I.J.S.N., VOL.5 (3) 2014: 577-589 ISSN 2229 – 6441

INTERNATIONAL JOURNAL OF SCIENCE AND NATURE

www.scienceandnature.org

Case Study

IMPACT OF FLUVIO-MORPHIC CONTROLS ON CHANNEL CONFIGURATION - A FLUVIO-MORPHIC ANALYSIS OF RANIKHOLA RIVER (Tista Drainage System) SIKKIM, INDIA

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ABSTRACT
Ranikhola River in Sikkim is one of the significant streams of Tista river system in the hilly terrain of Sikkim. The present analysis involves the stream channel forms; its geomorphic units along with the involved processes which play the most significant role in the deformation of channel, bed and bank along with the typical features registered in the study. The Ranikhola River found in varied environments displayed amazing diversity of forms in different stretches from source to mouth. A number of geomorphic parameters and features have been selected for study and mostly field data collected for specific objectives have been used for representation. The present study is the outcome of intensive field survey following modern methodology and techniques. The study is based on the evolutionary methods in terms of both qualitative and quantitative processes. Final arrangement, tabulations, processing, work schedule calculations presentations interpretation and final measures and suggestions are prescribed based on the collected information through the use of modern field methods (qualitative and quantitative) and analytical processes. Ranikhola River rising in the Sikkim Himalaya (the Lesser Himalaya) is one of the multitudes of south-west flowing Himalayan Rivers of rain fed characteristics, facing different type of hazards which is natural and also man-made. Ranikhola is solely a boulder stream within the hilly terrain of Sikkim Himalaya which gave rise to the varied types of landscape and channel forms. River Ranikhola, possess a dynamic characteristics, as far as materials are considered. Its material ranges from very large boulders to fine sand. Wet channel is characterized by pebbles, cobbles, huge boulders in some parts and very fine sand was also observed. Dry portions of the channel also exhibited the presence of different types of material ranging from big boulders to fine sand. Channel bars, are characterized by accumulation of pebbles and cobbles. Varied nature and characteristics of channel geomorphic units offer spatial uniqueness in relation to their processes and forms. Hill-side slopes, boundary conditions, channel gradient and boundary conditions are major fluvio-morphic controls of channel configuration of the studied river.

KEYWORDS*:* Hilly Terrain, Channel geomorphic units; Boundary conditions; Boulder Streams; Valley confinement; Channel substrata; pool-riffle system

INTRODUCTION
The interaction between river channel forms and processes at a range of space and time scales is most significant in the present geomorphic study. The present analysis involves the stream channel forms; its geomorphic units along with the involved processes which play the most significant role in the deformation of channel, bed and bank along with the typical features registered in the study. Rivers found in varied environments displayed amazing diversity of forms in different stretches from source to mouth. The form of a given reach (length) of channel is controlled by the supply of flow and sediment to its upstream end. Also significant are the channel substrate, valley width, and valley side slope along with the bank composition and vegetation. All these controls vary, both between rivers and along the same river. This creates a long range of fluvial environments and resultant channel forms. The three-dimensional shape of a river is described in terms of its plan form, slope and cross-sectional shape. Rivers continuously adjust their channels in response to fluctuations in flow and sediment supply. An important balance exists between the erosive force of the flow and the resistance of the channel boundary to erosion. Here in this paper the forms and processes of channel and its geomorphic units of River Ranikhola have been studied by primary observation from field survey. A number of geomorphic parameters and features have been selected for study and mostly field data collected for specific objectives have been used for representation. A micro level study has been carried out to determine the geomorphic status of the stretches of the channel, a detailed study (observation and analysis) and finally interpreting the observed character relating to the present status and problems of the channels.

Problems Defined and Objectives of the Study
The major objective is to carry out the micro-level study to determine the geomorphic status of the stretches of the channel and finally to interpret the observed character of the channel in relation to the present status and relevant problems. Any stream channel is invariably controlled by various litho-structurals and tectono-topographical faces which finally reshape and modify the channel bed and boundary condition of the respective channel. Apart from that, other ***crux of the problems studied are*** – i) to define

the channel as specific geomorphic units; ii) to delineate and distinguish the channel geomorphic units along with their causes of formation and spatial nature; iii) to extract the in stream forms from the different segments of the river and to define their processes and nature and finally, to highlight the fluviometric controls and processes for differential nature of channel configuration. Notwithstanding that, rate of discharge, velocity, volume of water and sediment load along with channel and bank parameters are very much responsible for configuring the channel shape and sizes.

METHODOLOGY

The present study is the outcome of intensive field survey following modern methodology and techniques. The study is based on the evolutionary methods in terms of both qualitative and quantitative processes. The functional methodology and land use map of the area have been prepared based on field observation in relation to socio-cultural characteristics. The data were collected and analyzed to understand the morphology of the settlements of the region. Hence to achieve and fulfill the objectives of the study, the whole field work has been conducted in these stages—pre field, field and post field.

In the pre field study relevant information, literature, maps and statistical data relating to the study of the area have been analyzed to acquire sufficient knowledge for conducting the survey work conveniently. Relevant secondary data are searched and collected to acquire knowledge of the area beforehand where survey work is to be conducted. The base map has been prepared and work schedule has also been formulated in this stage. The field work is concerned with the collection of data, information, photographs, with the help of dumpy level, clinometers and prismatic compass. During the field work different type of survey is carried out to get relevant information about the fluvial impact on the channel configuration. These surveys provide us the data, the analysis of which forms the major and integral part of the survey. Field work is related to field methodology especially for carrying out the observation and collection process in the field. Primary data have been collected through ground observation. Post field work is very much significant especially for presentation, analysis, interpretation and drawing inferences. In the post field stage, study of collected data and information were analysed and different maps were prepared with proper statistical and cartographic methods for the transmission of data, helping us to evaluate the study in a systematic manner. Final arrangement, tabulations, processing, work schedule calculations, presentation, interpretation, and finally measures and suggestions are prescribed based on the results and discussion through the use of modern field methods (qualitative and quantitative) and analytical processes.

Materials used for the study

Different instruments have been used during the field survey for the collection of primary data in order to get relevant information for respective works. Data has been extracted by different type of survey. Data obtained by different surveys form the major and integral part of the study. Primary data collection has been collected using various traditional and modern instruments like the dumpy level, prismatic compass clinocompass, GPS etc. Velocity and discharge variations have also been measured by current Meter and by traditional method according to spatial situation. Secondary data has been collected from topographical survey sheets and Google Earth.

Constraints of the study

I surveyed the river basin of Ranikhola, on 4th, 7th to 9th April, 2013. I had measured the characteristics like shape, size, height, width and slope of the banks and also found some very special and interesting feature in the basin. But the limitation of my work is due to short time span. Though Ranikhola River is more or less narrow, still the high discharge and high velocity of the river along with great depth caused problem in crossing the channel and extract the data. Moreover the river is full of boulders; even at places surrounded by thick vegetation cover and therefore many sections of this river were not reachable.

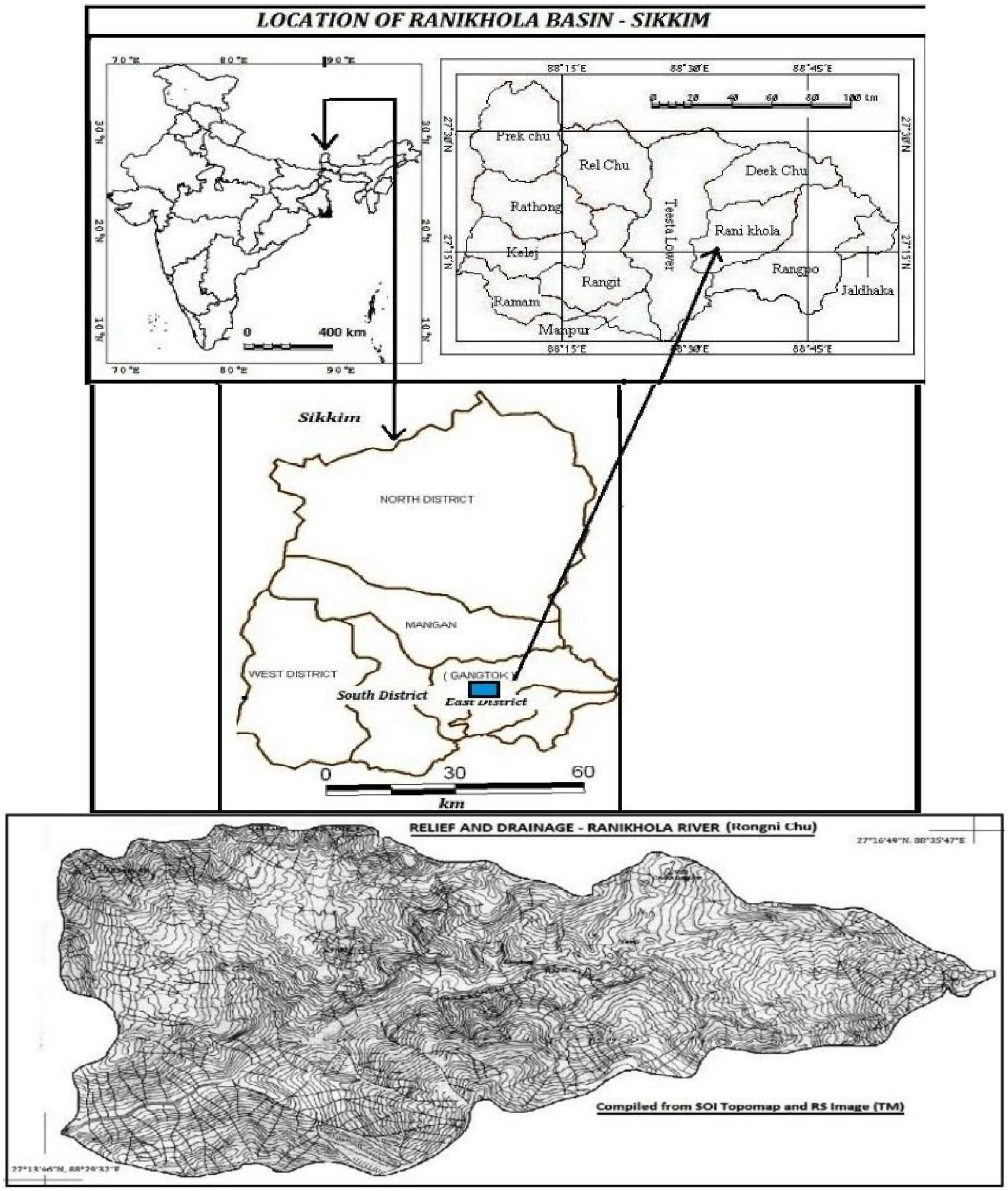
Study area

Ranikhola River rising in the Sikkim-Darjeeling Himalaya (the Lesser Himalaya) is one of the multitudes of south-west flowing Himalayan Rivers of rain fed characteristics. Sikkim is a part of Lesser Himalayas. The study area which is situated in the southern mountain ranges of Eastern Himalayas, facing different type of hazards which is natural and also man-made. The region is the interfluves of numerous rivers and rivulets. Because of highland situation, rivers are swift and fast flowing. They are able to erode and carry the detritus as per specific gravity, like boulders, pebbles, singles, coarse sand, fine sand and silt. These diversities bring about local modification of slope configuration by way of bank velocity distribution and other related fluvial variables. Ranikhola River Basin spreads over an elongated stretch in the Lesser Himalayas in the Indian state of Sikkim from Ranipool to Singtam within the geographical co-ordinate 27°16'49.02"N, 88°35'47.11"E and 27°13'45.50"N, 88°29'31.71"E respectively. The north-east to south-west flowing tributary of Teesta, Ranikhola river basin has a total area of 118.31 km². Problem selected, i.e., the status of the bank and channel with special reference to bank erosion – a micro-level study of Ranikhola River and for this purpose the land mark of the studied span is from Sikkim Science Centre (where Kalikhola and Taksam Chu meets) to Singtam (where it meets Teesta River).

Drainage and Channel Characteristics

The form of a channel is largely a function of the water and sediment supplied to it. Adjustments to channel form occur as result of process feedbacks that exist between channel form, flow and sediment transport. At the reach scale, the type of adjustment that can take place is constrained by the valley setting, the nature of bed and bank materials and bank vegetation. This gives rise to a wide diversity of different channel forms. There are various controlling factors responsible for formation of varied channel forms. Flow and sediment supply both fluctuate through time which result in continuous adjustment through erosion, reworking and deposition of sediment. The flow and sediment regimes are called ***driving variables*** because they drive these processes. Along a given reach, channel adjustment is constrained within certain boundaries that are imposed by local conditions. Energy availability is also important and channel adjustments are often limited for rivers that flow over low gradients, especially where cohesive banks are protected by vegetation. These constraints are called boundary conditions. *These include – i) Valley side slope, ii) Valley confinement, iii) Channel substrata, iv) Riparian Vegetation, v) Cohesive and non-cohesive bank, vi) Bank with solid bed rock.*

This refers to the downstream slope of the valley floor and determined the overall rate at which potential energy is expended along a given reach. The valley slope imposed on a given channel is determined by a combination of factors including tectonics, geology, the location of the reach within the drainage basin and the long term history of erosion and sedimentation along the valley. A channel may be defined as confined, or unconfined, depending on how close the valley sides are. In confined settings channel adjustment are restricted by valley walls, which also increase flow resistance. In partially settings some degree of lateral migration and flood plain development is possible. In unconfined setting the hill slopes are a long way from the channel and have relatively little influence in contributing to the channel load.



Relief and Drainage of Ranikhola Basin- Totally a hilly Bedrock stream

The substrate determines how resistant channel is to the erosive force of the flow. It also determines the boundary roughness. Alluvial channel formed in sand and gravel is generally more easily adjusted than those with cohesive silt and clay substrata. Bedrock and mixed bed rock alluvial channels are influenced over a range of scales by various geological controls. Vegetation on the banks and bed of river channels control channel form in various ways. It often acts to protect and strengthen the banks. As a result, channels with vegetated banks are often narrower than those with non vegetated banks under similar formative flows. Ranikhola River in Sikkim is a tributary of Teesta. It flows from north-east to south-west direction and at the end of its course it drains into Teesta at Singtam. Topography of the entire river course is characterized by uneven elevation. It varies from 784m (Ranipool) to 341m (Singtam) above mean sea level. Ranikhola river basin encompasses an area of 118.31 km² and covers a distance of nearly 17 **km** until it meets Teesta River in Singtam. Shape of the basin is sub-circular (2.44) which highlights moderate flood discharge. The form factor calculated shows the basin to be of moderately elongated nature. Elongation ratio value of the basin calculated also signifies the basin to be of elongated to oval shape. The difference between the highest and lowest relief of the basin is 472 meters. The entire basin of Ranikhola river sets on a highland area. The entire river course has been sub-divided into three distinct stretches, viz., the upper course, the middle course and the lower course in order to study the entire drainage basin on the basis of fluvio-morphic controls on channel configuration and their impact. The upper stretch extends for nearly 4.20 kilometers. The stretch is irregular in the upper portion and more or less meandering in the lower. Mid channel bars are present in some portions of the studied channel and the channel course is rocky in character. The middle stretch extends for about 8 kilometers. Due to a long course the middle stretch has been divided into two sub-stretches, viz., the middle-upper stretch and the middle-lower stretch. The middle stretch being more or less straight and presence of sediment load is less in comparison to the upper course. The lower stretch is the shortest stretch and extends for 3.60 kilometers. It has an irregular pattern before it drains into Teesta. In order to study the drainage characteristics and fluvial processes, affecting bank configuration of Ranikhola River Basin, the basin has been divided into four distinct courses, viz., the upper course, the middle-upper course, the middle-lower course and the lower course. The upper course stretches from the point where Kalikhola and Setikhola meets near Sikkim Science Centre also locally known as Chota Singtam to Samdang. The middle course has been divided into two parts for convenience. The upper part extends beyond Samdang till Nimtar, including the area covered by Nimtar water park and the middle lower part extends beyond water park till its confluence with Rangdo khola. The lower course stretches from the confluence of Ranikhola and Rangdo khola till its confluence with Teesta in Singtam. River Ranikhola, possess a dynamic characteristics, as far as materials are considered. Its material ***ranges from very large boulders to fine sand***. Wet channel is characterized by pebbles, cobbles, huge boulders in some parts and very fine sand was also observed. Dry portions of the channel also exhibited the presence of different types of material ranging from big boulders to fine sand. Channel bars, are characterized by accumulation of pebbles and cobbles.

Longitudinal and cross valley profile

Longitudinal profile of the river basin has been plotted. A break in slope has been observed at two sections of the longitudinal profile. The longitudinal profile of a stream shows its slope or gradient. It is the visual representation of the ratio of fall of a stream to its length over a given reach. The longitudinal profile of the river is a graph of height against distance downstream. Rivers occupy the lowest part of the saucer shaped catchments, so channels tend to have progressively gentler gradients from the headwaters to river mouth.

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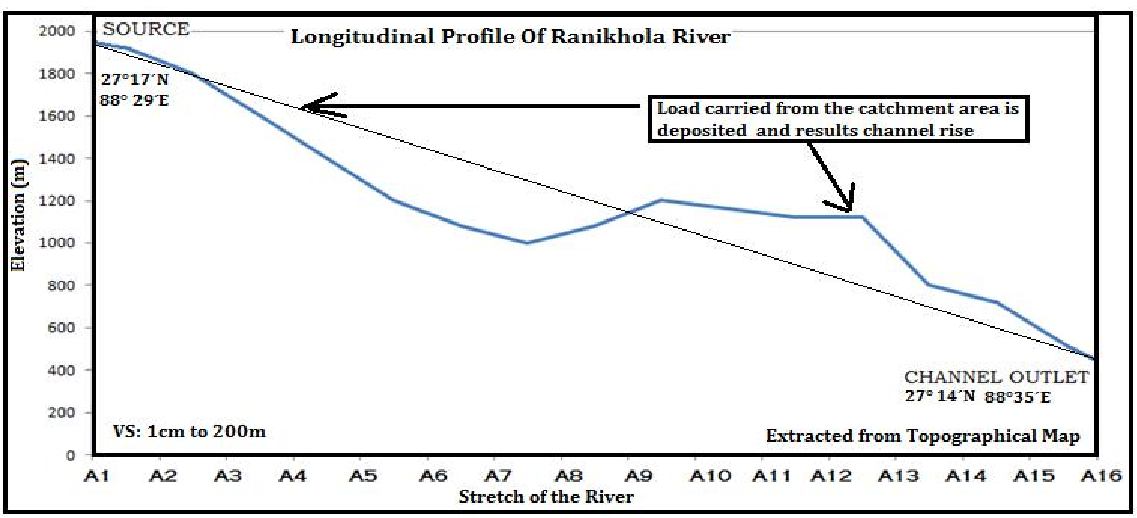
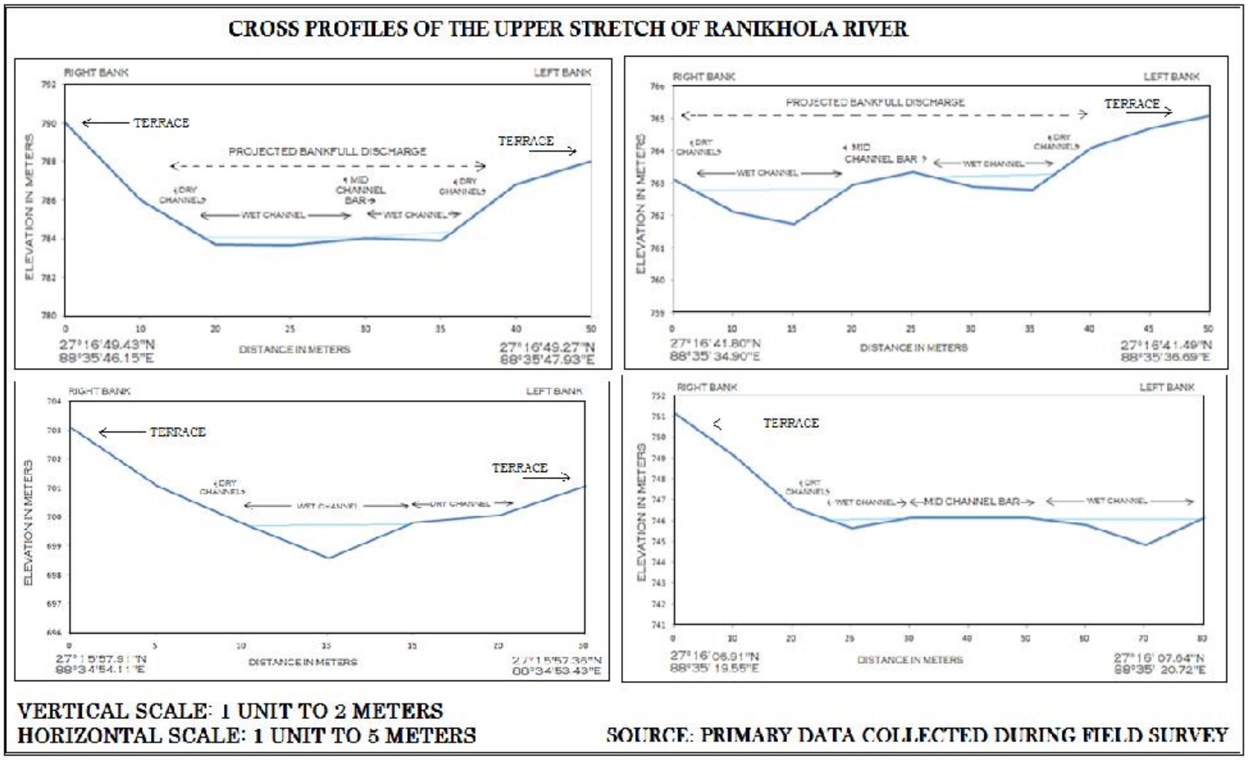
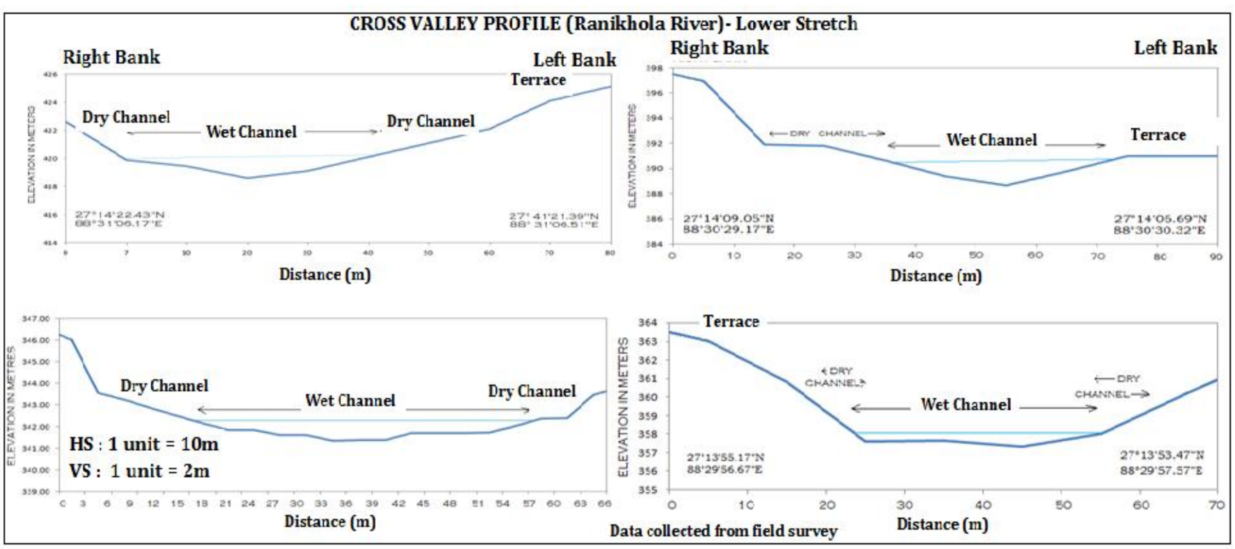


The overall slope decline is interrupted where river cross bedrock and where tributaries join main channel. When the long section of the channel is examined a closely spaced alternative deep and shallow reaches i.e., '***Riffles and Pools'*** can be identified.



Cross profiles across the river has been taken, in all the three courses. The cross profiles are taken across the river north-west to south-east direction. In each of the profiles, the river valleys, including the right bank, left bank, wet channel as well as the dry channel are demarcated. These cross profiles, are tremendously useful in studying the valley characteristics and form. From these profiles, it is quite clear that Ranikhola do not experience bank full discharge throughout the year and the wet channel flow is confined in a particular area. Valleys are comparatively wide in order to accumulate large volume of water during high discharge periods. From the *cross profiles of the upper stretch of Ranikhola river* one can notice a change in the river pattern, configuration of river changes. A change in bank slope and bank height is observable. A close study also reveals a change in channel materials. In most cross profiles of the upper stretch, mid channel bars are observed. During bank full discharge, the cross sectional area and mean flow depth of the river increases in turn increasing the wetted perimeter of the channel. In the above cross profiles present water channel, dry channel and mid channel bars has been marked along with its projected bankfull discharge.



Cross valley Profile of the Lower Stretch of the Ranikhola River

In the ***upper part of the middle stretch,*** no mid channel bars are observed. The depth of the river is comparatively more in comparison to that of the upper stretch of the river. Even an observable change in bank height, bank slope and configuration can be observed. More or less in all the cross profiles the left bank is higher than that of the right. Similar to that of the upper part of the middle stretch, ***the lower part of the middle stretch*** shows similar characteristics. Mid channel bars are not observable in this stretch. Orientation of bank and its configuration, bank height, bank material, bank slope and other characteristics changes as one move down slope the channel. A very different characteristic feature can be observed by studying the cross profiles of the *lower stretch of the Ranikhola River*. The depth of the stream decreased rapidly in this stretch while the width of the channel increases. The characteristic feature of this stretch is completely different to that of the other stretches studied. From the field survey and from the above cross profiles of every stretch of Ranikhola River we can conclude that in areas where the channel is narrow with a deep valley the flow velocity is fast and the flow is concentrated in a short width. In areas where the depth of the valley is less, the width of the channel increases and the velocity decreases considerably. Roughness of the channel bed decreases the velocity where it is moderately fast. It can also be concluded from the studies that studying the velocity across a stream in case of straight sections, it is maximum in the centre of the stream. Studying the vertical velocity profiles one can conclude that fastest flow can be observed just below the water surface.

Channel pattern: Controls and Nature

Considering the pattern it is seen that in the upper course, river Ranikhola is a *boulder stream with a swift flow*. Small rapids are observed all along the channel especially in the middle stretch where the depth is comparatively more. The studied upper stretch of the river is characterized by boulders all over mainly along its banks. *Channel bars* are observed in certain parts of the channel. While in the middle stretch a combination of *pool-riffle* system is observed. Considerable depth can be identified where pools are formed. The middle stretch is characterized by fewer boulders in comparison to that of the upper part. Riffles are seen in this stretch where the channel is comparatively deep and subsequently velocity is minimum. In some regions due to the effects of landslide the width of the channel has been narrowed. In those sections of the valley 'Boulder bars' are observed and the flow is diverted though the channel gradient is high. Though a rapid flow is observed in the lower course due to high discharge, but the amount of boulders in the stream is minimal. Fine grains sediment load characterize the stream in its lower course. Discharge is very high in the lower stretch as the river is joined by sub tributaries all along its course. No bifurcations are observed in the above mentioned stretches. The lower course is very flat as compared to other stretches. The width of the channel varies from 6 to 30 meters. The channel is straight in some stretches, irregular in some and also in some parts have sinuous and meandering nature. The channel is characterized by mid channel bars, convex bank depositional feature at meanders, alternate pool-riffle system, finer sediments in areas of low velocity has formed ripples, prominent bank erosion in all the stretches of the river. Erosive nature of the river has compelled man to construct guard walls in order to protect the surrounding. With so many environmental variables influencing channel form, an enormous range of channel forms and behavior is possible. ***Bedrock channels*** represent a wide diversity of form from source to mouth. In comparison with alluvial channels, bedrock and mixed bedrock-alluvial rivers have received relatively little attention until recently. These channels are strongly influenced by the resistant nature of substrata. Structural controls, such as joints, bedding planes, and the underlying geological strata can all have a significant effect on flow processes and river morphology. The River Ranikhola;, both have a variable channel pattern including braiding, meandering, and straight and even forming gorges at places as well. Landslides are common along the river bank as cliff like bed rock is well exposed along the river valley wall. The evident forms of channel in the study area were Boulder trapped braided flow, boulder streams. The river have bedrock channels and show variations in channel slope and bed roughness. River Ranikhola, possess a dynamic characteristics, as far as materials are considered. Its material ***ranges from very large boulders to fine sand***. Wet channel is characterized by pebbles, cobbles, huge boulders in some parts and very fine sand was also observed. Dry portions of the channel also exhibited the presence of different types of material ranging from big boulders to fine sand. Channel bars, are characterized by accumulation of coarse grains, pebbles, cobbles and boulders.

Channel Configuration – A Trait of Channel Pattern

The alignment and layout of channel on the part of existing topography portrays the channel pattern with all its inherent characteristics display the channel configuration while there are different circumstances of the development of the varied channel characteristics. In this respect the quantitative, qualitative and geometric parameters are most useful for the channel pattern changes in terms of hydraulic and geomorphic laws and other relevant factors. Actually, by the term channel pattern denotes the nature and pattern of flow or the nature of velocity and discharge within the channel and its impact on the channel slope and bed topography and ultimately the interaction between flow pattern and valley confirm the configuration of channel. So, initially with the help of channel pattern indices the present attempt will try to ascertain the channel configuration status of the river Ranikhola. Within the studied stretch a composite pattern is observed and as the composite pattern owe to different geomorphic processes of development, the need for outlining a classification under different geomorphic environments may even be attempted but the basic indices of channel configuration can be assessed from the degree of their sinuosity.

Factors Controlling Channel Pattern

From the initial stage of growth and development of Ranikhola river network its nature, characteristics i.e., overall configuration are significantly controlled by and the reflection of a number of physical, tectonic-structural and anthropogenic factors in particular for subsequent changes and modifications. the significant components are – a) Topographic , b) structural, c) Tectonic, iv) Lithological, v) Hydrological, and the resultant geomorphic processes play a significant role individually or jointly and some interesting empirical relationships have been established of forms and hydrological identity which can perform distinguishing role to represent the channel as an independent unit on all its controlling parameters. Undoubtedly, the controlling factors of channel configuration have the significant role to distinguish the channel characteristics. So, now the significant variables and indices have been identified and their index values can give the channel a distinct status in fluviometric point of view. Channel configuration based on specific channel parameters are actually the behavioral response of several natural factors and geomorphic processes and the usual consideration of linear and aerial aspects of the channel itself. *So, the resultant indices which can qualify the channel configuration and their varied characteristics are as follows:*

I) The **span of channel** considered for quantify, analysis and interpretation.

II) The **observed and actual length of the channel**.

III) Besides actual length of the channel, **valley width and extension, thalweg length, observed status of meander, length of the mid channel axis etc.** are considered as important.

IV) Micro level divisions of the channel within the studied span and distinguish them as straight, meandering, braided and compound channel pattern.

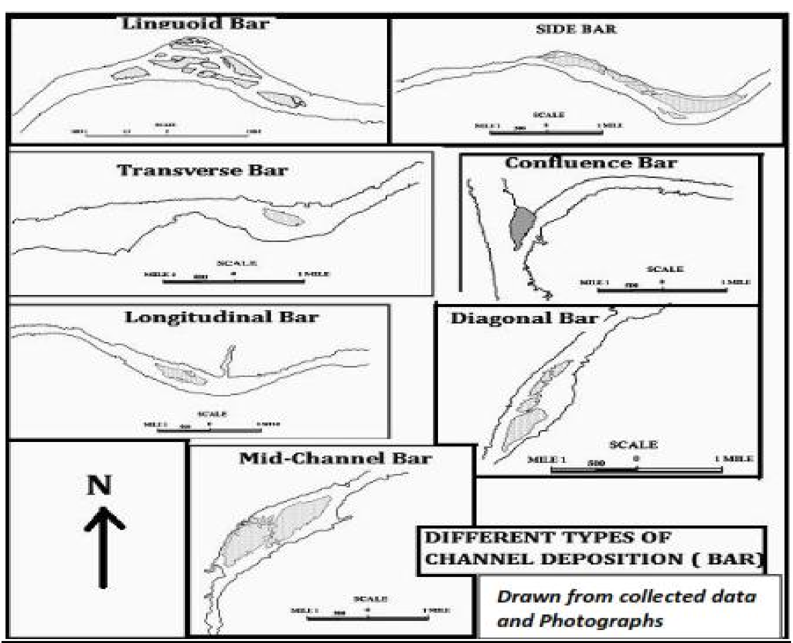
V) To recognise the pattern perfectly different indices are to be considered for the delineation of the configuration characteristics distinctly.

VI) Particularly with the help of sinuosity index configuration characteristics of **straight valley length (l) – actual and mid channel length, width (w), nature of wetted channel etc** are to be observed. For meandering channel ***different types of meander indices, i.e, meander belt, meander belt axis, meander core , meander scour, meander wave length and nature of scouring offer significant configuration traits for the present problem.***

For **Braided pattern,** channel length and width are most important in terms of flow pattern. In this respect seasonal flow pattern, variation of discharge and velocity with the increasing and decreasing volume of water, nature and characteristics of load significantly influence the channel morphology and topography. In assessing the configuration and characteristics of studied span the channel has been divided into distinct segments according to its morphometric distinctiveness and based on the differentiation of other important indices analytically considered. In most cases indices are to be determined by field observation or from the high resolution true color images and from GPS recording along and across the channel.

Morphological Classification of Channel Geomorphic Units

Channel geomorphic units are features at the sub channel scale and are erosional or depositional in origin. Geomorphic units also affect hydraulic processes and provide a range of different habitats for in stream flora and fauna. However, we can distinguish the various in stream geomorphic units in the studied river. Among all the bars of different shape, alignment and sizes are most significant. Those are formed in different segments within the channel. Bars may classified as --- ***a) Longitudinal Bars, b) Transverse Bars, c) Point Bars, d) Diagonal Bars, e) Medial Bars, f) Lateral Bars g) Boulder Bars.***



Different Types of In Stream Deposits (Bars) of Ranikhola River from different Location from the Field

Bar Identity	In- Stream	Size	Slope	Area in sq m	Perimeter	Location	Shape	Composition
1. Channel Junction Bar	Ranikhola Teesta confluence	Length 78.2 ft Breadth 167.2 ft Altitude 1117ft	Downstream (N – S)	4.017	0.355 km	7° 13'48.40"N 88°29'31.75"E	Lobate or Oval	Medium to fine grained sand, coarse grained rock fragments and boulder mixed with pebbles
2. Linguoid Bar	Rongpo chu	Length 69 ft Breadth 45 ft Altitude 1407 ft	Downstream (W-E)	13.76	2.49 km	27°11'12.70" N 88°32'57.22"E	Irregular and Lobate	Pebbles, boulders and coarse grains
3. Transverse Bar	Rongpo chu	Length 89.6ft Breadth 27.9 ft Altitude 1476ft	Downstream (E-W)	1.38	0.21 km	7°11'31.78"N 8°31'04.66"E	Lobate shaped	Gravels, boulders, rock fragments
4. Longitudinal Bar	Rongpo chu	Length 112.3 ft Breadth 30.3 ft Altitude 1537 ft	Downstream (NE-SW)	0.0036 78 km²	0.51 km	7° 11'39.43"N 8°36'37.30"E	Elongated	Sand, silt like fine materials along with boulders

Morphologic and Morphometric characteristics of In-Stream deposits (Bar)

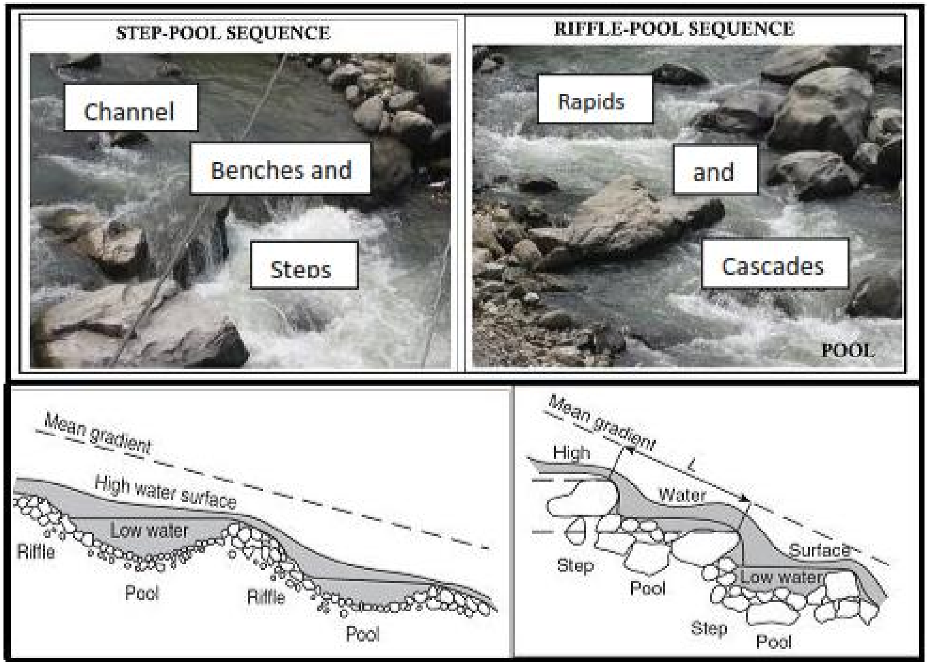
Bar Identity	In- Stream	Size	Slope	Area in sq m	Perimeter	Location	Shape	Composition
5. Diagonal Bar	Rongpo chu	Length 22 ft Breadth 139 ft Altitude 1776 ft	Upstream (SW-NE)	0.0034 52 km²	0.78 km	7°12'18.73"N 8°38'34.37"E	Obliquely oval	Gravels, Boulders, cobbles and silty materials
6. Mid Channel Bar	Ranikhola	Length 370 ft Breadth 189 ft Altitude 1560 ft	Downstream (NE-SW)	0.0018 99 km²	0.39 km	7°16'24.12"N 8°35'22.69"E	Symmetrical and lobate	Coarse grained rock fragments and boulder mixed with pebbles
7. Triangular Bar	Ranikhola	Length 260 ft Breadth 90 ft Altitude 1420 ft	East wards	0.0079 77 km²	0.58 km	7°14'25.78"N 8°31'05.21"E	Asymmetrical shape	Clay, silt, boulder and cobbles
8. Side Bars	Ranikhola	Length 246 ft Breadth 78 ft Altitude 1354 ft	Stream ward	0.0292 52 km²	2.45 km	7°11'13.23"N 8°33'48.80"E	Irregular shaped	Sand, silt and clay

Morphologic and Morphometric characteristics of In-Stream deposits (Bar)

Longitudinal bars are elongated in the direction of flow. They form in the centre of the channel typically where the channel is wide. The bar growth is brought about by the accumulation of finer materials, both in an upwards and in a downstream direction. Transverse bars are lobe shaped with relatively steep downstream faces. They are commonly found where there is an abrupt channel expansion and downstream from confluence. They are not usually attached to the bank. Mid channel bar are symmetrical bars detached from the bank and have characteristic lobate shape. One such bar was found at the River Teesta and River Ranikhola. Lateral Bars are attached to one bank and have asymmetric shape while boulder bars form in channels is dominated by coarse bed load. Diagonal Bars are common in gravel bed channels. They are bank attached features that run obliquely across the channel. They have a steep downstream front.

CHANNEL BENCHES

Channel Benches are flat topped or sometimes gently sloping, elongated, depositional features that can form along one or both banks of channels. They typically are found on the inside of the bends and along straight reach, and are intermediate in height between level of the channel bed and floodplain.



Different Types of Channel Benches and Steps of Ranikhola River
Correlation Between Riffle-Pool sequence and Channel Gradient- Ranikhola River

They are also found in the mid channel position in different orientation. In boulder bed or rocky channel heaps of boulder may form a *boulder berm* may form at the edge of the channel benches also occur where flow separation occurs at the outer (concave) bank of tightly curving meander bends which results in deposition. The major channel benches observed on the channel bed of the studied river are - *Riffle pool sequence, Steps and pools, Rapids and cascades, Potholes, Bed rock Bars.*

Riffle pool sequence come from trout angling and refer to large scale undulations in the bed topography. They are commonly found in gravel bed channels with low to moderate channel slopes but do not tend to form in sand or silt bed channels. The difference between riffles and pools is most obvious at low stages, when the flow moves rapidly over coarse sediments in relatively steep riffle sections and more slowly through deeper pools. These features can be found in straight, meandering and braided reaches. Steps and pools often characterize steep, upland channels and have been observed in a wide range of humid and arid environments. The steps are formed from coarser material and form vertical drops over which the flow plunges into the deeper, comparatively still water of pool immediately downstream. Channels in which step pool sequences are observed, typically wide range of sediment sizes, from fine gravel to large boulders are found. *Rapids and cascades* are also associates with steep channel gradients. *Rapids are characterized* by transverse, rib like arrangements of coarse particles that stretch across the channel, while cascades have a more disorganized, 'random' structure, 'random' structure. *Potholes are deep*, circular scoured features formed in bed rock channels by abrasion. *Bed rock bars* are usually formed in incised bed rock channel when multiple sub channels are incised into the bedrock substrata, leaving islands or bedrock bars between them.

Morphology and Morphometry of the Banks

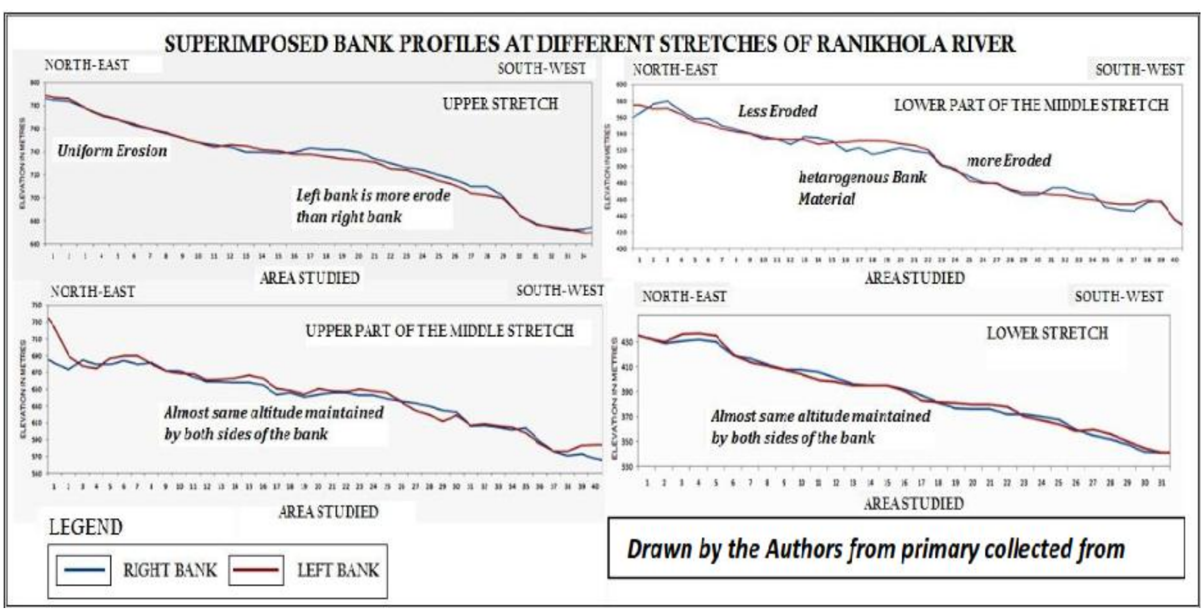
Stream bank erosion is explained by two major aspects- *stream bank characteristics* (erodibility *potential) and hydraulic and or gravitational forces.* The nature and extension of bank erosion also depends on the nature of the stream. Though a small hill torrent, Ranikhola River has carved its banks differently in all its stretches. The distinctiveness of eroded banks can be traced to the nature of the bank materials as well as the flow properties of the river. Small to large scale erosion of the bank can be observed as one move along the entire stretch of the river. Bank Erosion is most prominent in the middle stretch of the river, where even the protective walls constructed in order to protect the surrounding village has been severely broken by channel action. Both the banks in the middle stretch are under severe threat to bank erosion. Even the lower stretch is prone to bank erosion where protective walls have been constructed. As a whole the status of the bank is said to be vulnerable by the erosive action of the stream. From the perspective of Bank Configuration and Fluvial Dynamics, Ranikhola River Basin holds a very vital place in fluvial geomorphology. Distinct bank characteristics in terms of slope, inclination, altitude, width, composition were observed, which has made my study more interesting as well as significant. Starting my study from the upper course, it was revealed, that in this stretch the right bank height and inclinations were high in comparison to that of the left bank. As a result erosion in the form of sliding was high. Since the original left bank was protected by concrete revetments, therefore the flow was diverted and bifurcated. Due to the flow conditions, erosion was active in both the banks of the channel. In the upper stretch of the middle course, presents a typical feature, the right bank was great in height and inclination, compared to the left bank. As a result erosion in the form of scouring and rock fall was also high. Construction for bank protection on the left bank has been done though not recently, is even severely damaged by the river erosion. The right bank has severely been affected by landslides, anthropogenic activities and to some extent the erosional activity of the channel. *In the lower part of the middle stretch*, both the banks were more or less uniform in terms of height. But variation was observed in case of inclination and composition. In this stretch constructions for protection have been done in some parts, especially gabions in order to save the village. Protective walls has been previously constructed on the right bank of the middle stretch but the erosive nature of the river has destructed it either by scouring-undercutting process or block slumping. Erosional processes of the river have affected both the banks in this stretch. The right bank of the lower course has been protected by construction of guard walls for a large stretch in order to protect the village situated along the right bank of Ranikhola. But as far as the left bank was concerned no man made protective construction has been made, and the height of the left bank was comparatively lower to that of the right. The left bank of the upper stretch has the highest elevation of 787 metres, whereas 785 metres was found in the right bank. The lowest elevation was higher in right bank as compared to the left. Elevation of the right bank was 673 metres and that of the left was 670 metres. In the upper part of the middle stretch, the highest elevation of 732 metres was found in the left bank whereas 686 metres was found in the right bank. Lowest of 590 metres and 570 metres was recorded for left and right bank respectively. In the lower part of the middle stretch, the highest elevation of 575 metres was observed in the left bank whereas 560 metres was found in the right bank. Lowest of 440 metres was recorded for both the banks. In the lower stretch a different picture was observed. Both the left and the right banks has the highest elevation of 436 metres and lowest elevation of 340 metres. These illustrations are further shown in diagrammatic forms in the following pages. Irrespective of the above calculations from Google Earth, some field measurements have also been done and the data has been plotted in the form of superimposed profiles determining the height calculated of both the right and the left bank. After studying the profiles it has been observed that there is compatibility between data and the profiles calculated from the Google Earth and field survey. In the upper part of the middle stretch of Ranikhola River it has been observed that the height of the left bank is comparatively less to that of the right. The difference in height is higher in the upper part which decreases as one moves down-stream. But in the lower part of the middle stretch a different scenario is observed, where the left bank's height is more to that of the right's. The difference remains more or less same throughout the area studied. In general, the height of both the banks decreases considerably as we move down-stream. A profile of the left bank of Ranikhola River in its lower stretch has been done during the field survey for a total distance of 210 meter. It shows the difference in elevation of the bank. The range of variation was approximately 5 meters. From this survey we can relate to the bank topography. The bank was highly eroded.

For studying bank configuration, detail analysis of inclination, altitude, slope, width of the bank along with the composition is required. Each of these parameters is discussed intricately in the following paragraphs. Superimposition of the bank profiles in the middle stretch of Ranikhola River has been drawn. A change in bank height, bank slope, bank configuration can be observed. Even change can be observed in the channel pattern: its width, depth changes as we go downstream. The width of the channel in the middle reach is highest and that in the upper reach is the lowest. The height of the left bank is lower in comparison to that of the upper bank in the upper reach of the studied area. Both the banks are more or less equal in height in the middle reach again in the lower reach the height of the left bank decreases. The height and inclination of the right bank remains same all throughout the studies part of the stretch. The inclination of the right bank for a distance of 92 meters varies between 75° to 85° and the variability increases as one moves downstream. The inclination of the left bank more or less remains constant for a distance of 100 meters (80° to 85°). In the middle part bankline is protected, almost naturally processed. The inclination of the right bank varies between 55° to 65°. And that of the left bank varies between 70° to 75°. In the later section of the surveyed area we observe that the inclinations of both the banks are mostly similar ranging from 65° to 75°. This last stretch is slide prone due to anthropogenic interference. The valley side slope is rocky and affected by construction work.

Bank Composition and Materials

From upper to lower stretch Ranikhola River shows differential bank composition on both right and left bank in various stretches. It varied from ***cohesive clay, sand to non-cohesive sand, coarse grain, pebble, gravel, cobbles, singles, boulders and organic matter***. However, according to observation and collection of data from various stretches of the bank following compositional characteristics are found. In the upper stretches the valley sections are narrow to moderately narrow and usually enormous amount of big boulders and rocks are transported from the catchment areas due to mass movement and hydraulic erosion and those are deposited on both sides of the bank during lower flow regime. Moreover, the flowing track is also rocky and during its journey on its source region (Upper stretches) the river clear its way by cutting the rocky layer and so, both sides of the bank are dominated by big rocks and boulders. Notwithstanding that, the areas are also disturbed by building and construction and so disturbing the bank line and sometimes slumping and sliding are common feature on valley side slopes. In comparison to right bank, left bank is less disturbed by building and construction and so, is less rocky. In side boulders and rocks are covered by coarse grain soil and rocky fragments. The composition of the left bank would show 0.5 meters to upper terrace-- ***pebbles, gravels, coarse grain rocks, silty clay forming the bank with thick vegetative cover,*** below 0.5 meters the bank is mainly composed of moderate sized boulders along with pebbles, gravels, coarse grains. The lower portion mainly comprises a talus slope composed of big to moderate boulders, gravels and coarse rocks. In the middle stretches the bank is mostly disturbed by road construction and anthropogenic interference; so bank lines are disturbed and modified by recurring incident of rock sliding and soil flow. Huge amount of waste materials are slided down bank and extensively modified by all those materials. Bank lines are constructed by loose rock materials to cover the valley side slope. Bank lines are composed of loose rock materials (mainly by coarse rock fragments), but intrusion of big to moderate size big boulders mixed with coarse materials is also common. In comparison to right bank left bank is natural in composition with mixed particles, extensively disturbed and modified by sliding and slumping. As it is observed, the materials are non-cohesive in nature and so distracted by sliding and washing action during intensive rain. In the lower stretches the bank is mostly characterized by the presence of only the left bank, therefore a comparative study was not possible. ***In this stretch mainly the bank was altered by the presence of concrete revetments and guard walls.*** Therefore while analyzing the vertical bank profile, it was seen that major portions were covered with revetments. Bank lines are constructed by loose rock materials to cover the valley side slope. Bank lines are composed of loose rock materials (mainly by coarse rock fragments). But intrusion of big to moderate size big boulders mixed with coarse materials is also common. In comparison to right bank left bank is natural in composition with mixed particles, extensively disturbed and modified by sliding and slumping. As it is observed, the materials are non-cohesive in nature and so distracted by sliding and washing action during intensive rain. Fluvial dynamics is a very important factor, which controls bank erosion. Seasonal changes in velocity and discharge are the primary factor causing bank erosion in Ranikhola river basin. I have studied by taking sample sites from different courses, observed and noted significant patterns and characteristics in terms of fluvial dynamics.

Starting our study with the upper course, it is inferred, that during rainy season, the flow is vehemently turbulent and non-uniform, usually dwindle its path. Occasional rain increases the volume and discharge of the river and resultant turbulent flow which usually and easily reorients and re-figures the banks' shape and slope. Flow of water is more or less uniform with few eddies near ripples. The flow in this stretch during rainy season is very destructive, which is appearing through the alignment of the bank, size of material. Though the bank reorientation process is discontinuous, but during rainy season scouring, effect due to turbulence and helical consequences always renew the bank configuration. Considering the upper part of middle course, we find that the flow here is mostly non-uniform and turbulent and therefore non-resistant banks has recurring effect of sliding, scouring, during rainy season with high volume of discharge. The high volume of discharge usually submitted towards left portion of the channel is slightly inclined towards the right bank. In the lower part of the middle stretch, we find that the flow is swift, though non uniform. The river though concentrated in small portion of the channel but when the volume increases in turn increasing the discharge, the resultant turbulent flow easily reorients the characteristics of the bank which is evident from the configuration and alignment of the bank. In some stretches protective walls have been constructed in this stretch recently, and in some parts the protective walls have been destructed by the turbulent flow of the channel. This highlights the destructive attitude of the stream during high discharge. In the lower course flow is concentrated towards the right bank, where bank erosion is dominating. During rainy season the nature of flow is vehemently turbulent. No channel diversion is present. The river meanders right bank. While considering the velocity and discharge, a peculiar pattern is also noted and explained. Usually with increase in stage or course, the discharge tends to increase and velocity tends to decrease, but in case of river Ranikhola a reverse scenario is explained. In the upper stretch velocity is 1.21 m/s and discharge is 1.488 m^3/s, whereas in the middle stretch velocity is 1.34 m/s and 0.83 m/s and discharge is 2.46 m^3/s and 1.743 m^3/s respectively for the upper and the lower parts.



EROSIONAL STATUS OF THE BANK

The factors, which are responsible for bank erosion, are significantly present in all the three courses of Ranikhola River basin. Since, river Ranikhola flows in the Sikkim hills, therefore it results in carrying a large volume of water and sediment almost every year. During flashfloods high amount of runoff concentrated within this river. So, this flashing affects resulting high velocity and discharge of water and considerable width of the river. Large volume of discharge during rainy season, annually accelerate the channel and bank configuration. But as this river is unable to maintain its bankfull discharge all throughout the year, this width is also unable to maintain its flow continuity. So flows are concentrated either close to the right or the left bank, which usually affect the bank configuration, and causes erosion of the same. In the

upper stretch, not only washes process but continuous slumping, subsidence, sliding effects maintaining the renewed down cutting and sliding processes. Non cohesive bank material of clay, coarse grains of pebbles, cobbles other debris detriments the erosion process in the right bank. Upper part of the left bank is covered by grass, but still slope washing process due to runoff towards the channel primarily accelerated by foot track, cart track created by man, burrowing effects of animals, and also in places, vehicles disturbing the bank strength and stability on both the left and right bank of the river. Slopes are almost uniform to free face, so after a long dry season, when rain fall sand pour into the cracks and the clay cover accelerates the sliding and the slumping processes. So the upper part has significant pedo-geomorphological consequences due to the join effect of fluvio-climatic effects. Considering the middle stretch, we find here too bank erosion is quite active. Almost a stretch of more than 200 meters, bank slope is very steep and due to presence of non-cohesive material, overhanging, slumping and scouring processes takes place. The left bank is protected by gabions walls and baskets, so the destructive effects of the bank wash is partially checked, but the flow is slightly diverted and the old retaining walls on the right bank is severely affected and destructed. The turbulent flow attacks the right bank only during rainy season, when high volume of discharge and sediment jointly flows during bankfull discharge. In the later section of the middle stretch, bank erosion affects both the banks. Right bank is very steep with high inclination and slope. The base of the right bank is being severely attacked at some stretches. The turbulent flow attacks the left bank only during rainy season when the volume of discharge increases, in turn increasing the velocity. The meandering nature of the river also causes bank erosion. The steep right bank is composed of non cohesive materials, and the erosive nature of the river leads to slumping and scouring processes. Some parts of the left bank composed of bank material like sand and clay which in turn accelerates the erosion process. The stretch of the lower course flow is concentrated close to right bank and it is assumed that during rainy season, when large volume of discharge passes through this stretch, intense scouring, washing processes accelerates the bank erosion. During rainy season the nature of flow is vehemently turbulent and with fine clay and non-cohesive coarse sand with helical flow attacks the bank resulting accelerated bank erosion. Revetments caused more scouring. The meandering nature of the river also causes bank erosion. Due to large deposition towards the left bank, the elevation there is more and therefore the channel is slightly inclined towards the right bank which also appears from the concentration of the flow towards right bank, causing erosion.

FINDINGS & CONCLUSIONS

Ranikhola is one of the significant rivers in lower Sikkim Himalaya and solely flowing through the rocky terrain from source to mouth. It has been ascertained from the aforesaid analysis and interpretation that the total course of the Ranikhola river is basically controlled by various environmental, lithological, tectonic and structural factors. The following findings and inferences are extracted from the results and discussion-

i) The Ranikhola valley is totally hilly terrain controlled and structure, lithology and topography are playing dominant role for reshaping the valley and channel of the rover.

ii) The whole watershed is intensively rugged, steeply dipping and controlled by heterogeneous lithological composition; so, channel, bank, terraces and flats are strongly controlled by aforesaid parameters.

iii) The channel gradient is high to very high in upper stretch and moderate to moderately high in the middle and lower stretches. Along valley issues are very complex because invasive flow energy vehemently disrupted the channel bed and innumerable steps, benches, cascades and cataracts are found along the course.

iv) Cross-valley profiles are also drawn from the field data which highlighted that the there is no such hierarchical system in the valley development. Channel bed, Valley-side slope, bank, terraces and depressions in some areas are the major corridor segments which are developed and re-shaped in relation to the lithology, structure, topography and tectonic influence of the respective areas of the basin.

v) The river is strongly controlled by boundary condition in most cases where the channel is delimited by channel boundary and the width of the river is narrow there. The river is also flowing in the straight channel due to lithological barrier

vi) The Ranikhola has varied channel pattern, though it is flowing through hilly terrain. Apart from interlocking spur and slip-off-slope, the river also displayed meandering and braided channel pattern. Meandering is caused by lithological bar mainly and river changed its direction due to obstruction, whereas, braiding is mainly due to boulder obstruction within the stream. Water stream bi-furcated due to the in stream boulder obstruction and finally transformed to a braided stream.

ACKNOWLEDGEMENT

Authors like to extend their deep gratitude to all organizations, personals and co-workers for their constant and unconditional help for the preparation of this research paper.

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