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Morpho-hydrology and classification of Sayali Gad river, Doti district, lesser Himalaya

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ABSTRACT

The Sayali Gad River basin in the Lesser Himalaya of western Nepal exhibits complex morpho-hydrological behavior shaped by rugged topography, active tectonics, and variable lithology. This study investigates basin-scale morphometry and reach-scale channel characteristics to understand river classification and instability patterns. Morphometric parameters, including drainage density, stream frequency, relative relief, and stream order, were derived using GIS, while detailed field-based measurements were conducted along an approximately 24 km stretch of the fifth-order Sayali Gad at eleven transects spaced at 2 km intervals. Stream classification followed Rosgen's Level I and Level II framework, incorporating planform geometry, entrenchment ratio, width–depth ratio, channel slope, and bed material characteristics. Results show that the basin has an elongated, crocodile-shaped geometry with dendritic drainage and pronounced spatial variation in relief. The river transitions from steep, vertically unstable upstream segments dominated by A- and B-type streams to laterally unstable midstream and downstream reaches characterized by C- and E-type streams with wide, shallow channels and developed floodplains. Sediment size decreases systematically from boulders upstream to fine materials near the confluence with the Seti Nadi. Evidence of channel shifting, bank erosion, and flood impacts is most prominent in the midstream and downstream sections, amplified by human interventions such as unplanned extraction of riverbed materials. The findings highlight critical zones of instability and provide a geomorphic basis for river management and hazard mitigation in Himalayan river systems.

Keywords: Entrenchment ratio; W/D ratio; Channel shifting; River instability

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INTRODUCTION

River form and fluvial processes evolve simultaneously and operate through mutual adjustments toward self-stabilization (Rosgen 1994). The morphology of the river depends upon the channel material, basin relief, climate, topography, geology, and tectonic activity of that area.

Morphometric analysis is crucial in the initial stage of stream classification to clarify basin geometry, relative relief, drainage texture, and stream order. These parameters help to figure out spatial zones of erosion and sedimentation, and the competence of stream channels. The morpho-hydrologic analysis takes into account stretch scale planform parameters such as sinuosity (K), meander belt width (W_{blt}), meander wavelength (L_m), and radius of curvature (Rc), and morpho-hydrologic parameters such as bankfull depth, width, entrenchment ratio, water surface slope, and cross-section morphology.

Sayalai Gad watershed has an area of 185 sq km shown in Fig. 1. This river is east-west flowing from an elevation of 3276 m to 722 m. The basin has a crocodile shape and a dendritic drainage pattern. The Sayali Gad is nearly 45.6 km in length and is a tributary of the Seti Nadi.

Streams can be classified based on valley and channel slope, channel morphology, bed material such as sand, silt, and clay, and channel sinuosity. Rosgen (1994) proposed a stream classification system grounded in geomorphic and morpho-hydrological analysis.

OBJECTIVES

The main objective of this study is to investigate the morpho-hydrological characteristics of the Sayali Gad River basin in the Lesser Himalaya of western Nepal. The study focuses on quantifying basin-scale morphometric parameters, including stream order, drainage density, drainage texture, stream frequency, and relative relief, using GIS-based analysis. In addition, reach-scale morphological and morpho-hydrologic parameters such as sinuosity, meander geometry, entrenchment ratio, width–depth ratio, channel slope, bankfull dimensions, and bed material characteristics are evaluated through systematic field investigations along the fifth-order channel. Based on these parameters, the Sayali Gad River is classified into distinct stream segments following Rosgen's Level I and Level II classification framework. The study also aims to examine spatial variations in channel form, sediment characteristics, and valley types from upstream to downstream reaches, and to identify zones of vertical and lateral channel instability influenced by geomorphology, hydrology, and human activities.

MATERIALS AND METHODS

The methodology adopted in this study, as shown in Fig. 2, is organized into three main components: desk-based analysis, field investigation, and compilation and interpretation of results for the assessment of fluvial morphology and morphometry.

Morphometric parameters

The stream order of the river is calculated by using Strahler and Chow (1964) method, and the drainage density, drainage texture, stream frequency, and relative relief map were prepared in geographic information system (GIS) environment. The planform parameters, i.e., sinuosity (K), a radius of curvature (Rc), meander belt width (W_{blt}), and meander width ratio (W_{blt}/W_{bkf}) were calculated from Google Earth and topographic map.

Morpho-hydrologic parameters

The morpho-hydrologic parameters are entrenchment ratio (ER), width/depth ratio (W/D), bankfull width (W_{bkf}), bankfull area (A_{bkf}), flood-prone width (W_{fpa}), wetted perimeter (Wp), channel bed slope (Sb_{avg}), and water surface slope (Se_{avg}).

The entrenchment ratio (ER) = Width of the flood-prone area/ width of the bankfull channel.

Width/Depth ratio = Bankfull surface width/mean depth of bankfull channel.

The bankfull width of a channel is defined as the elevation at which water begins to spill onto the floodplain during high discharge conditions. The bankfull area is calculated by multiplying the bankfull width (W_{bkf}) by the mean bankfull depth (D_{bkf}). The flood-prone level is determined as twice the maximum bankfull depth. Channel bed slope is derived from the longitudinal profile of the river, while the water surface slope is measured in the field between the crests of two successive riffles separated by a distance equivalent to twenty times the bankfull width.

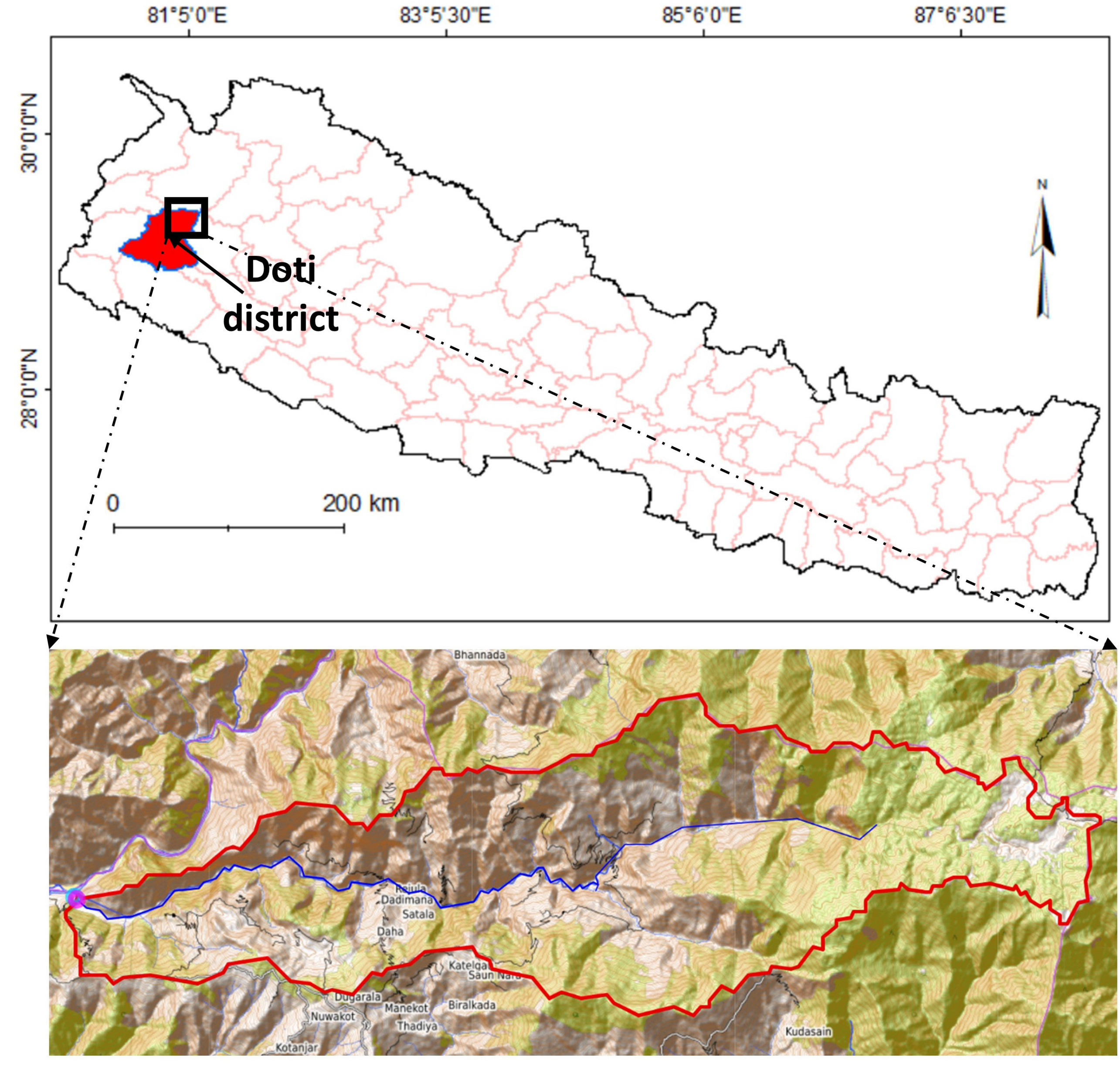

Fig. 1: Map showing Doti district and the study area.

Field study

Field survey for valley type

The shape of a river valley is controlled by geology and tectonics, the longitudinal gradient from source to mouth, and prevailing climatic conditions. In the Sayali Gad basin, valley development is governed by both the main river and its tributaries. Field investigations were conducted along the entire river course, from the source to the confluence, to delineate valley types. Based on structural control, slope, and associated landforms, the valleys were classified into several types: structurally controlled valleys as type VIII, steep-sided valleys as type IV, gently sloping valleys as type II, and very steep valleys as type I. Broad valleys characterized by well-developed alluvial terraces were grouped as type V.

The major criteria to classify valley types are structural control, entrenchment ratio, width/depth ratio, gradient, and sinuosity Rosgen 1994). These valleys are classified based on their shape, confinement, and slope as shown in Table 2. Rosgen (1994) classifies the valley from I through XII based on morphometric parameters. Valley Types (Linked to Stream Types) Valley type I: V-shaped, confined, structurally controlled, Valley type II: Moderate relief, residual/alluvial soils, gentle floor slopes (supports B types), Valley type III: Depositional (alluvial fans), moderately steep slopes (supports C/E types), Valley type III: Broad alluvial valleys, low relief (supports C/E types), Valley type VII: Highly dissected fluvial slopes, steep (supports A/G types) etc. as shown in Table 2.

Field survey for Level II fluvial morphological study,

The level II study was carried out in the field by taking 11 (T_1 to T_{11}) transects within the interval of 2 km along the fifth-order stream. There are four levels, level I, level II, level III, and level IV, for determining stream characteristics worked out

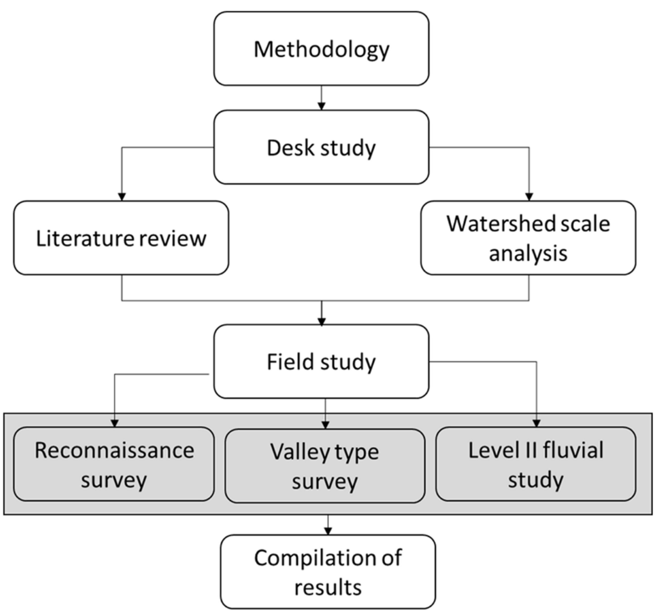

Fig. 2: Methodological framework of study.

by Rosgen in 1994. This research focuses on the level I and level II classification of Sayali Gad. The level I classification divide stream from A through G based on channel pattern, sinuosity, meander width ratio, channel slope, and channel shape, as shown in Tables 2 and 3.

The major criteria to classify the stream based on the level II are to determine stream type based on the entrenchment ratio, sinuosity, width/depth ratio, dominant bed material by using Wolman pebble count method, stream slope, area at bank-full, hydraulic radius, etc., as shown in Table 4. A total of 11 transects were carried out within 5th order stream at an interval of 2 km, and all the parameters were calculated in the field as shown in Tables 2, 3, and 4, and Figs. 8 and 9.

Level II classification characterize stream from A1-A6 through G1-G6 based on the morphological parameters of stream, channel slope, channel materials, entrenchment ratio, width/depth ratio, and sinuosity, as shown in Table 3.

Cross-section survey and longitudinal survey

The cross-section survey was done by using the labeling, staff, measuring tape, and the Brunton compass. The labeling equipment was placed at the bank full height of the river, and the staff is placed at a 1m distance. The reading from the auto label was taken as the mid-point as a height, and the upper and lower readings as the distance from the label to the staff. Successively, the location of the staff along the cross-section changed to cover the bank full width from one side to another across the river. The thalweg of the water was measured. The point at which water touches the bank of the river on the right side is REW, and on the left side is LEW. The width of the flood-prone area is measured at an elevation 2 times the maximum bank full height across two banks of the river.

The longitudinal survey was carried out 100 m upstream and 100 m downstream from the cross-section points. The staff was placed at an interval of 20 m, and the data were taken. The thalweg at every interval is measured to determine the slope of the water surface. A total of 200 m longitudinal survey of the channel was measured from the labeling equipment.

Wolman pebble count

This survey was done perpendicular to the flow direction of water Wolman (1954). Total 50 samples were taken across the channel width within the equal interval and noted in the notebook. Then the D50 value calculated is used for the level II classification of the stream.

Channel migration

River channel migrations are associated with local variation in geology, geomorphology, tectonic conditions, natural bank geometry, flood dynamics, land use alterations, the flow regime of the river, hydrology, and human-induced factors. The river channel shifting is studied from the Google Earth images by analyzing different time intervals from 2002 to 2022.

RESULTS

Geology of the study area

The study area consists of three groups and seven formations, as shown in Fig. 3. The three groups are the Surkhet Group, Midland Group, and Dadeldhura Group after DMG (2020).

The Surkhet Group comprises the Suntar Formation, the Midland Group consists of four formations they are the Lakharpata Formation, the Syangja Formation, the Galyang Formation, and the Ranimatta Formation, and the Dadeldhura Group consists of two formations i.e. the Kalikot Formation and the Sallyani Gad Formation as shown in Fig. 3.

The Sallyani Gad Formation comprises Dadeldhura Group coarse-grained, white, weathered, Granite and Gneiss. The Granite comprises small cobble-shaped xenoliths within it. The gneiss is highly weathered forming the sandy soils at the Khaptad area where 22 grasslands were developed. The attitude of foliation plane is 355/65 NE shown in Fig. 4a. The Kalikot Formation of this group consists of fine-grained, white, bluish Quartzite intercalated with grey-colored Schist at the right bank of the Baluwa suspension bridge. The attitude of foliation plane at this location is 310/ 25NE, shown in Fig. 4b.

The Ranimatta Formation of Midland group shown in Fig. 4c consists of white quartzite intercalated with schist, grey phyllite, and dolomite. and do. The attitude of foliation plane measured at the Juke Khola was 345/79 NE and the lithology was fine-grained white quartzite. The Galyang Formation of Midland Group consists of fine-grained grey slates intercalated with the calcareous slate and the dolomite. The attitude of foliation plane measured at the right bank of Sayali Gad 100 m downstream from the Chhapali-Kauradi road is 265/68 NE. The Galyang Formation comprises the Baitadi Carbonate group which consists of silicious dolomite. Its upper end is marked by the Ramgarh-Munsiari thrust shown in Fig. 4d.

The Syngja Formation Formation comprises white quartzite intercalated with dolomitic limestone as shown in Fig. 4e. The Lakharpata Formation is overlain by the Syngja Formation and it rests on the Tertiary Units at the base. It comprises fine-grained grey limestone and dolomite intercalated with grey to purple shales. The attitude of the bed is 238/75 NE shown in Fig. 4f.

The Suntar Formation of Surkhet Group consists of greenish grey, reddish brown, fine to medium-grained sandstones and purple, dark red even mottled shales interbedded with

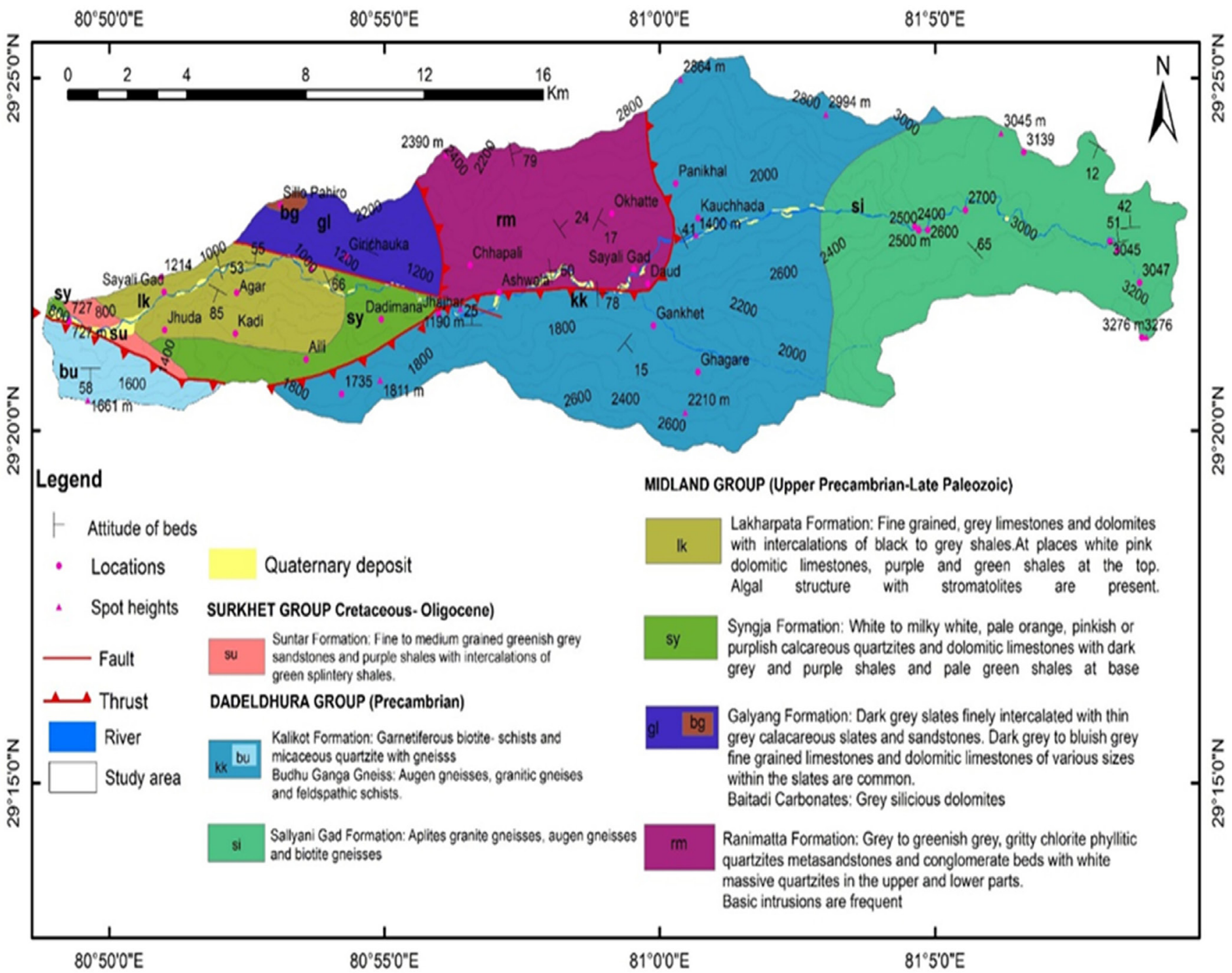

Fig. 3: Geological map of the Sayali Gad basin after DMG (2020).

occasional bands of marls, mudstones, intraformational pebbly shales, and conglomeratic sandstones as shown in Fig. 3.

The quaternary deposits of the study area are the depositional terraces made by rivers as shown in Fig. 3. The terraces are narrow and steeped in the midstream around Baltada, Chama, and Daina and wide in the downstream at Talar. The debris deposits, landslide deposits, and colluvial soils are found at the base of high relief peaks.

Fig. 4: Exposure of different formations: a) Ortho Gneiss of Khaptar Klippe, b) white quartzite of the Kalikot Formation on the right bank of Sayali Gad at transect T1, c) intercalation of dark grey slate with white quartzite of the Ranimatta Formation at Sattarfalne Dhar Okhatte village, d) Silicious dolomite of Galyang Formation at the top of Salghari towards Saukhola Gaon, e) intercalation of dolomite and quartzite of the Syangja Formation on the right bank of Sayali Gad, and f) dark grey slate of the Lakaharpata Formation

Watershed scale parameters

Morphometry of the Sayali Gad basin

The morphometric study of Sayali Gad basin includes stream order, drainage texture, drainage density, stream frequency, and relative relief (Table 1). The relative relief map shows that there is a very high relative relief value at the north-facing side of the Saukhola and Silla as shown in Fig. 5. Most of the basin area has moderate relative relief and the low relief area lies in the lower part of the basin and the source area has very low relief shown in Fig. 5. The Sayali Gad is a fifth-order stream shown in Fig. 6a. The value of stream frequency is categorized here from very low to very high shown in Fig. 6b and the value of drainage density ranges from 0.2 to 1.5 and is categorized from very low to very high shown in Fig. 6c.

Valley types and landforms

Rosgen (1994) classifies the valley from I through XII based on morphometric parameters. The valleys within the Sayali Gad basin were characterized based on the morphohydrological parameters as shown in Table 2. Based on the tectonic effect, slope, depositional environment of the stream, bed material of stream valley types was allocated. Valley type I: V-shaped, confined, structurally controlled, Valley type II: Moderate relief, residual/alluvial soils, gentle floor slopes (supports B types), Valley type III: Depositional (alluvial fans), moderately steep slopes (supports C/E types), Valley type III: Broad alluvial valleys, low relief (supports C/E types), Valley type VII: Highly dissected fluvial slopes, steep (supports A/G types) etc. as shown in Table 2.

There are 6 types of valleys lies within 5th order stream of Sayali Gad, as shown in Table 2. These are I, II, III, IV, VI, and VIII. The type I valley is a V-shaped valley with high relief, a valley slope gradient greater than 2%, and is structurally controlled Rosgen (1994). The bedrock and residual soil are highly dissected by streams. The Valley type II has moderately low relief, is relatively stable, and the valley floor slope is less than 4% with residual sandy soil developed from the granite, gneiss weathering at the Khaptad Patan area. Valley Type III is a depositional valley, having a steep valley floor slope greater than 2%. The upstream section of the fifth-order stream comprises a type III valley. The landforms are narrow flood plains, debris deposits, and colluvial deposits. The valley consists of classic meandering of the river, highly incised and entrenched, gentle elevational relief, and valley floor slopes of less than 2%. The valley is structurally and tectonically controlled, having a moderate valley floor gradient, colluvial and alluvial deposits. The upstream part around Basela, Kaphalkot, and the midstream part around Khinikhet, Baluwa Bridge, and Chama consists of a type VI valley. This type of valley consists of multiple terraces placed laterally along the river. The slope of the valley floor is gentle, and the predominant depositional features are alluvial deposits and flood plains.

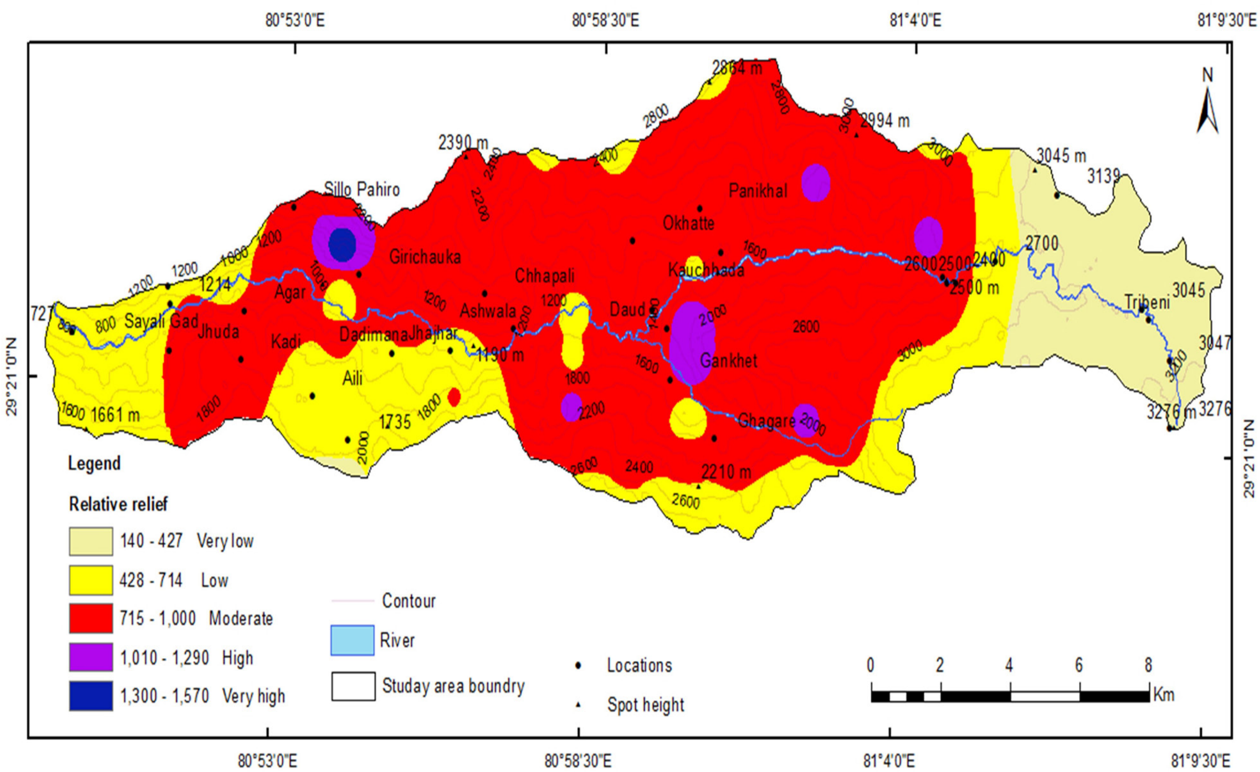

Fig. 5: Relative relief map of Sayali Gad basin.

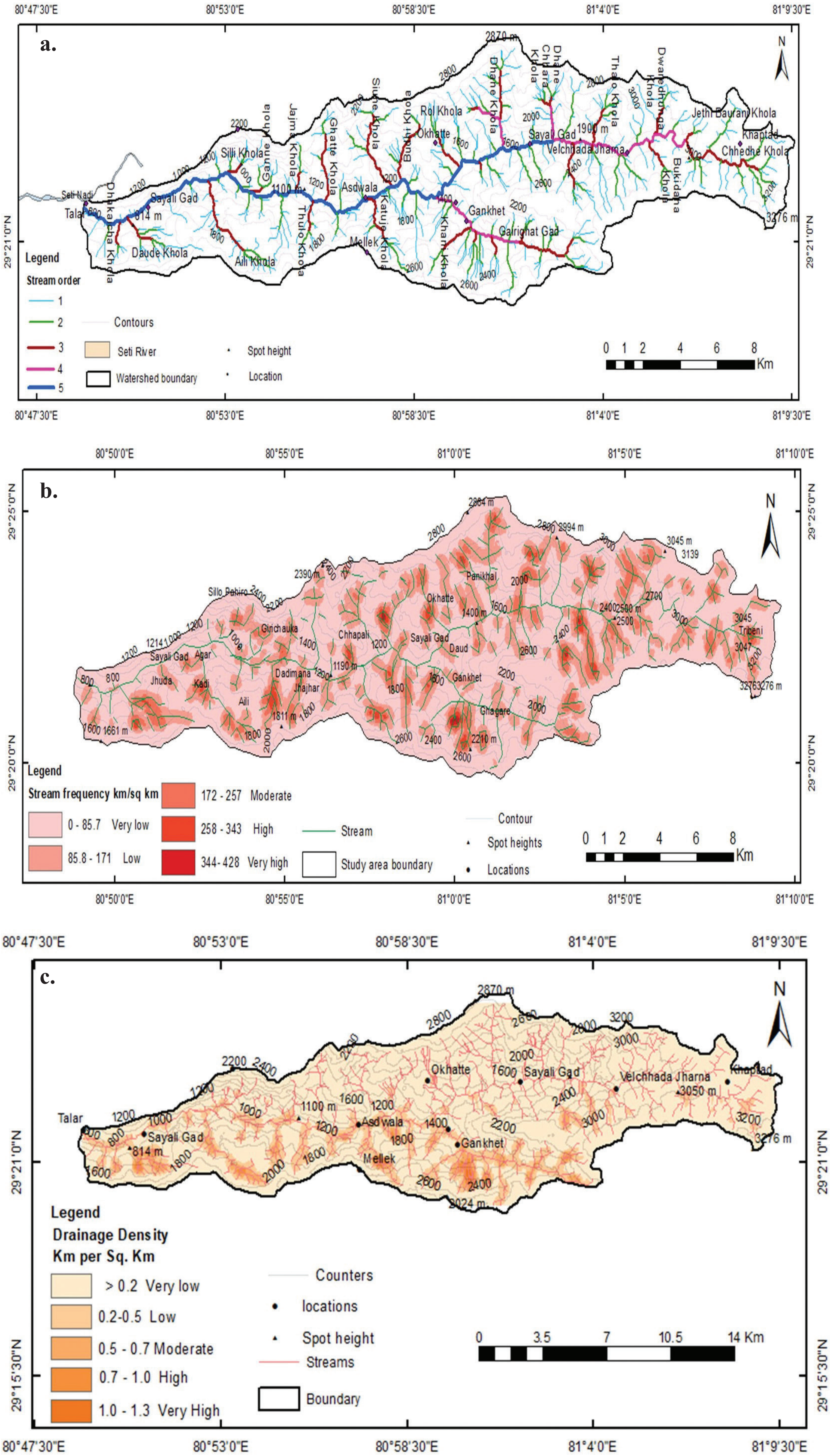

Fig. 6: a) Stream order, b) stream frequency, and c) drainage density map of Sayali Gad basin

Level I classification of the stream

The Sayali Gad is classified into B3, A3a+, B3a, E2b, C3b, C2b, B4, C4c, E4b, C4 and C4 types of streams from transect T1 to T11 respectively as shown in Table 2. Level I stream classification is geomorphic characterization, which is done based on the channel shape, channel slope and channel patterns Rosgen (1994).

Aa+ type stream

The majority of Aa+ type streams found upstream and headward sections have very high relief, erosional features are developed, and cascade-pool morphology is deeply entrenched. The main trunk has two Aa+ streams, the first-order stream at the source and another at the Velchhada Jharna. The waterfall is about 65-70 m long in the quartzitic and gneissic terrain. The Aa+ river is found in the type I valley as shown in Table 2.

A type stream

The A-type streams are found in the upward section of the basin where there is slope percentage greater than 4%. The trunk Sayali Gad evolved into A3a+ stream at transect T2 as shown in Table 2. The A stream has high relief greater than 4% to 10%, entrenched, cascading, steep-pool morphology, relatively high energy, and constitutes debris depositional soils.

B type stream

The B type of stream is found at the transect T1, T3, and T7 the T1 is at the upstream part, T3 is at the upper part of the midstream and the T7 is at the mid part of the midstream segment of the fifth-order stream as shown in Table 2. The B-type stream has moderate relief, erosional terraces, and narrow alluvial deposits. The basin has other small B stream-type tributaries. The associated valley type for T1 and T3 is IV, and for T7 is VI.

C type stream

The C-type streams are found at the midstream and downstream sections of the river at the transects T5, T6, T8, T10, and T11 as shown in Table 2. The characteristics of the C type of stream are moderate to high sinuosity, slightly entrenched, broad valleys, developed into alluvial flood plains, low gradient, riffle-pool morphology, and alluvial soils.

E-type stream

The Sayali Gad at transect T4 and T9 evolve into E-type streams as shown in Table 2. The E type of stream is slightly entrenched, low gradient, has a low width depth ratio, and broad valleys, and consists of alluvial soil. The E-type stream lies in the up section of the midstream and at the downstream section.

Reach scale parameters

Morphohydrologic parameters

The reach-scale parameters are shown in Table 3. The radius of curvature is a maximum m 350 m at T7 and a minimum of 32 m at T2. The meander belt width is large for T7 337 m and small for T1 183.81 m. The sinuosity of the river increases downstream. The minimum value of sinuosity is 1.1 for T2 and the maximum value is 2.3 for T7. The value of morpho hydrologic parameters varies in every transect of the river. The maximum value of Dmax is 4 m at transect T9 and the lowest value is 1.22 m at transect T2. The area of bankfull is a maximum of 95.22 m2 at T1 and a minimum at T5. The bankfull width of the channel is a maximum of 73 m at T10 and a minimum of 19 m at T4. The W/D ratio is highest at 106 m at T11 and the lowest at 9.5 m at T4. The maximum width of the flood-prone area measured is 170 m T T10 and the minimum is 38 m at T2. The highest value of wetted perimeter is 16.33 at T9 and the lowest value is 6.23 at transect T1. The maximum value of the entrenchment ratio is 2.66 at T5 and the minimum for 1.37 at T2.

Table 1: Channel parameters.

Stream order	Channel length (m)	Valley length (m)	Sinuosity (K)	Meander belt width (Wblt) (m)	Radius of curvature (RC)	Meander Wavelength (Lm)
1	111	111	1	20	-	-
2	1116	1034	1.07	98	30	113
3	4394.07	3361.91	1.3	210	19	202
4	8274.18	5948.43	1.39	275	31	410
5	37454.2	26310.34	1.42	330	38	546

Table 2: Level I classification of the stream transect of fifth-order Sayali Gad.

Transect	Valley type		Pattern Sinuosity	Shape	Channel slope	Bed feature	Stream type
T_1	IV	Structurally controlled	Low Sinuosity	Shallow/wide, low entrenched meandering channel	Moderately steep	Riffle-pool	B
T_2	VI	Alluvial colluvial deposits	Relatively Straight	Low W/D ratio more entrenched than E	Moderately steep	Step-pool	A
T_3	IV	Structurally controlled	Low Sinuosity	Low W/D ratio more entrenched than E	Steep	Riffle dominated	B
T_4	VIII	Alluvial colluvial deposits	Meandering	Low W/D ratio more entrenched than E	Steep	Step-pool	E
T_5	IV		Low Sinuosity	Shallow/wide, entrenched meandering channel	moderately steep	Riffle-pool	C
T_6	IV		Torturously meandering	Low W/D ratio more entrenched than E	Moderately steep	Riffle dominated	C
T_7	IV	Structurally controlled	Torturously meandering	Shallow/wide, entrenched meandering channel	Moderately steep	Riffle-pool	B
T_8	IV		Low Sinuosity	Highest W/D ratio	Moderately steep		C
T_9	VI		Meandering	Low W/D ratio more entrenched than E	Moderately steep	Step-pool	E
T_{10}	VI	Wide floodplain deposits	Low Sinuosity	Highest W/D ratio	Gentle	Riffle-pool	C
T_{11}	VI		Low Sinuosity	Highest W/D ratio	Extremely gentle	Riffle-pool	C

Table 3: Planform and morpho-hydrologic parameters.

Transects											
Planform parameters	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Length of thalweg (m)	749	259	440	421	650	688	1104	772	501	574	422
Length of valley (m)	609	235	356	290	466	420	478	654	336	506	348
Sinuosity (K)	1.22	1.1	1.23	1.45	1.39	1.63	2.3	1.18	1.49	1.13	1.21
Meander wavelength (m)	707	261	262	368	487	425	774	770	469	588	393
Meander Belt width (m)	183	219	294	206	319	246	337	243	141	240	206
Radius of curvature (m)	112	32	48	92	56	103	350	246	170	248	161
Meander belt width ratio	4.08	7.85	6.44	10.8	10.6	8.51	11.2	6.76	6.42	3.28	3.32
Hydrologic parameters											
Width at bankfull (m)	45	28	41	19	30	29	30	36	22	73	62
Max depth at bankfull (m)	2.53	2.92	2.09	2.86	1.22	2.54	1.98	1.6	4	2.5	1.08
Mean depth bankfull (m)	2.11	2.37	1.12	1.98	0.84	1.9	0.92	0.6	3	1.13	0.58
Flood-prone width (m)	90	38	88	45	80	55	53	80	50	170	145
Entrenchment ratio	2	1.37	2.14	2.36	2.66	2.24	1.76	2.22	2.27	2.32	2.33
Hydraulic radius (m)	1.91	1.96	1	1.51	0.77	1.61	0.81	0.64	2.2	1.05	0.56
Width/depth ratio	21.2	11.84	36.8	9.5	34	15.2	32.6	55.3	7.3	64	106
Max. Bank height (m)	5.1	5.9	4	6	2.6	5.2	4	3	8	5	2
Bank height ratio	2.01	2	1.91	2.09	2.13	2.04	2.02	1.87	2	2	1.8
Slope of channel	0.02	0.03	0.06	0.06	0.03	0.02	0.027	0.014	0.021	0.013	0.005
Slope of water surface	0.03	0.03	0.07	0.06	0.04	0.02	0.031	0.019	0.029	0.017	0.013
Bed material size D50	0.1	0.07	0.13	0.52	0.02	0.35	0.04	0.05	0.05	0.02	0.003
Area at bankfull (sq m)	95.22	66.36	45.51	37.62	25	55	27.6	23.4	66.22	82.49	35.96

Longitudinal profile of the river

The longitudinal profile of the river shown in Fig. 7 from the source (Sahasralinga 3300 m) east to the mouth west (Talar 711 m) shows a gradual change in slope. There is a slight change in slope at knick point 1 in the Khaptad area and a rapid change in slope at knick point 2 where 65 m long Velchhada Jharna was formed. From midstream to downstream the slope decreases gradually. The longitudinal profile shows the major tributaries, the D_{50} value of the Wolman particle size count, and the change in stream order.

Level II classification of stream

The fifth-order Sayali Gad is classified as B3, A3a+, B3a, E2a, C3b, C2b, B4, C4c, E4b, C4, and C4 from upstream to downstream. The cross-sections from T1 to T11 are shown in Figs. 8 and 9 and Table 4

Transect T1 (B3 type stream)

The B3-type stream lies upstream of the fifth-order stream at transect T1 at the base of the Kachali village, shown in Table 4 and Fig. 8. The stream is moderately entrenched having a value of 2, the W/D ratio is 21.26 is a narrow deep channel, single-threaded, low sinuosity, moderate valley slope 0.02 and the bed material D_{50} size is 0.1 as shown in Table 4.

Transect	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
D50 (mm)	108	70	130	520	25	350	40	50	50	20	3
Stream type	B3	A3a+	B3a	E2b	C3b	C2b	B4	C4c	E4b	C4	C4

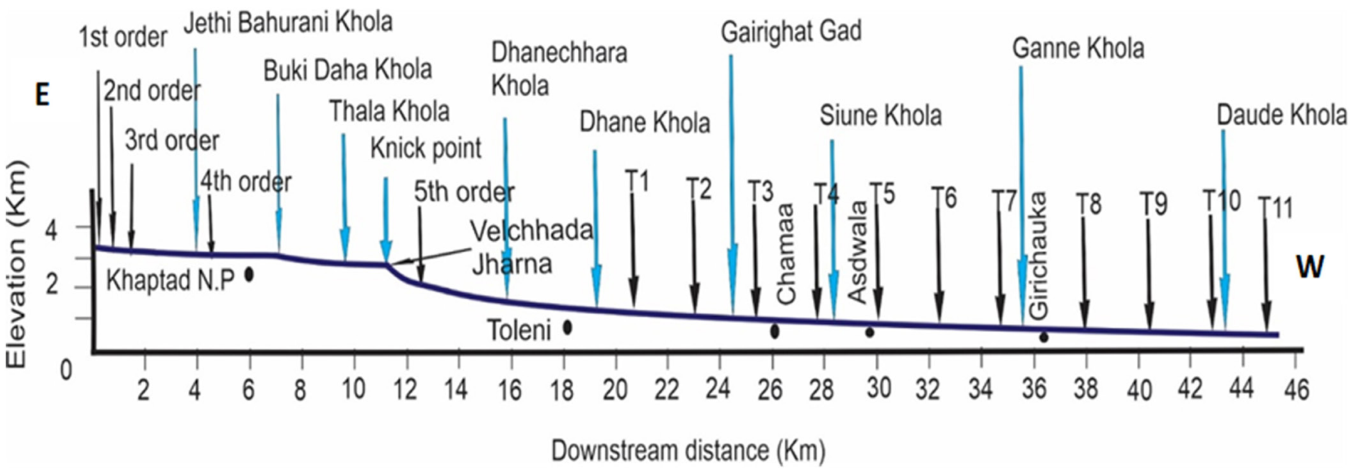

Fig. 7: Longitudinal profile of Sayali Gad.

Table 4: Level II classification of stream.

Parameters	Transects										
	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11
Entrenchment Ratio (ER)	2 B	1.37 A	2.14 B	2.3 C	2.66 C	2.24C	1.76B	2.22C	2.27 E	2.32C	2.33 C
Width/Depth Ratio (W/D)	21.26 B	11.84 A	36.89 B	9.5 E	34 C	15.2C	32.6B	55.3C	7.3 E	64 C	106 C
Sinuosity (K)	1.22 B	1.1 A	1.23 B	1.45E	1.39 C	1.63C	2.3 B	1.18C	1.49 E	1.13 C	1.21 C
Slope (S)	0.02 B	0.03 Aa+	0.067 Ba	0.06Eb	0.035Cb	0.02Cb	0.02B	0.014Cc	-0.021Eb	0.013C	0.005C
D50	0.1 B3	0.07 A3a+	0.13 B3a	0.52E2b	0.025C3b	0.35C2b	0.04B4	0.05C4c	0.05 E4b	0.02 C4	0.003C4

Transect T2 (A3a+ type stream)

The A3a+-type stream lies upstream at about 200 m downstream from Futa Pad Ghatta at transect T2 and is shown in Table 4 and Fig. 8. The stream is entrenched (ER=1.37), Narrow/deep (W/D=11.84) channel, relatively straight (K=1.1), moderate gradient (slope=0.03), and the D50 particle size value is 0.07 as shown in Table 4.

Transect T3 (B3a type stream)

This stream is slightly entrenched (Er = 2.14), wide/shallow channel (W/D = 36.89), meandering (K=1.45), single-threaded, moderately gentle (slope = 0.067), and the D50 value of channel material is 0.13 as shown in Table 4 and Fig. 8. The channel materials are small boulders to cobbles, pebbles, and fines. Both banks are filled up with sand and silt. The bank is sparsely vegetated. The channel has more lateral erosion than vertical erosion.

Transect T4 (E2b type stream)

The Transect T4 is shown in Fig. 8. This is E2b type stream of T4 is slightly entrenched (ER = 2.3), Narrow/deep channel (W/D = 9.5), low meandering (K = 1.45), moderately gentle (slope = 0.06), and the D50 particle size value is 0.52 as shown in Table 4. The channel materials are large boulders in the

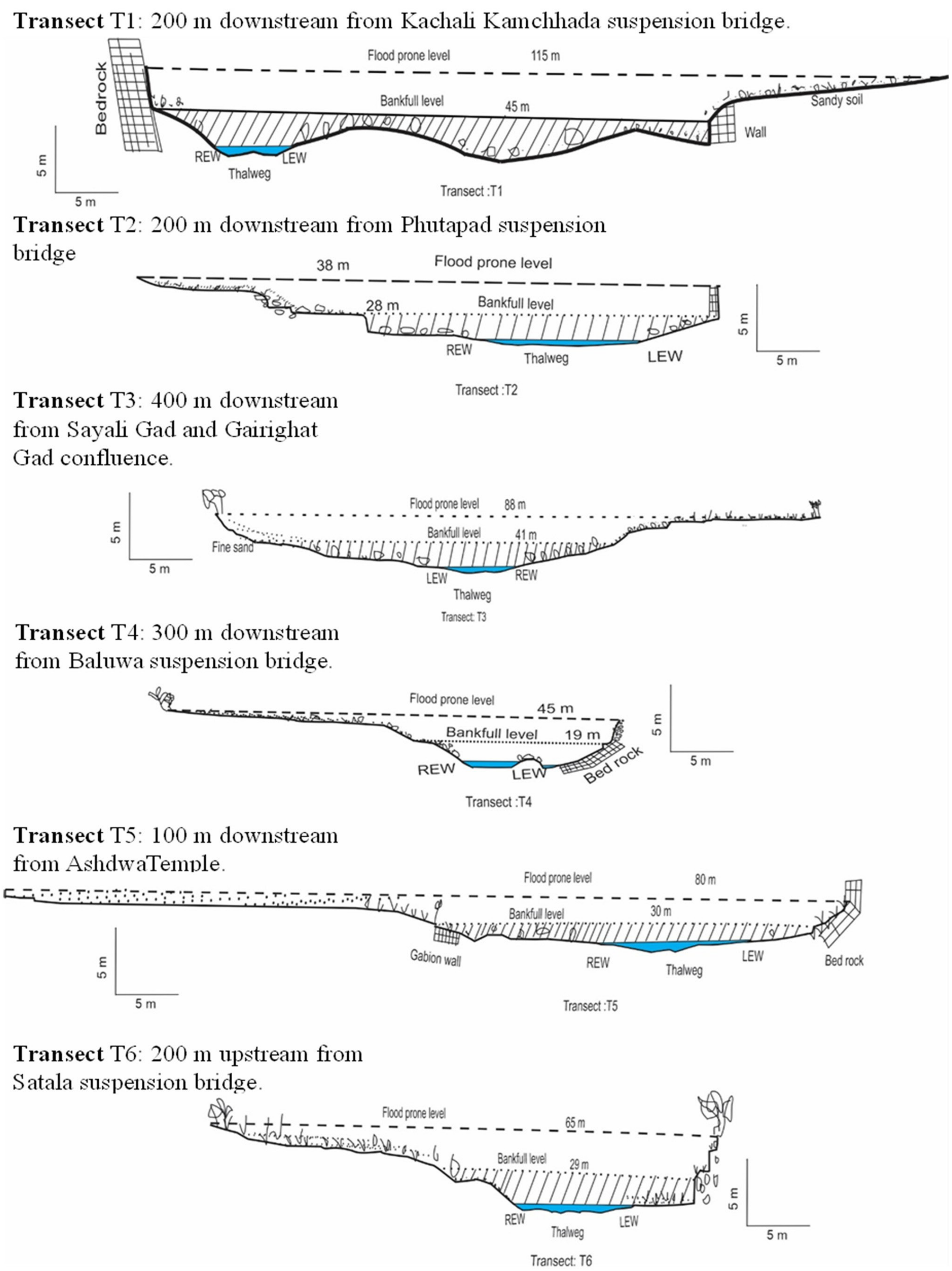

Fig. 8: Cross-section of the river from transect T1 to T6.

middle, a quartzite bed at the left bank, and the alluvial deposit at the right bank.

Transect T5 (C3b type stream)

The B2-type stream shown in Fig. 8. The stream at this transect is gentle (slope = 0.035), single-threaded, slightly entrenched (ER = 2.66), and low meandering (K = 1.39). The mean D50 value of channel material is 0.025mm as shown in Table 4. The overall channel materials are medium size boulders at the channel and comprise cobble, pebble, gravels, coarse to fine sand, and silt.

Transect T6 (C2b type stream)

Slightly entrenched (ER = 2.24), narrow/deep channel (W/D = 15.26), single-threaded, meandering (K = 1.63), gentle (slope = 0.02), and the D50 value is 0.35 mm is shown in Table 4 and Fig. 8. The stream channel consists of boulders, cobble pebbles, gravel, mostly dolomitic composition, sand, and silt.

Transect T7 (B4 type stream)

The F3 type stream of T7 as shown in Fig. 9 is moderately entrenched (ER = 1.76), wide/shallow channel (W/D = 32.6), tortuously meandering (K = 2.3), gentle (slope = 0.02), and the D50 particle size is 0.04 mm as shown in Table 4. The river cuts laterally in the convex side of the channel and deposits in the concave side due to its meandering nature.

Transect T8 (C4c type stream)

The stream is slightly entrenched (ER = 2.22), wide/shallow channel (W/D = 55.38), low sinuosity, and gentle (slope =

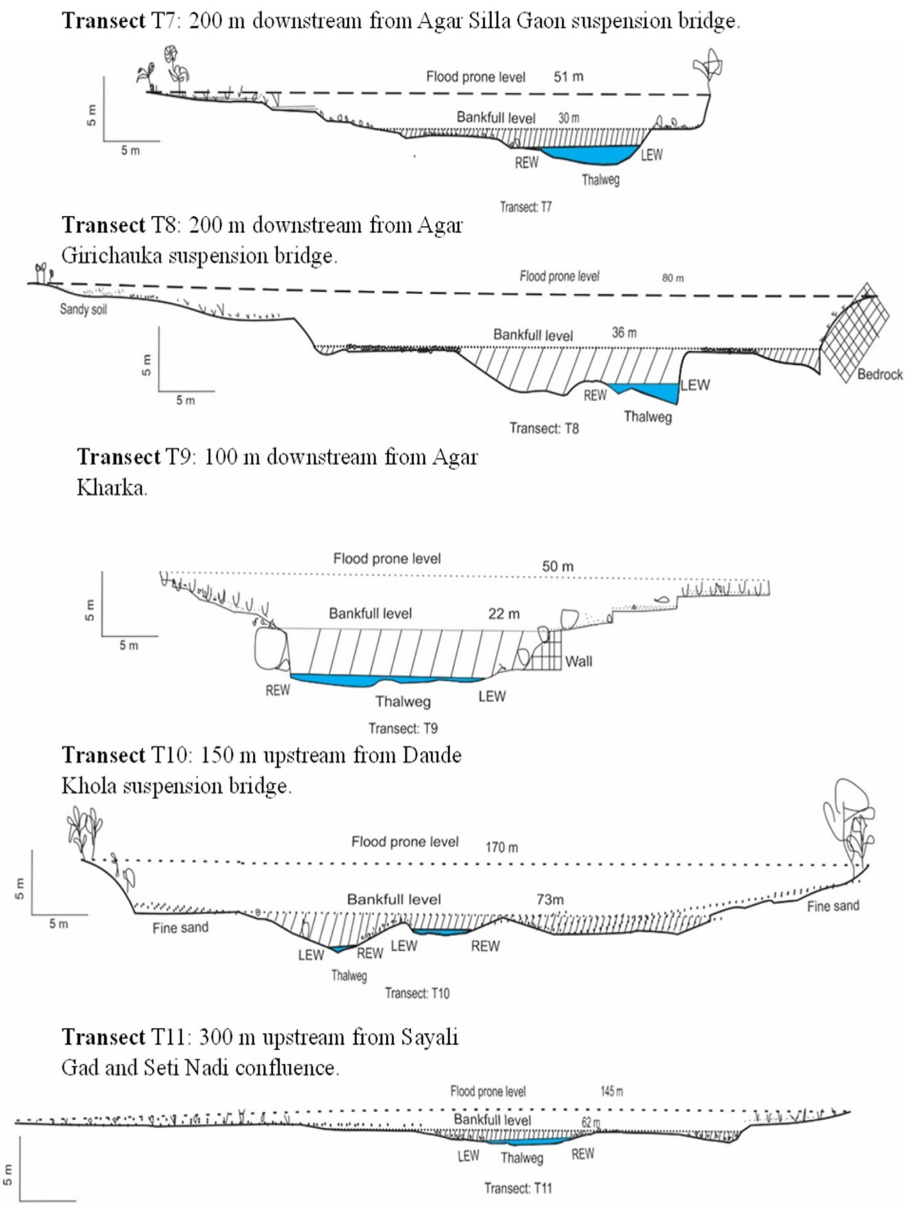

Fig. 9: Cross-section of the river from transect T7 to T11.

0.014) as shown in Table 4 and Fig. 9. The mean particle D50 value is 0.05 mm as shown in Table 4. The channel materials are medium to fine boulders, cobbles, pebbles, sand, and silt. The right bank comprises of sand, silt, and colluvial deposits, and the left bank weathered bedrock and colluvial materials and is vegetated.

Transect T9 (E4b type stream)

The stream is moderately entrenched (ER = 2.27), narrow/deep channel (W/D = 7.3), low sinuosity (K = 1.49), gentle (slope = 0.021), and the D50 value is 0.05 mm as shown in Table 4 and Fig. 9. The river is single-threaded, channel materials are boulders, cobble, pebble, and gravel. Sand and silt. The vertical as well as lateral erosion by the river is pronounced.

Transect T10 (C4 type stream)

The single-threaded river is moderately entrenched (ER = 2.32), wide/shallow channel (W/D = 64), low sinuosity (K =1.130), gentle (0.013), and the particle size D50 value is 0.02 mm as shown in Table 4 and Fig. 9. The channel materials are cobble, pebble, gravel, sand, and silt. Both banks of the river have flood plains.

Transect T11 (C4 type stream)

This stream is a single-threaded meandering, large floodplain deposit as shown in Fig. 9. The river becomes anastomosed downstream where it makes a confluence with Seti Nadi. It is moderately entrenched (ER = 2.33), has very wide and shallow channels having the highest W/D ratio (W/D = 106), is Extremely gentle (slope = 0.005), and the D50 channel material size is 0.003 mm as shown in Table 4. The channel materials are pebbles, cobbles, gravel, sand, silt, and organic pits.

Channel instability

The channel shifting of river is studied based on the temporal channel change, flooding history, bank erosion and human intervention of the fifth-order stream. The temporal channel change is insignificant in the upstream sections, and more in the middle and downstream sections. The significant channel change occurred at Baltada, between Chama and Balwa, and at Khinikhet in the midstream. The major flood events of Sayali Gad are the flood of 2000, 2008 Sep 27, 2016, 2021 October 17. The Dipayal Patihalne Sadak was under construction, which produced excessive sediment in the basin and caused a devastating flood. The sediment carried by Katuji Khola blocks the Sayali Gad and causes flood upstream. Bank erosion is more pronounced in the midstream portion of the river. The unconsolidated, river deposits were transported during flood in river. The loose deposits of Khinikhet were swiped away in the 2016 flood. Human intervention is less pronounced in the upstream section, moderate in the midstream, and high in the downstream. The gradual increase in human settlement across the river aids nondegradable plastics, and metallic materials into the river shown in Fig. 10.

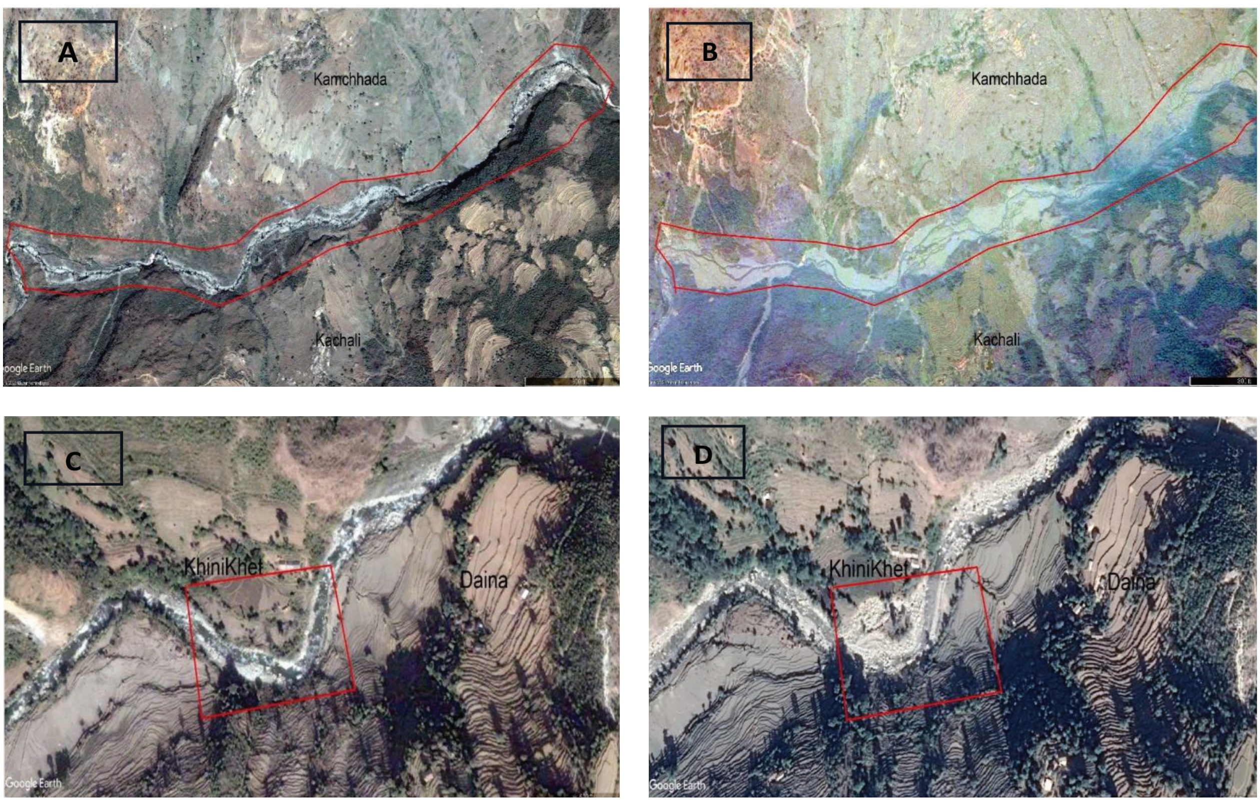

Fig. 10: a) Channel shape in 2009 in upstream part of Sayali Gad, photaken from google earth 4-2009, b) channel shifting of Sayali Gad at its upstream course due to 2016 flood. Photo taken from google earth 4-2016., c) channel state before erosion caudes denundation, 11-2002 , and d) after erosion caused by 2016 flood.

DISCUSSION

The topography is rugged, with very high relative relief at the Silla Saukhola village where a large landslide called Silli Pahiro lies. The evolution of the stream is not in a continuous fashion this indicates that the stream is tectonically as well as structurally controlled, vertically and laterally unstable, and bank erosion is high downstream. Rosgen (2001) concluded that the BHR greater than 1.5 is unstable. The BHR and ER are taken into consideration for vertical instability and MWR and W/D for lateral. Tamrakar (2014) found that the Kodku Khola is highly unstable. The Sayali gad has BHR 2.01, 2, 1.91, 2.09, 2.13, 2.04, 2.02, 1.87, 2, 2, 1.8 from T1 to T11 which is vertically very unstable. The high value of MWR and W/D in the downstream indicate the stream is laterally unstable. Tamrakar (2014) found that the Kodku River is laterally unstable and bank erosion is high. The extraction of bed material causes the disturbance of river flow. Tamrakar (2004) concluded that the excessive removal of channel bank material is another cause of channel erosion. The river is bouldery upstream from T1 to T4, cobbly from T4 to T6, and pebbly from T6 to T11. The stream is active in the upstream and passive in the downstream, indicated by the very gentle gradient.

Tamrakar et. al. (2006) concludes that BHR and ER higher values for Bishnumati river indicates the vertical instability, and MWR and W/D ratio causes lateral instability.

There seen excavation of the gravel/sand materials for construction purpose in the downstream segment 1 km upstream from confluence of Seti and Sayligad. This causes the lateral instability of stream.

CONCLUSION

The basin is elongated crocodile shape having an area of 185 sq km and the drainage is dendritic. The Sayali Gad is a fifth-order stream having a length of 45.6 Km. The relative relief is low in the source area around Khaptad and highest in the Saukhola and Silla villages. The basin has coarse drainage texture, high stream frequency, and stream length in the Khaptad area and south-facing slope. The value of drainage density ranges from 0.2 km per sq km (very low) to 1.3 km per sq km (very high).

The morpho-hydrologic parameters of the fifth-order stream were calculated at an interval of 2 km. There are altogether 11 transects from T1 to T11 respectively. The value of the entrenchment ratio is lowest at T2 is 1.37 and the highest at T5 is 2.66. This indicates that the stream is entrenched at T2, moderately entrenched at T1, T7, T9, T10, and T11, and slightly entrenched at T3, T4, T5, T6, and T8. The W/D ratio increases downstream at T11 it becomes a maximum of 106 and the minimum at T9 is 7.3. The W/D ratio indicates that the channel shape in the upstream is narrow and deep and in the downstream it becomes wide and shallow. The slope of the channel bed gradually decreases downstream and highest greater than 10% at the Velchhada Jharna. The river has low sinuosity at T1 (1.22), and relatively straight (1.1) at T2. The sinuosity also increases downstream and tortiously meandering (2.3) at transect T7. The channel sediment distribution shows that the channel consists of large boulders (520 mm) at transect T4 and lowest at T11 (93 mm). The sediment progressively becomes finer from source to mouth. The valley types are types I, II III, IV, VI, and VIII. The steam types at all transects from T1 to T11 are B3, A3a+, b3a, E2b, C3b, C2b, B4, C4c, E4b, C4 and C4 respectively. The river has pronounced channel shifting throughout the river. The main reason for channel shifting is high discharge, bank erosion, flood, and human intervention.

The river is vertically unstable in the upstream because of high incision, steep sided valley and high entrenchment ratio. Rosgen (2001) concluded that the BHR greater than 1.5 is unstable. The BHR and ER are taken into consideration for vertical instability and MWR and W/D for lateral. Vertically as well as laterally unstable in the midstream and laterally very unstable in the downstream section. At downstream the MWR and W/D ratio is high as shown in Table 4. The channel is very narrow in the upstream and wide but shallow in the downstream which is prone to flooding events. The channel shifting is high, with excessive sediment production. The concerned authority should minimize the risk of flood and make embankments in the bank erosion bed bioengineering is applied and unplanned mining of bed should be prohibited.

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