximum and minimum joint spacing of each joint set from every location. The RQD value was calculated in the laboratory from the hand sample and the value ranges from 55-62. The highest value of K_b was detained by location 7 i.e., 18.44 and the lowest value by location 12 i.e., 14.4 Table 1).

Inter-particle shear strength number (K_d)

The shear strength number (K_d) also uses the two parameters i.e., joint roughness no. (J_r) and joint alternation no. (J_a) The joint roughness number refers to the roughness condition of the facing walls of a discontinuity whereas the joint alternation number reflects the weathering condition of the joint face materials. The roughness of the joint surface along with its weathering pattern was noted down in the field and with their characteristics, and a number was assigned to each parameter for each location, and then inter particle shear strength number was deliberated adapting the table as suggested by Kristen (1982). For this parameter, the joint spacing also plays some role. The sampling location 10, K_d value was found to be 0.231 while for location 5,8 and 9, K_d value was 0.752 (Table 1).

Table 1: Table showing values of Rock mass strength number (M_s), Block size number (K_b) and Inter-particle shear strength number (K_d)

	Mass strength number (M_s)			Block size number (K_b)				Inter-particle shear strength number (K_d)		
Location	I_{s50} (MPa)	UCS (Mpa) = n $(I_{s50})^{0.6818}$	M_s	RQD	No. of Joint sets	J_n	K_b	J_r	J_a	K_d
DSL1	2.57	11.1	8.39	55	3	3.34	16.47	3	7.33	0.41
DSL2	4.07	13.76	17.7	61.1	4	4.09	14.94	2	7.33	0.27
DSL3	1.86	9.014	8.39	59.8	4	4.09	14.62	2	7.33	0.27
DSL4	3.44	11.44	8.39	57.3	3	3.34	17.16	2	7.33	0.27
DSL5	4.72	15.68	17.7	57	3	3.34	17.07	2	2.66	0.75
DSL6	4.20	12.8	8.39	56.2	3	3.34	16.83	2	7.33	0.27
DSL7	3.53	11.8	8.39	61.6	3	3.34	18.44	3	8.66	0.35
DSL8	4.26	14	17.7	58.5	3	3.34	17.51	2	2.66	0.75
DSL9	7.96	19.5	17.7	61.4	4	4.09	15.01	2	2.66	0.75
DSL10	1.64	7.94	8.39	61.3	3	3.34	18.35	2	8.66	0.23
DSL11	2.62	10.6	8.39	59.1	3	3.34	17.69	2	7.33	0.27
DSL12	3.50	12.2	8.39	58.9	4	4.09	14.40	2	7.33	0.27
DSL13	6.21	17.4	17.7	58	3	3.34	17.37	2	7.33	0.27

UCS = Uniaxial compressive strength, RQD = Rock quality designation, J_n = Joint set number, J_r = Joint roughness number, J_a = Joint alternation number

Table 2: Joint structure number (J_s)

Sample	Joints Sets	Joint Spacing Max. (m)	Joint Spacing Min. (m)	Average Joint Spacing (m)	y/x	r = (1: y/x)	Dip amount	Dip Direction	River Flow Direction	|DD-FD|	GS		Strike	Strike-FD	AD	ED
DSL_1	J_0	0.70	0.015	0.36	2.04	0.49	29	28	210	182	1.89	against	298	88	29.0	27.1
	J_1	0.66	0.014	0.34			51	154	210	56		along	64	146	34.6	32.7
	J_2	0.34	0.010	0.18			53	224	210	14		along	134	76	52.2	50.3
DSL2	J_0	2.10	0.020	1.06	3.31	0.30	47	33	210	177	1.89	against	303	93	47.0	45.1
	J_1	1.30	0.200	0.75			66	290	210	80		along	200	10	21.3	19.4
	J_2	1.25	0.030	0.64			45	210	210	0		along	120	90	45.0	43.1
	J_3	0.60	0.040	0.32			73	130	210	80		along	40	170	29.6	27.7
DSL3	J_0	1.10	0.030	0.57	3.71	0.27	61	15	210	195	1.15	against	285	75	60.2	59.0
	J_1	1.20	0.080	0.64			77	265	210	55		along	175	35	68.1	66.9
	J_2	0.73	0.090	0.41			44	156	210	54		along	66	144	29.6	28.4
	J_3	0.33	0.015	0.17			65	307	210	97		against	217	7	14.6	13.5
DSL4	J_0	0.80	0.020	0.41	2.18	0.46	61	25	210	185	1.15	against	295	85	60.9	59.8
	J_1	1.06	0.030	0.55			58	210	210	0		along	120	90	58.0	56.9
	J_2	0.49	0.010	0.25			74	310	210	100		against	220	10	31.2	30.0
DSL5	J_0	1.10	0.020	0.56	3.81	0.26	75	25	230	205	1.322	against	295	65	73.5	72.2
	J_1	0.35	0.010	0.18			86	285	230	55		along	195	35	83.0	81.7
	J_2	1.25	0.122	0.69			26	306	230	76		along	216	14	6.7	5.4
DSL6	J_0	0.68	0.020	0.35	1.20	0.84	72	22	236	214	1.322	against	292	56	68.6	67.3
	J_1	0.57	0.015	0.29			65	307	236	71		along	217	19	34.9	33.6
	J_2	0.56	0.015	0.29			14	224	236	12		along	134	102	13.7	12.4
DSL7	J_0	1.04	0.040	0.54	2.94	0.34	79	19	230	211	1.29	against	289	59	77.2	75.9
	J_1	2.06	0.050	1.06			20	117	230	113		against	27	203	8.1	6.8
	J_2	3.00	0.180	1.59			49	281	230	51		along	191	39	35.9	34.6
DSL8	J_0	0.95	0.020	0.49	2.02	0.50	81	39	245	206	1.29	against	309	64	80.0	78.7
	J_1	1.21	0.100	0.66			52	138	245	107		against	48	197	20.5	19.2
	J_2	0.61	0.040	0.33			17	305	245	60		along	215	30	8.7	7.4
DSL9	J_0	1.80	0.040	0.92	1.60	0.63	23	66	240	174	1.109	against	336	96	22.9	21.8
	J_1	1.40	0.050	0.73			78	207	240	33		along	117	123	75.8	74.7
	J_2	2.00	0.030	1.02			75	292	240	52		along	202	38	66.5	65.4
	J_3	1.20	0.070	0.64			77	101	240	139		against	11	229	73.0	71.9
DSL10	J_0	2.30	0.050	1.18	1.90	0.53	83	29	200	171	1.109	against	299	99	82.9	81.8
	J_1	1.70	0.020	0.86			28	217	200	17		along	127	73	27.0	25.8
	J_2	1.20	0.040	0.62			60	283	200	83		along	193	7	11.9	10.8
DSL11	J_0	2.80	0.050	1.43	1.49	0.67	78	33	200	167	2.049	against	303	103	77.7	75.6
	J_1	2.30	0.050	1.18			80	120	200	80		along	30	170	44.6	42.5
	J_2	3.40	0.090	1.75			9	306	200	106		against	216	16	2.5	0.5
DSL12	J_0	1.50	0.080	0.79	2.50	0.40	82	37	230	193	2.049	against	307	77	81.8	79.7
	J_1	0.80	0.020	0.41			84	110	230	120		against	20	210	78.1	76.1
	J_2	0.90	0.030	0.47			12	307	230	77		along	217	13	2.7	0.7
	J_3	2.00	0.050	1.03			75	216	230	14		along	126	104	74.6	72.5
DSL13	J_0	1.50	0.040	0.77	4.49	0.22	67	71	230	159	2.049	against	341	111	65.5	63.5
	J_1	3.00	0.050	1.53			62	119	230	111		against	29	201	34.0	31.9
	J_2	0.65	0.030	0.34			58	292	230	62		along	202	28	36.9	34.9

GS – Ground Slope, FD – Flow Direction, AD – Apparent Dip, ED – Effective Dip, DD – Dip Direction, r – ratio

Relative joint structure number (J_s)

The relative ground structure number (J_s) parameter describes the relationship between the block's shape and orientation relative to the direction of flow direction of the river or stream and it simplifies that whether the river flow can penetrate the discontinuities and dislocate the rock blocks. To find out the J_s value all we need is the effective dip of each joint sets of every location and joint spacing ratio (r). The value of J_s is expressed in terms of the relative spacing of the two joint sets, the dip angle, and the dip direction of the closer spaced set relative to the direction of flow of the river. The rating for the J_s is determined as a function of the dip and dip direction of the rock block as well as the joint spacing ratio. It's rating, as proposed by Kristen (1982), ranges from 0.37 to 1.5. The data obtained from the field showed us that the highest rating value was from location 10 i.e., 1.09 while the lowest value from location 1 i.e., 0.55 (Table 2).

Erodibility index (K_h)

The Erodibility index is the scalar product of the indices of its constituent parameters. The rock masses when subjected to the action of flowing water, causes the pressure fluctuation that progressively results in the jacks out the rock masses from its position of rest. When the rock mass is pulled out by the turbulence of water, then finally it will be displaced. Weathering is one of the most convincing mechanism for receding rock tensile strength and thereby lowering the critical stress necessary to alter rock, which makes rock more vulnerable to erosion (Sklar and Dietrich 2001).The Erodibility index (K_h) of the site 5 which falls in the Lower Siwalik Subgroup has the highest value of 197.59 whereas the site 4 which also falls in the Lower Siwalik Subgroup has the lowest value of Erodibility index (K_h) i.e., 22.1 (Table 3). Location 5 has the highest erodibility value because of very hard rock, along with unaltered rock with joint separation of less than 5 mm and the orientation of the bed is along the flow direction of the river. Higher joint sets, hard rock with less UCS value, the weathered rock having joint separation more than 25 mm and the orientation of bed is against the flow direction of the river, these are the characters possesses by location no. 4 that's why it has the lowest value of erodibility.

In addition to that, when we look at the Erodibility index value of the Lower Siwalik sandstone there is a remarkable fluctuation, ranging from the highest to the lowest value, whereas the value of Erodibility index of Middle Siwalik sandstone shows not that much fluctuation or can say have lower Erodibility index value compared to the Lower Siwalik sandstone value except at Location 9 which lies in between the boundary of the Middle Siwalik Subgroup and Lower Siwalik Subgroup. Being said that we are well aware that the Lower Siwalik Subgroup is lithologically composed of interbedding of siltstones and mudstones which will ultimately cause the mineral composition to mix up. It is a

Table 3: Hydraulic Erodibility index (K_h)

Location	Mass strength (M_s)	Block Size Number (K_b)	Shear Strength Number (K_d)	Relative Ground Structure (J_s)	Erodibility Index (K_h)
DSL_1	8.39	16.47	0.41	0.53	29.97
DSL_2	17.7	14.94	0.27	0.68	48.70
DSL_3	8.39	14.62	0.27	0.69	22.93
DSL_4	8.39	17.16	0.27	0.56	22.10
DSL_5	17.7	17.07	0.75	0.87	197.59
DSL_6	8.39	16.83	0.27	0.83	31.97
DSL_7	8.39	18.44	0.35	0.78	41.81
DSL_8	17.7	17.51	0.75	1.08	181.81
DSL_9	17.7	15.01	0.75	0.62	124.27
DSL_{10}	8.39	18.35	0.23	1.09	27.74
DSL_{11}	8.39	17.69	0.27	0.75	30.38
DSL_{12}	8.39	14.40	0.27	1.03	25.71
DSL_{13}	17.7	17.37	0.27	0.61	51.41

factual truth that, whenever there is an alternation in mineral composition there is a lowering of the strength of the rock which applies to the sandstone of the Lower Siwalik Subgroup. Handin et al. (1963) studied fine and coarse limestone and found that the fine-grain limestone is generally harder than the coarse-grain limestone. From the above statement it is clear that grain size is also one of the important factors for determining the mechanical properties of the rock. Hence, with the grain size greater than the sandstones of the Lower Siwalik Subgroup, the sandstones of the Middle Siwalik Subgroup have weak mechanical properties compared to that of the sandstones of the Lower Siwalik Subgroup which will alternatively impact the erodibility value and the variation in value of erodibility.

Stream Power Parameters

The morpho-hydraulic characteristics of the river such as channel slope, bank-full area (A_{bkf}), bank full depth (D_{bkf}), bank full width (W_{bkf}) also riverbank sediments were evaluated in order to get the knowledge about the stream power and the present condition of the river section in 6 different transects. The field studies have shown that the bank full discharge commonly approximates a flow event with a 1.4-1.6-year recurrence interval in the annual maximum series (Rosgen 1994; Annandale 1995). Rock erodibility may also vary within and across channel cross-sections (Small et al. 2015), and may play a significant role in setting channel geometry and gradient (Hancock et al. 2011). Table 4 shows the value of all these geomorphologic parameters.

- **Velocity of stream (V)**

  Velocity of the stream is also a common simplification for the examination of streamflow which is generally downstream. Here, the calculations were made on the basis of the average velocity at a given cross section because the actual velocities may vary markedly from top to bottom, side to side, and in direction varying with time and space. The velocity of the stream was taken from six transects including both the Lower Siwalik Subgroup section and the Middle Siwalik Subgroup section. The velocities of the Manahari River were determined in the upstream reach and in the downstream reach. Transect no. 6 has highest velocity of 7.79 m/s whereas transect no. 2 has lowest velocity of 3.95 m/s. Bringing together, the slope gradient and the hydraulic radius, the velocity of the stream was assessed.

- **Hydraulic radius (R)**

  For the Hydraulic radius (R_h), the cross-sectional survey was carried out for the geometrical and geomorphological parameters of the stream comprehending bank full width and height, width of flood prone width and bank materials. Transect no.5 has highest hydraulic radius i.e., 2.46 m and transect no. 2 has the lowest value of hydraulic radius i.e., 1.19 m. The area of bank full has increased in the upstream part of the Middle Siwalik Subgroup but as we move towards the transection zone between the Middle and the Lower Siwalik Subgroups there is decreasing trend in the bank full area. As we move down from the transection zone towards the Manahari Bazar area then again, the bank full area has shown the increasing trend which will subsequently increase or decrease the hydraulic radius. Hydraulic radius is directly proportional to its stream cross-sectional area of stream. Therefore, the more the hydraulic radius more the stream will feel free to flow which will initially cause more flow of water in the stream that means an increase in the stream power.

Table 4: Values of Morpho-Hydraulic Parameters

Site	Max. Bankfull Depth D_{bkf} (m)	Max. Bankfull width W_{bkf} (m)	Max. Bankfull area A (m^2)	Wetted Perimeter W_p (m)	Hydraulic radius R_h	Manning (n)	Stream slope S (m/m)	Velocity V (m/s)
1	1.98	50	99	53	1.83	0.04	0.033	6.74
2	1.24	61	76	49	1.19	0.04	0.020	4.00
3	1.41	58	82	37	1.35	0.04	0.023	4.57
4	1.51	49	74	32	1.42	0.04	0.023	4.77
5	2.46	81	200	55	2.32	0.04	0.019	5.68
6	2.23	88	197	60	2.13	0.04	0.036	7.80

- **Slope (S)**

  To determine the stream slope, longitudinal survey of 6 sections were done in terms of the width and nature of the channel of the river, with 3 sections in the Middle Siwalik Subgroup section and 3 in the Lower Siwalik Subgroup section. The ratio of the measured water level in upstream and downstream transects determines the sloping channel or the vertical drop of the stream bed from upstream to downstream in comparison with the adjacent floodplain features. Transect no. 6 has the highest slope gradient (tan θ) with the value of 0.036 and the lowest value of 0.019 for transect no. 5. In the end, there is not much a drastic change in the river slope of the Manahari River.

Stream Power (P)

The amount of energy that a stream has available for carrying materials such as rock, woody vegetation, and sediment is referred to as stream power. Water flowing in an open channel typically gains kinetic energy as it flows from a higher elevation to a lower elevation. The stream power here comes to be in a unit of W/m. Then, this stream power is converted into a unit stream power by dividing it by the bankfull width and we get values in W/m^2 which can be converted to kW/m^2 by dividing by 1000. The transect no. 6 has the highest stream power of 6.1 kW/m^2 while the lowest stream power is 0.974 kW/m^2 of the transect no. 2 (Table 5). The transect which has the greater bank full area (A_{bkf}) and bank full depth (D_{bkf}) and sometimes bank full width (W_{bkf}) also, usually have high stream power than the other transects with a smaller bank full area and bank full depth. For this reason, the stream power values fluctuate from different transect sections. The role of the slope is found to be not that significant for the stream power as we can conclude from the data of slope gradient that there is barely a fluctuation in the slope gradient of the channel slope. But, whenever the value of the channel slope has increased, we can see an increase in the velocity of the stream, which has been proved true from the relation between slope and velocity in transects no. 1 and 6.

Table 5: Stream Power of the six transects

Location	Siwalik Sub Group	Bankfull Area A_{bkf} (m^2)	Velocity V (m/s)	Slope S (m/m)	Density of water ρ (Kg/m^3)	Acceleration due to gravity g (m/s^2)	Discharge Q (m^3/s)	Stream Power P (kW/m^2)
DSL1	Lower Siwalik	98.5	6.74	0.033	1000	9.8	663.89	4.34
DSL2	Lower Siwalik	76	4.1	0.02	1000	9.8	300.2	0.97
DSL3	Lower Siwalik	82	4.57	0.023	1000	9.8	374.74	1.46
DSL4	Middle Siwalik	74	4.77	0.023	1000	9.8	352.98	1.59
DSL5	Middle Siwalik	200	5.68	0.019	1000	9.8	1136.21	2.67
DSL6	Middle Siwalik	197	7.81	0.036	1000	9.8	1534.63	6.10

Table 6: Stream Power at different consecutive time intervals (Log Pearson III Method)

Location	Siwalik Sub Group	Stream Power at 10 years interval (kW/m^2)	Stream Power at 25 years interval (kW/m^2)	Stream Power at 50 years interval (kW/m^2)	Stream Power at 100 years interval (kW/m^2)	Threshold Stream Power (kW/m^2)
DSL1	Lower Siwalik	9.54	14.05	18.22	23.14	15.67
DSL2	Lower Siwalik	4.75	6.99	9.07	11.52	10.35
DSL3	Lower Siwalik	5.73	8.43	10.93	13.89	33.07
DSL4	Middle Siwalik	6.61	9.74	12.63	16.04	32.97
DSL5	Middle Siwalik	3.44	5.07	6.57	8.35	24.61
DSL6	Middle Siwalik	5.84	8.60	11.15	14.16	14.49

The power of the Manahari River at a different consecutive time is listed in Table 6. The consecutive time includes several time intervals i.e., 10, 25, 50, and 100 years. The discharge of the Manahari River at these intervals of time was calculated by using the Log Pearson III method with the data collected from the Department of Hydrology and Meteorology (DHM) and from that value of the discharge, the stream power was also calculated at the same time intervals.

And obviously, the discharge of the stream will increase in that interval of time which will ultimately trigger the power of the stream to be high as can be seen in Table 6. The normal stream power value ranges from 1 to 6 kW/m^2 but when we inspect the stream power value at different time interval periods in Table 6, the value ranges from 5 to 24 kW/m^2 which is more than 4 times greater than that of the value poses by normal stream power.

DISCUSSIONS

Hydraulic Erosion potential of the Siwalik bedrocks

The correlation between Stream power (P) and Erodibility index (K_h) represents an earth material's relative ability to resist erosion can, at the erosion threshold. The erosion Threshold parameter was obtained following Annandale's criteria of erodibility. The value above the dashed line indicates that the material is erodible whereas below that dashed line indicates the material is non-erodible.

The calculated value to the threshold line of scouring of the Lower Siwalik sandstone is about 10-55 kW/m^2 while for the Middle Siwalik sandstone is 10-40 kW/m^2. The calculated value of the present research gives the idea about the Middle Siwalik sandstone and the Lower Siwalik sandstone need greater stream power for the higher erodibility value and need low stream power for the low erodibility value of the sandstones. A similar result was also obtained from the analysis of the Hydraulic erodibility vs. Stream power in Fig. 8. The threshold line of scouring in the graphical representation is above from the samples of the Lower and the Middle Siwalik Subgroups. This also suggests that both the Siwalik Subgroup sandstones are rigid and need more stream power for the scouring. The Middle Siwalik sandstones are more likely to be softer than that of the Lower Siwalik sandstones in the present study. Both the Siwalik Subgroups seem to be equally resistible to the scouring from the stream power, achieved during the bankfull discharge of stream.

The result of the relation between Erodibility index and Stream power shows that some (mostly the Lower Siwalik sandstone) bed rocks of the Manahari River at the bankfull stage are not that favorable for erosion but few of the sandstones of the Lower and the Middle Siwalik Subgroup are near about the threshold to erosion under the action of stream power of the bankfull flow.

This result of the Hydraulic erodibility index (K_h) shown in Fig.8 is only valid for the normal flow of a stream having normal stream power but as river flow at different time intervals increases the value of the discharge will also increase which ultimately increases the stream power. As already mentioned, the stream power becomes four times more in different consecutive time intervals than in the normal stream power. In such conditions, the sandstones exposed in the Manahari River section will be in erodible condition which will definitely jeopardize the settlement area, infrastructures, and the ongoing developmental work being carried out.

Lithology versus erodibility

Erosion of bedrock by the action of water is itself a very complex method that was combined with various erosion processes. Why is the rock not favorable to erosion in the study area, various factors acting in this case. The first reason is the strength of the rock mass. As already discussed, the rocks are of hard type also the conditions of the discontinuities are also of very good conditions i.e., the weathering pattern of the rock is faintly or slightly while observing from the field condition. The spacing of the joints is also not that much (1-25 mm) and the continuity of the joint is also wide. Along with that, the dipping of most of the joint sets is along the flow direction of the river which is not a favorable condition for the erosion of bedrock. The depth of the bank full comparatively high, and it already mentioned in the above paragraph that, with greater depth, the flow will be contained within the channel bank causing the larger floodplain to decrease and as a result, the interaction between the channel bedrock and floodplain is reduced which automatically will decrease the incision of the bedrock. Besides that, the stream power is not that much enough to erode the rock type (sandstones) of the study area. Although, we can clearly see that there was the small scale to medium scale erosion of the mudstone and siltstone in many parts along the Manahari River section. Other than these factors, the probable reasons may be due to the mudrock that is interbedding with sandstones and

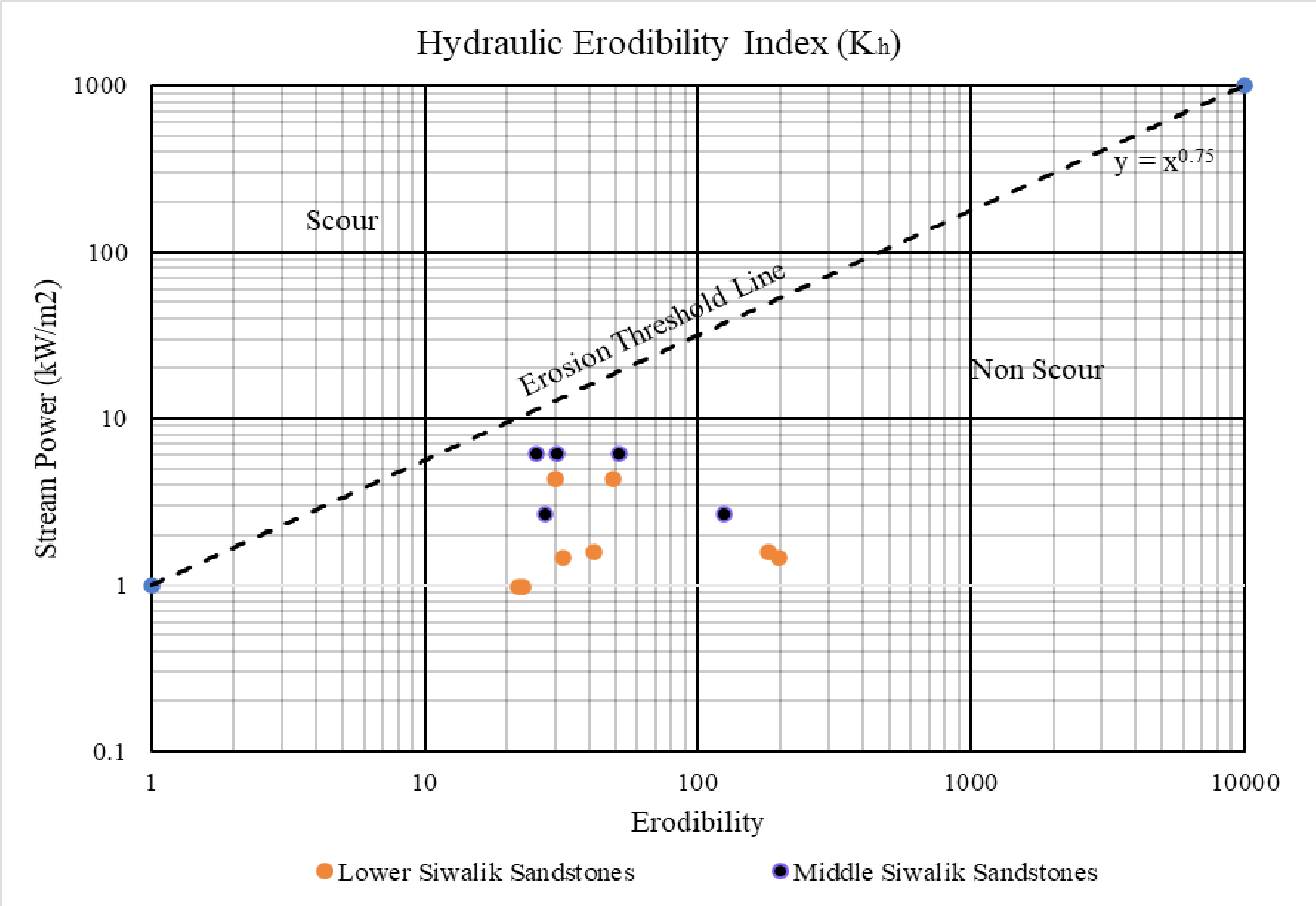

Fig. 8 Graphical representation showing relation between Hydraulic Erodibility Index (K_h) and Stream power (P) Annandale (1995)

whose erodibility is less than that of the interbedded sandstones are eroded by the stream power after which the sandstones bed are left with joints and may easily dislodged and eventually eroded. The same goes for the sandstones in hillslope, even if the sandstones are strong enough, once the mudrock interbed gets eroded away, the sandstones become unstable due to the void spaces and removal of underlying supports which later on fall and in due course erode away. In the case of hydraulic erosion of riverbeds, a similar situation arises and therefore erodibility of sandstones that we have calculated diminishes. When the erodibility diminishes, the plots on K_h vs. P lie above the curve and riverbed will be the potential for scour. The true intension of this research was to elucidating river channel stability, rather than linking with the study of tectonics along the Manahari River section.

CONCLUSIONS

- The erosive power of the Manahari River is not adequate for the erodibility of sandstones of both the Lower Siwalik Subgroup and the Middle Siwalik Subgroup. Sandstones can be eroded either due to increased level of stream power or due to diminish of erodibility by weathering and mass wasting of sandstones and associated lithology.
- The construction works for the road alignments and bridge can be carried out in the Manahari-Chainpur area in the present condition and in the near future without any obstruction. But this is only valid for the area with a large bed of sandstones.
- While, for the area with the lithology of shale, mudstones, and siltstones, necessary precautions should be taken while carrying out the developmental work in the Manahari-Chainpur road section along Manahari River.

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