River Classification of Nepal

Final Draft Report

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Section 1: **Introduction**

1.1 Background

A river is a natural flowing watercourse, usually freshwater, flowing towards another river or to the ocean, sea or lake (Wikipedia, 2019). In some cases, a river flows into the ground and becomes dry at the end of its course without reaching another body of water. Small rivers can be referred to using names such as stream, creek, brook, rivulet, and rill (USGS, 2019).

Rivers are the part of hydrological cycle. Water generally collects in a river from precipitation through a drainage basin from surface runoff and other sources such as groundwater recharge, springs, and the release of stored water in natural ice and snow (e.g., glaciers).

Rivers and streams are considered to be the major features within a landscape. However, they only cover only 0.15% (~ 773,000 km^2) of the earth surface (Allen and Pavelsky, 2018). They are made more obvious and significant to humans by the fact that many human cities and civilizations are built around the freshwater supplied by rivers and streams (Giller et al., 1998). Most of the major cities of the world are situated on the banks of rivers, as they are, or were, used as a source of water, for obtaining food, for transport, as borders, as a defensive measure, as a source of hydropower to drive machinery, for bathing, and as a means of disposing of waste (Wikipedia, 2019).

River and streams encompasses different nature and structures guided by the local geology, hydrology, topography, geo-morphology, climate, etc. Previously published literatures mentioend about the temporal and spatial variability of river system follwed by dynamics and complexity in terms of the process and shape of the whole course along its formation, development and evolution. Over the past rivers have been classified according to the need such as topographical, biotic, chronological and whitewater classifications. More recently, the classificaiton of the rivers are found to be better organized such as HydroSheds (Berndard, 2013; Lehner et al., 2008).

Classification of river system is imperative to distinguish spatial and temporal disparities, and is a basic way to recognize a river's complexities (Zhao and Ding, 2016). Th classification of river system or the river network is also important for the conservation point of view. River classification is the first step in understanding the complexity of rivers and it also serves as a essential component of river management (Zhao and Ding, 2016). Classificaiton of rierv system always has importance about water conservation as well as ecosysem restrotation.

The importance of river classification is as follows (Zhao and Ding, 2016):

1. provides a basic unit for river management by dividing the river network into reaches with similar structures and functions;
2. carries out resource cataloging according to river types, and to target different management goals for each river type;
3. chooses typical reaches to monitor to understand their structures, behaviors and function characteristics, which are extrapolated and applied to other similar reaches in the end;
4. promotes the communication between scholars and administrators with different backgrounds;
5. establishes the 'reference state' for each river type and can also be regarded as the basis of river design;
6. extracts the rules from same river types and predicts behaviors of rivers. Above all these points, important scientific value for river management is embodied by river classification.

1.2 Rational

River conservation is now becoming critical around the globe and threatened by climate change and anthropogenic activities such as building high dams, intensive water related recreational activities, excessive use of water resources (e. g. hydroelectric dams, irrigation withdrawals, construction of embankments or levees, pollution etc.). Population growth and technological advancement has greater pressures on water, food, energy, coupled with climate change threats are ever increasing. If unchecked, the potential to permanently alter the natural flow and ecological health of the world's rivers are imminent. The need for innovative institutional arrangements, which address the overuse of water, and under provision of ecosystem health is critical in order to maintain the ecological health of river systems (O'Donnell and Talbot-Jones, 2018). Classification of river network or river system contribute in river conservation and management by various ways. For this reason, researchers around the globe has explored/proposed different techniques/methods for river system classification such as:

- Schumm (1977) recognized three geomorphic zones within a watershed based on the sediment transport process: erosion, transport, and deposition zone. He also provided a conceptual framework to couple channel type and channel response potential;
- Brussock et al. (1985) developed a hierarchical system for large rivers that linked the river channel shape and the community structure;
- Frissell et al. (1986) adopted the nested levels (watershed, stream, valley segment, reach, habitat unit and microhabitat) to build an open hierarchical classification system;
- Frissell et al. (1986) proposed a river style framework that adopted the nested spatial pattern (ecoregion, valley, landscape, river, geomorphic unit (GU), hydraulic unit and microhabitat) to be used in Australia for river restoration;
- Rosgen (1994) has divided streams reaches in to 7 major stream type categories based on entrenchment, gradient, width/depth ration, and sinuosity in various landforms.
- Montgomery and Buffington (1997) classified streams into colluvial, alluvial and bedrock reach type in mountain drainage basins, and further broken down into colluvial, braided, regime, pool/riffle, plane-bed, step-pool, cascade and bedrock.
- Thorp et al. (2010) described rivers as a set of large hydrogeomorphic patches from upstream to downstream, and recognized a variety of functional process zones including constricted, meandering and braided, anastomosed, leveed, reservoir, etc. followed by the the estimation of river ecosystem service functions of each river type according to hydrogeomorphic patches;

These classifications are very useful especially in focusing on small channels and used in river conservation and management activities.

The importance of river classifications in Nepal provides opportunities to better understand river ecosystems and their function, highlight similarities or differences between climatic or physiologic regions, allow for international comparisons of freshwater resources, enable assessments of the representation of system types, and frame other analyses. However, in Nepal river classification is limited to their origin and order.

Nepal one of the richest countries in fresh water and fresh water ecosystem in the world, is facing lots of challenges to preserve freshwater river ecosystem due to climate change and unplanned developmental activities. World Wide Fund for Nature (WWF) has been working on freshwater ecosystem conservation for many years in Nepal and many other countries. WWF-Nepal's freshwater program strategic plan 2017-2021 has a goal of maintaining freshwater ecosystem integrity in the major river basins of Nepal. In order to achieve this goal, WWF Nepal has been working on protecting, managing and restoring freshwater habitats while safeguarding freshwater biodiversity, ecosystem services and cultural heritage. WWF Nepal has also been involving in conducting research and assessments and implementing the conservation activities in different wetlands of Nepal over the last few decades.

Freshwater ecosystems provide several critical functions because they provide the critical habitats for many species, and abundant food, nutrition and services to people's livelihood. In addition to clean water supply, energy supply, sediments and nutrients retention, flood and climate regulation, groundwater recharge, they also act as basis of life for aquatic flora and fauna. Sediment generation in the mountains due to weathering, transportation, and deposition plays important role for the physical environment of river. Transportation of sediments along the river channel provides accommodation zone for aquatic life as well as floodplain agriculture and floodplain dependent wildlife. However, developmental activities such as dams of various kinds suspend sediments from flowing downstream, is posing a serious threat to those that depend on the sediments for nutrients.

In order to better understand the importance of the river system/network and underlying causal impacts of the degradation of fresh water, it is highly recommended to classify the river network/system in terms of geomorphic, physio-climatic and hydrologic indicators accordingly river conservation/management measures shall design.

River classifications can provide opportunities to better understand river ecosystems and their function, highlight similarities or differences between climatic or physiologic regions, allow for international communities to compare the freshwater resources, enable assessments of the representation of system types, and allows various other analysis. In context this study attempted to classify the river system/network of Nepal for which the database of "Global River Classification (GloRiC)" maintained by WWF (Berndard, 2013) and known as **Hydro**logical data and maps based on **SH**uttle **E**levation **D**erivatives at multiple **S**cales (HydroSHEDS).

1.3 Objectives and Scope

The basic objective of this study was to classify the river system/network of Nepal according to the GloRiC utilizing the provided river network of Nepal to the consultant. The specific objectives of the study were to:

- Review of various published literatures related to river system classification and understand adopted methodology;
- Review of GLORIC database and explore how the results of this study can be linked;
- Geomorphic classification (e. g. stream power, gradient, and order);
- Hydrologic Classification (e. g. mean annual flow), and
- Physio-climatic Classification (e. g. sources, altitude and climate).

The scope of the study includes extensive use of available digital resources such as DEM, climatic and physiographic (Dhital, 2015) and topographic map of Nepal and freely available remote sensing (RS) data (e. g. Landsat and google earth). The use of such datasets was to make sure the river system classification more realistic and practical at the national scale.

Most of the analysis and interpretation of the datasets were implemented in ArcGIS platform while the rive order was manually implemented.

1.4 Limitations

This study basically used the information/data from the GloRiC and attempted to derive the information from the available digital data such as DEM. The river classification attempted at data scare situation of Nepal, where high resolution data is limitedly available. The GlORiC data is also based on 500-meter grid, which is probably useful for the global scale, however may not provide required information at local level.

Additionally, this study was conducted at limited resources and allocated time was much less as this study is resources and time driven.

Section 2: **River System Classification – An Overview**

The history of stream classification was extensively reviewed by Wasson (1989), Naiman et al. (1992) and Rosgen (1994). The dominant conceptual approaches range from biological to physical features over different scales. Therefore, it is important to understand whether these classifications are founded on mechanistic arguments and explanation of the physical processes associated with a given channel morphology (Buffington and Montgomery, 2013). The river system classification was always forefront research priorities for hydrologist. However, many other researchers from different discipline such as: geologist, biologist, ecologist and geomorphologist were also focused on river classification. Davis (1890) has classified whole-river as young, mature or old on the basis of observed erosion pattern. Later on, Shelford (1911) attempted to produce a biological classification scheme for whole rivers in Michigan (USA) based on his idea of succession, however, because of longitudinal differences in physical and biological characteristics, whole-stream classification has been of little use. Some researchers (Horton 1945, Strahler 1957) have classified the river in a basin-wide based on drainage network characteristics such as stream order, linkage number and drainage density. Some early attempts at stream classification based on the patterns of biotic zonation using species of fish or invertebrates as indicators of segment types (Carpenter 1928, Ricker 1934, Huet 1954) and numerous invertebrates e. g. Plecoptera, Ephmeroptera, Trichoptera (Macan 1961, Illies and Botosaneanu, 1963). Therefore, there are different approaches and techniques have been established for river system classification for different purpose such as river management, ecosystem management and conservation. Some of the recognized and pertinent classifications are briefly discussed in the following section:

2.1 Topographic Classification

Topography classification refers the physical shape and features of the river. According to this classification rivers are classified as bedrock, alluvial, or a mix.

Bedrock rivers are formed where water cuts through the sediments and reach to the bedrock. This type of classification is very common in active seismo-tectonic zone such as Himalaya. Himalaya is a product of collision between two continental plates where the Indian plate is moving towards the Eurasian plates at rate of ~20 mm/year. In addition, the denudation rate is also very high in the Himalaya. Alluvial deposits (mix of loose soil or sediment) move with bedrock rivers shaping the rivers along its way.

Alluvial rivers are characterized by the presence of floodplains and channels that have been formed in loosely consolidated sediment. Flooding is an important component of alluvial rivers as it maintains the primary route filled with water and allows for the formation of oxbow lakes, side channels, and wetlands. As alluvial river water flows, it erodes the banks of the river and deposits the resulting sediment into the floodplains or sandbars in the middle of the river (Richards, 1982). These rivers are further categorized by the pattern of their water flow such as straight, braided, meandering, and anastomose.

Mixed bedrock-alluvial rivers, as the name suggests, the combination of bedrock and alluvial rivers are under this category. These rivers flow through layers of bedrock while some sections pass through the deep alluvial deposits.

2.2 Biotic Classification

Biotic classification refers to the type of ecosystem found in a particular river and includes the cleanest rivers as well as the most contaminated river. One common system divides river into three principal zones: potamon, rhithron, and crenon (Petts and Amoros, 1996).

The **potamon zone** describes (Kownacki, 2008; Pinder, 1995) the downstream area of a river. Because this area has slower water flowing speeds, its temperature is generally warmer than other areas of the river. Additionally, the potamon zone is characterized by a sandy river bed and lower oxygen content (Petts and Amoros, 1996).

The **rhithron zone** describes the upstream area of the river (Kownacki, 2008; Pinder, 1995). It is characterized by faster and more turbulent and contains higher oxygen level than in potamon (Petts and Amoros, 1996).

The **crenon zone** describes the area near the source of the river (Kownacki, 2008). This zone is subdivided into the eucrenon, which is the spring zone, and the hypocrenon, which is the headstream zone (Petts and Amoros, 1996). Because this is where the river starts, its flow speeds are slower than those in rhithron zone. The rivers in crenon zone has lower oxygen levels and colder temperatures (Kownacki, 2008).

2.3 Geomorphic Classification

Wide ranges of geomorphic classificaion of river system has been proposed over the past. Geomorphic classification of river system is process based (Buffington and Montgomery, 2013) such as stream power. The concept of stream power for the fluvial geomorphology was first introduced by Knapp (1938) and was later applied by other for different purpsoe such as bed load and suspended load estimation, river bank stability and ban erosion, and to better understand the flood plain dynamics (Kondolf et al., 2003).

2.3.1 Stream Order

In general, the words stream is to be used rather than river for this classification. Stream order is a positive whole number used in geomorphology and hydrology to indicate the level of branching in a river system (Wikipedia, 2019). Several options are available to classify the river order such as top-down (e. g. Strahler and Horton classification) or bottom-up (e. g. classic classification), and their hierarchical position within the river system (Huang et al., 2007).

Strahler Stream Order

Strahler stream order is based on the Strahler number, which is used to demonstrate the complexity of branching numbers. The order classifications range from the 1st order to the 12th order. Headwaters, for example, belong to the 1st order, while the Amazon River belongs to the 12th. Researchers have determined that approximately 80% of the world's rivers and tributaries belong to the 1st and 2nd orders. These waterways are typically located on steep inclines from which they flow downward at a quick pace until joining the next order of waterway. The larger the order number, the larger and slower the river.

2.3.2 Process domains classification

Schumm (1977) divided rivers into three types: sediment production, transfer, and deposition. This classification is based on a process-based view of sediment movement through river networks over geologic time. The process domains are portions of the river network characterized by specific suites of interrelated disturbance process, channel morphologies, and aquatic habitats, and at a general level roughly correspond with source, transport, and response reaches in mountain basins (Montgomery, 1999). This classification is a coarse filter (typically lumping several channel types), however, it identifies fundamental geomorphic units within the landscape that structure general river behavior and associated aquatic habitats.

2.3.3 Channel pattern classification

Most of the river classification that have been developed involve classification of channel pattern (i.e. straight, meandering, and braided) which can be broadly divided into two approaches: quantitative relationships and conceptual framework.

Quantitative relationship is based on discharge and factors affects channel pattern such as grain size, sediment load, riparian vegetation, channel roughness, width and depth. However, Lane (1957) and Leopold and Wolman (1957) observed that for a given discharge, braided channels occur on steeper slopes than meandering rivers. Both studies recognized a continuum of channel pattern, but Leopold and Wolman (1957) proposed a threshold between meandering and braided rivers. Beechie et al. (2006) developed a GIS model for predicting channel pattern as a function of slope and discharge, demonstrating that unstable and laterally migrating channels have correspondingly younger and more dynamic floodplain surfaces than stable, straight channels. Process-based explanations for hydraulic and sedimentary controls on channel pattern have been presented but the slope-discharge framework for classifying channel pattern remains empirical and descriptive.

Conceptual frameworks is mostly based on Schumm's (1960) work on sand- and gravel-bed rivers in the Great Plains of the western U.S. emphasized that channel pattern and stability are strongly influenced by the imposed load of the river and the silt-clay content of the flood plain. Based on these observation, Schumm (1977) proposed a conceptual framework for classifying alluvial rivers that related channel pattern and stability to (1) the silt-clay content of the banks, (2) the mode of sediment transport, (3) the ration of bed load to total load, and (4) the slope and width-to-depth ration of the channel. Other studies have also noted the role of riparian vegetation and root strength in affecting bank cohesion, channel width, and channel pattern.

2.4 Channel-floodplain classification

Several classifications explicitly incorporate channel-floodplain interaction. Melton (1936) synthesized work based on previous studies (Gilbert, 1877; Powell, 1896; Davis, 1913; Matthes 1934) to classify channels based on whether their floodplains were formed by meandering (lateral accretion), overbank (vertical accretion), or braiding process. This classification describes longer term process and recognize that channel and floodplain conditions represent a distribution of flood events, with smaller floods modifying and sculpting the morphologic legacy of larger floods. Although this classification system is inherently process based but their explicit inclusion of channel-floodplain interactions allows the development of stronger linkages between fluvial process, riparian ecosystem and human uses of floodplain corridors.

2.5 Channel unit's classification

Bisson et al. (1982) developed a detailed, descriptive classification of channel units in Pacific Northwest streams to quantify different types of physical habitat for salmonids. Most of the channel-unit classifications focus on the wetted channel, generally excluding bars, but detailed classification of bar types and associated physical process. This classification is one of the most popular approaches for describing physical habitat in fisheries studies, however, is too detailed for most basin-scale applications and channel units are not uniquely correlated with reach-scale morphologies.

Section 3: Climate, Physiography and Rivers in Nepal

3.1 Introduction

Nepal is predominantly a mountainous country formed due to the tectonic upliftment. Nepal Himalaya can be divided into five physiographic regions, viz High Himalayas, High Mountains/Hills, Middle Hills (Mahabharat hill), Siwaliks (Churia Range) and the Terai plains. Due to orographic features, Nepal Himalaya experiences a wide range of climates varying from the sub-tropical to the Alpine type as the elevation varies from 64 (amsl) above sea level up to maximum of 8,848 (amsl) within a span of about 200 km (WECS, 2005).

The country also experiences heavy rains during June to September due to the south-western monsoon, which accounts for 80% of the total rainfall, while November to January, is the winter rain season that accounts rest of the rainfall. The mean annual rainfall is about 1,500 mm, with a maximum annual rainfall record of 5581 mm in 1990 at Lumle in Kaski district in the mountain region; and a minimum record of 116 mm in 1988 at Jomsom in Mustang district located at 2,744 (amsl) in the Kaligandi river valley near the Annapurna Himalayan range (FAO, 2011).

3.2 Climate

In terms of climate Nepal is divided into three main regions according to the ecological belt as described in the National Water Plan (NWP) of the country is shown in the following **Table 1** (WECS, 2005).

Table 1. Climatic Condition of Nepal.

Ecological Belt	Climate	Average Annual Precipitation	Mean Annual Temperature
Mountain	Artic/Alpine	Snow/150mm-200mm	<3^{0}C-10^{0}C
Hill	Cool/Warm Temperate	275mm-2300 mm	10^{0}C-20^{0}C
Terai	Sub-Tropical	1100 mm- 3000mm	20^{0}C-25^{0}C

The temperature decreases from lowland Terai (northern part of the Ganges plain) to high Himalayan region. The extreme temperatures recorded show that in Lomangtang (Mustang district) located at an elevation of 3705 (amsl) the minimum temperature was -14.6 °C in 1987, while in Dhangadhi (Kailali district) located at an elevation of 170 (amsl) the maximum temperature was 44 °C in 1987 (FAO, 2011). Precipitation falls as snow at elevations above 5000 (amsl) in summer and 3000 (amsl) in winter (FAO, 2011).

However, the country can be divided into five different climatic zones which are: tropical and subtropical zone below of 1200m, cool-temperate zone above 1200 to 2400m, cold zone above 2400 to 3600m, sub-arctic climatic zone or sub-alpine above 3600 to 4400m and alpine or arctic zone above 4400m of Himalayan region.

3.2 Physiographic Classification of Nepal Himalaya

Nepal is divided into five major physiographic and climatic regions (**Figure 1**) as below (DHM, 2015):

- Terai plain (<200 amsl; Tropical to sub-tropical),
- Siwalik hills (>200<1200 amsl; Tropical to sub-tropical),

- middle hills (>1200<2500 amsl; Warm Temperate),
- high hills (>2500<4000 amsl; Cool Temperate) and
- high mountains/Himalayas (>4000 amsl; Artic/Alpine).

Terai region is the northern limit of Indo-Gangetic plain which encompasses nearly 800 km from east to west and 30 to 40 km north to south with elevation ranging from 60 to 200 amsl. It is generally flat with minor relief caused by river channel shifting and down warping of the region.

Siwalik is commonly known as Churia hills in Nepal. The hills abruptly rise from Terai and ends with the beginning of the middle hill range. The elevation of the Siwalik ranges from 200 to 1,200 amsl. The Siwalik which covers nearly 13 per cent of the total area of the country is generally characterized by low terraces and alluvial fan with steep topography. The Siwalik composed of mudstone, sandstone and conglomerate of sedimentary origin. The region is very much prone to landslides, mass wasting and debris flow which contributes significant amount of sediment load to the major rivers in the country.

Middle hills are also known as the Mahabharata Lekh. The elevation of middle hills ranges from 1,200 to 2,500 (amsl) and extends throughout the length of the country. In many places the range is intersected by antecedent rivers such as the Koshi, the Gandaki, the Karnali and the Mahakali. These rivers are the source of water originating from north of this range which drain to the south. It is the first great barrier to the monsoon winds that produces heavy precipitations on its southern slope due to orographic effects.

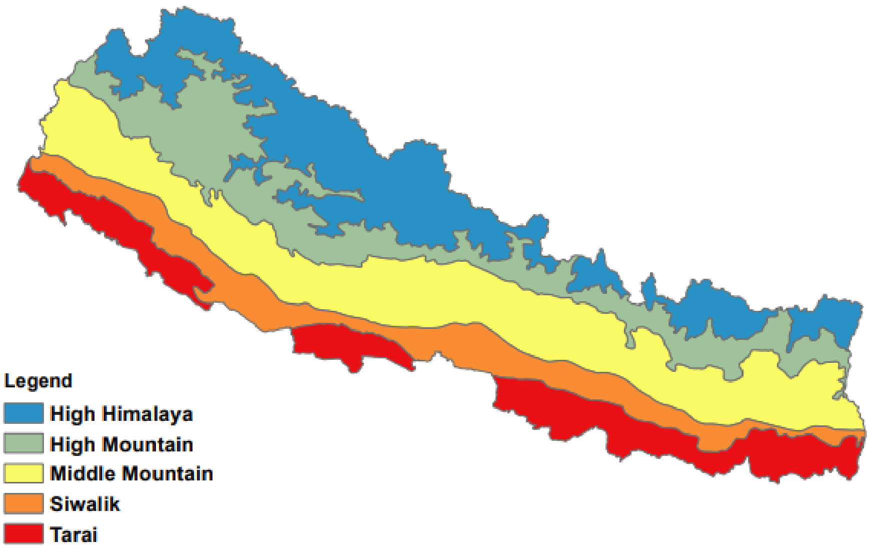

Figure 1. Physiographic map of Nepal (DHM, 2015).

High hills region lies further north of middle hills whose elevation varies from 2,500 to 4,000 amsl. It has an average width of 50 km and extends from east to west of the country. The high hills, consisting of low hills, river valleys and tectonic basins exhibit a mature landform. This region has cool temperate climate.

Mountains or the Himalayas is the mountain range, rise slowly to the north and make up the snowcapped high Himalayas. The elevation ranges above 4,000 amsl. The main north-south flowing rivers originating from northern side of the Himalaya have dissected this range forming some of the deepest gorges in the world such as Kali Gandaki gorges (5,791 m deep). The region is mostly occupied by glaciers, snow peaks, rocky slopes, talus and colluvial deposits.

3.3 Sources of Water and Rivers in Nepal

Water resources in the form of snow, rivers, springs, lakes, and groundwater are abundant throughout the country and over the Hindu-Kush Himalayas (Bajracharya et al., 2015) and Nepal. Water resources is one of the important natural resources of Nepal.

3.3.1 Snow cover Mountains

Snow cover Himalaya is a huge natural storage of freshwater. Glaciers, permafrost, and glacial lakes are main forms of water storage in the Himalaya. Snow-melt discharge from the Himalaya maintains the water levels in downstream rivers and wetlands and thereby provides dynamic ecosystem services and support peoples livelihood. There are about 3,252 glaciers with total coverage of 5,323 km^2 in Nepal while about 2,323 glacial lakes located in this region with total coverage area of 75.70 km^2 (Bajracharya et al., 2015). Due to impacts of global warming and climate change phenomenon glaciers are retreating at alarming rate and glacial lakes are expanding rapidly. Glacial Lake Outburst Floods (GLOFs) disaster pose imminent risk to downstream infrastructure, households and livelihood to the downstream.

3.3.2 River Basins

Nepal is a part of the Ganga Basin and it is estimated that approximately 70% of dry season flow and 40% of annual flow of the Ganga River comes from Nepal Himalaya. According Water and Energy Commission Secretariat (WECS), about 6,000 various types of rivers (including rivulets and tributaries) exist with the drainage density of about 0.3 km/km^2 and the overall cumulative length of rivers is about 45,000 km. There are 1000 rivers longer than 10 km and about 24 of them are more than 100 km (WEPA, 2019).

Rivers in Nepal can be classified into three broad groups on the basis of their origin (WECS, 2005). The first group of rivers is snow fed-types such as: Koshi, Gandaki, Karnali, and Mahakali. They originate from snow and glaciated regions in the Himalayas. As a result, flow in these rivers is perennial with sustain flow during the dry season. These rivers are reliable source of water and also provide potential opportunities for hydro-power generation and irrigation in the downstream. The second group of rivers originates in the middle mountains and hilly regions. Their flow regimes are affected by both monsoon precipitation and groundwater (i.e. springs). Contribution from groundwater yield maintains the minimum flow level and prevents from drying during non-monsoon periods. The Bagmati, Kamala, Rapti, Mechi, Kankai, and Babai rivers fall into this group. The third group of rivers originates in Siwalik zone. Tinau, Banganga, Tilawe, Sirsia, Manusmara, Hardinath, Sunsari and other smaller rivers are examples of rivers falling in this group. The flow in these rivers is mostly dependent on monsoon precipitation and their flow level could deplete significantly low during the non-monsoon period. Summer monsoon is important period when about 60-85% of annual runoff of all river systems in Nepal occurs during July to September.

The rivers originating in the Siwalik hills and further south in the Terai region are seasonal and mostly depending on the monsoonal rain (June -Sept.) and remains dry rest of the months.

Section 4: Approaches and Methods

4.1 Approaches

Literature Review:
Pertinent scientific articles, government documents/reports and other publications related to geomorphology, hydrology, classification of river and river ecology were collated and reviewed. In order to classify the given river network in the context of Nepal, the consultant has reviewed the following documents and dataset;

- GLoRiC documents (e. g. world river system classification related publications, legends, etc.);
- Digital maps/images provided by WWF (e. g. river network, DEM, etc.);
- GLoRiC data (e. g. DEM, river network, flow accumulation, flow direction, etc.);
- Published scientific and government documents/reports, and
- Remote sensing images (e. g. Landsat and Google Earth).

The database and relevant documents were reviewed and accessed for their usefulness to contribute to a river type classification in the context of data scare situation. Data from the GloriC database such as annual (mean) river discharge, river order, stream-power, were reviewed or enhanced to produce a river type classification appropriate for Nepal.

Use of Geographic Information System (GIS) and Remote Sensing (RS):
GIS tools and RS data were used to determine the major river types of Nepal along with the available data from the HydroSHEDS river network. Moreover, empirical models were used to classify the river system for the hydrologic, geomorphic and physio-climatic classification of the rivers.

4.2 Methods

This study established a comprehensive model with the application of GIS, RS and empirical models methods (**Figure 2**) to classify river network in terms of hydrologic, physio-climatic and geomorphic classes.

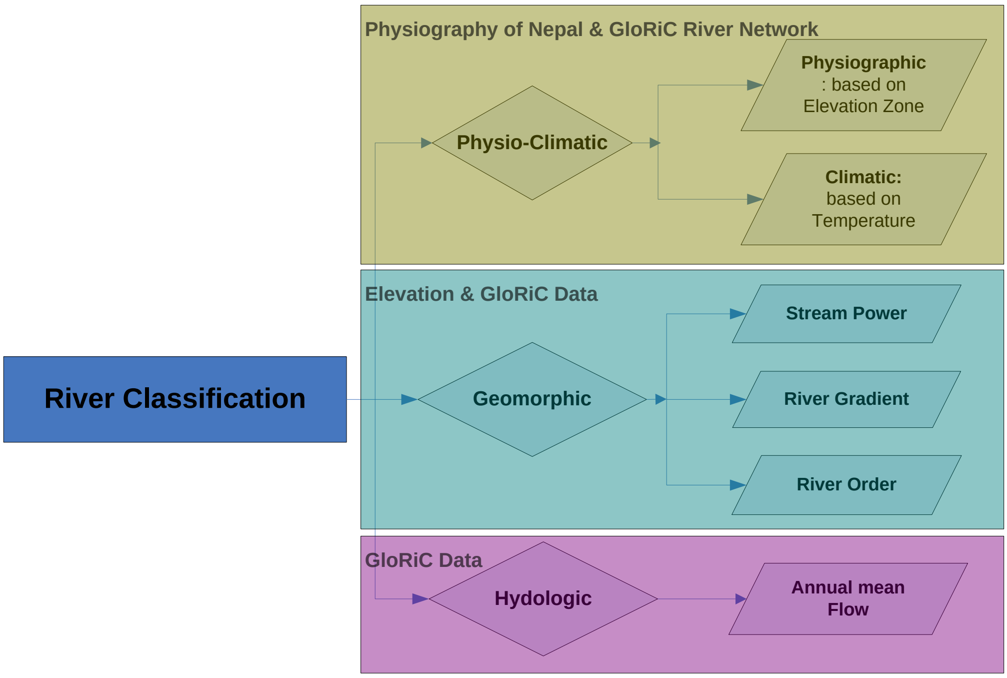

Figure 2. Methodological framework for the river network classification.

4.2.1 Data Preparation

The GloRiC data such as Digital Elevation Model (DEM), flow direction, flow accumulation, river network, etc. maintained by HydroSHEDS were downloaded and closely observed to have insights of the datasets and the region. The data were also compared with the available calibrated DEM of the Department of Survey (DoS) of the Government of Nepal. This study considered the available RS resources such as Google Earth, Landsat, Topographic map along with data available in the HydroSHEDS. Additionally, the downloaded river network and the given data of river network to the consultant were also reviewed.

Points were created at each river reach and mid points of the same drainage line features in order to extract the background information of the river network such as elevation, physiography etc. (

Figure *3*). These point features were overlaid on the top of the DEM (1arc. second Resolution) and other raster data such as physiographic data to extract the information of the locations in terms of elevation or physiography and climate.

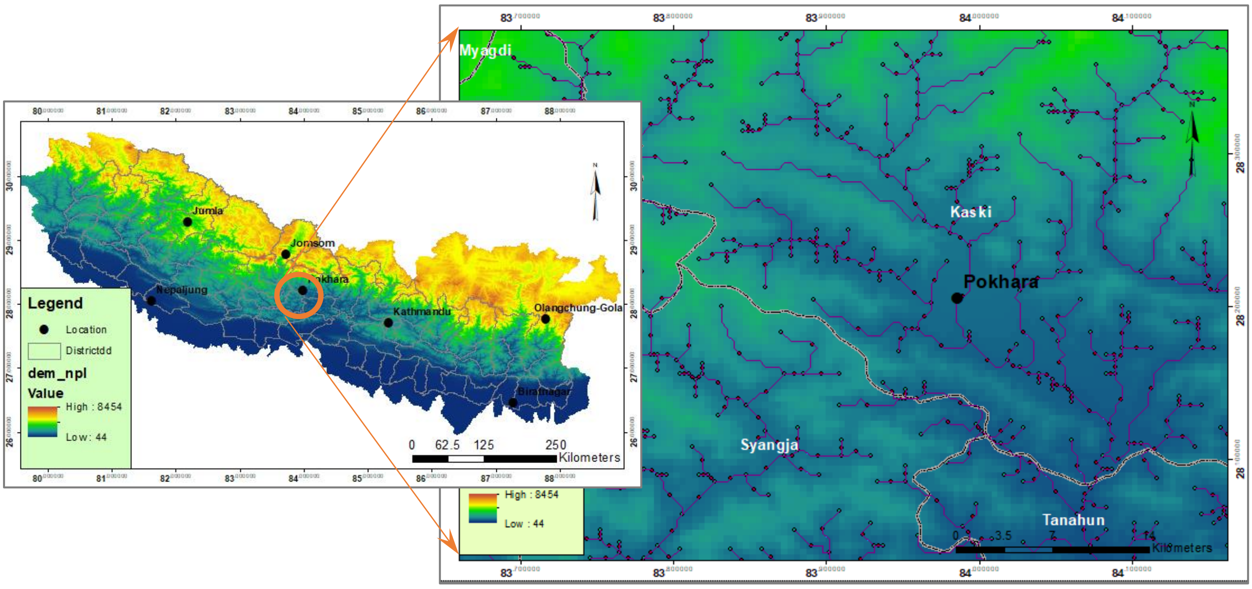

Figure 3. Example view of DEM (left) River Network and reach points (right).

Physiographic map of Nepal (**Figure 1**) available from Department of Hydrology of Meteorology (DHM) was used as references while the climate of each physiographic region was generalized in reference to the available published documents Karki et al. (2016); DHM (2015); WECS (2005).

4.2.2 Classification

Physio-Climatic Classification: The provided database of river network was reviewed and used where applicable. However, separate drainage network has been generated using the 30 m resolution DEM to check the quality and the goodness of fit to that of the provided river network. The drainage network was overlaid on the Google Earth and Landsat images to better understand the physio-climatic status of the rivers (**Figure 4**).

Additionally, Nepal has been divided into five physio-climatic regions based on the elevation, topography, geomorphology and climate (DHM, 2015; WECS, 2005) (Table 2). The digital data obtained from DoS was studied and prepared the dataset in GIS platform. The given river networks are also from outside of Nepal boundary flowing into the Nepal river system, which were consider in this study and classified according to the adopted approach).

Table 2. Physio-climatic classification of Nepal and surrounding area for GloRiC River Network.

Region	Elevation (amsl)	Type of Elevation (GloRiC Legend)	Climate	Temperature (GloRiC Legend)	Legends (Climate-Physiography)*
Terai	<200	Low (1)	Tropical to sub-tropical	High (3)	31
Siwalik & River Valleys	>200<1200	Moderate-High (2)	Sub-Tropical	High (3)	32
Middle Hills & River Valleys	>1200<2500	Medium High (2)	Warm-Temperate	Medium (2)	22
High Hills	>2500<4000	High (3)	Cool Temperate	Low (1)	13
High Mountains/Himalayas	>4000	Very High (4)	Alpine	Very low (1)	14

**First digit represents the temperature/Climate (i. e. 3 =high temp. and 1=very low temp) and second digit represents elevation (i. e. 4=very high elevation and 1=low elevation).*

In order to understand and classify river network in terms of the physio-climate the physiographic map of Nepal was converted to raster data to analyze the river network. The given river segments (line features) were used to create the point features at the middle of each line in GIS environment. The digital map of the physiography and climate were prepared in GIS platform. Overlying the points on the top of the physiographic maps, background information about physiography and climate was extracted. The data base of the classification was maintained in the river network attribute table. To make the consistency to the GloRiC database, similar legends has been used as shown in the Table 2.

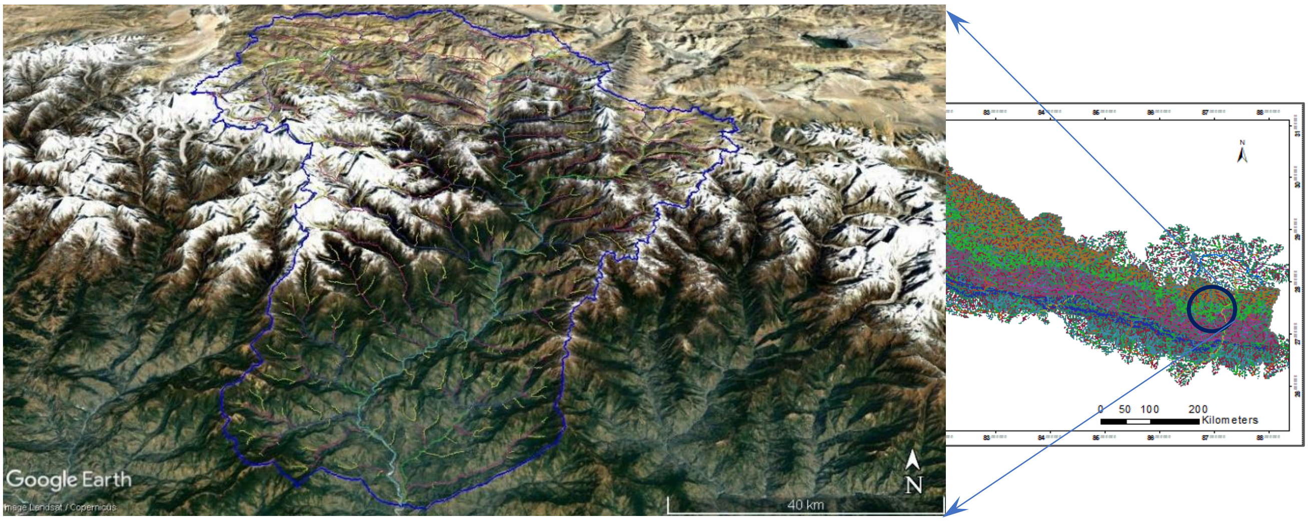

Figure 4. Drainage order overlaid on the Physio-climatic map of the Nepal and Google Earth Images.

In addition to the physiographic and climatic classification, an effort have been made to figure out the type of river reach according to the altitude and climate such as river reach located ≥4000 masl are designated as highland rivers, followed by high-hill rivers (≥2500<4000 masl), mid-hill rivers (≥1200<2500 masl), siwalik and inland river valley rivers (≥200<1200 masl) and terai rivers (<200 masl).

Geomorphic Classification: In this study river gradient, stream power (SP) and river order (i. e. Strahler river order) have been performed. According to the "top down" system devised by Strahler, rivers of the first order are the outermost tributaries. If two streams of the same order merge, the resulting stream is given a number that is one higher. River order was manually entered in to the attribute table in GIS to maintain the consistency of given river network following top-down approach of Strahler (1964).

Utilizing the river gradient (i. e. slope) and discharge stream-power (SP) was estimated for each river reach. The mean annual river discharge of each of the river reach was obtained in GliRiC database. The SP was estimated according to (Bagnold (1966)):

$$\Omega = \gamma . Q . S$$

where, Ω= stream power (in watt)

$\gamma = \text{sp. density of water } (\sim 9800 \text{ kg/m}^3)$

S= slope of the river reach section

Q= Annual (mean) discharge

The above model was implemented in GIS that allows to have SP of all the river section at each reach of the river network. The classified data has been provided in GIS attribute table (STRM-POW) together with the provided river network.

This study has generalized the river divided into four classes such as: 1) very high energy river (≥100 MW), 2) high energy river (≥10MW<100MW), 3) medium energy river (≥1<10MW) and 4) Low energy river (<1MW).

Hydrologic Classification: The GLoRiC data base provides the annual (mean) discharge and its variation at each river reach. The available annual mean discharge was linked to the corresponding river reach in the attribute table of the provided river network in GIS.

Further in this classification, an effort has been made to identify the river sources of each river reach and their variability in discharge. The source of the river reach has been classified into four type according to the contribution such as: 1) Snow and Glacial, 2) Snow and Rain, 3) Rain and Snow and 4) Rain. In order to better understand the river sources and contributing in discharge the Snow and Glacial rivers are said to be snow fed river similarly for those rivers in which snow contribution is high with some contribution from rain is classified as Snow dominated Rain Fed rivers. The river in which rain is major contributing factor and the snow contribution is fairly low is classified as Rain Dominated Snow fed rivers. Those rivers in which there is no contribution from snow is said to be the rain fed rivers.

The rivers located in highland region with first or second order rivers are the snow fed rivers. As the rivers flow further downstream more rivers get merged and increased the order. The rivers passing through the high-hill region are categorized as Snow dominated Rain fed rivers, where snow contribution is higher to that of rain. Rain contribution is high in the river is mid-hill region, however the base flow of the major rivers is the snow. Discharge in these rivers has high variability as the rivers flow is often 400 times higher than in dry season flow. The discharge in these rivers are rain dominated. The river originating in Siwalik and Terai are rain fed and has highly variable in discharge. These rivers are mostly dry during the off-monsoon season and demonstrates flash flood during monsoon.

Section 5: **Results and Discussion**

5.1 Physio-Climatic Classification

The region under investigation (**Figure 5**) for the river system classification has been broadly divided into five physio-climatic region (**Figure 6**) based on the physical and climatic patterns of Nepal.

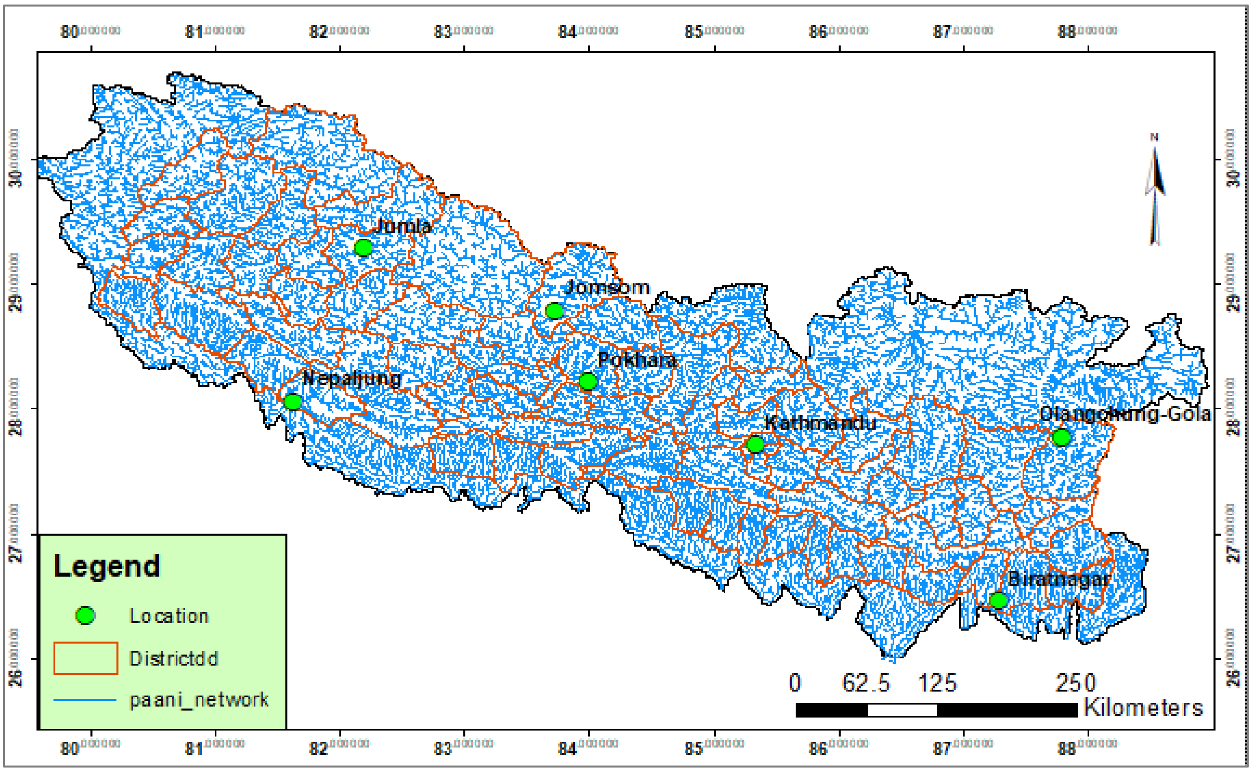

Figure 5. The map of Nepal and regional river network at about 500-meter grid (sources-GloRiC/WWF).

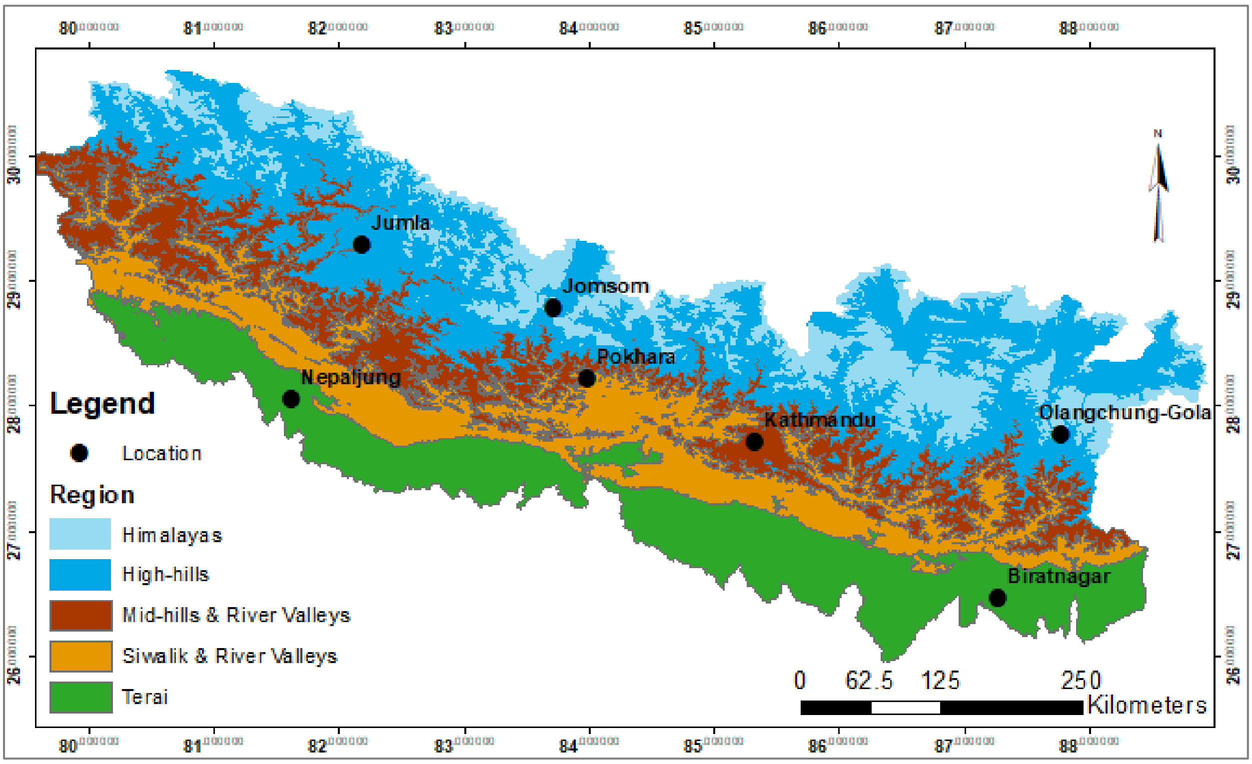

Figure 6. Physio-climatic region of Nepal locating some major cities and towns.

The region/areas out of Nepal have been classified considering similar physical and climatic patterns. It is also due to the fact that the climate and physical geography is mostly governs by the elevation and climate attributes such as rainfall and temperature (**Figure 7**).

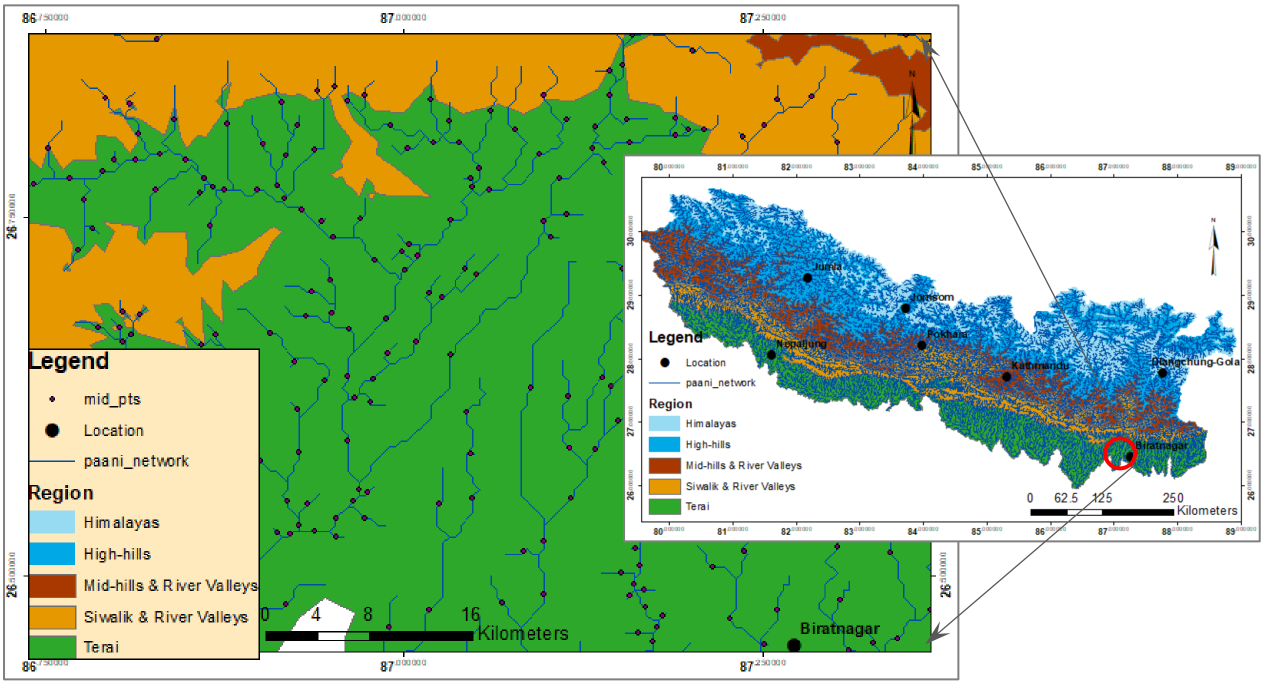

Figure 7. Physio-Climatic Classification of river network (note the points at the middle of the line features of river network and physio-climatic classified map in the background).

This classification indicated that the majority of the river segments are observed to be in high-hill region (30.45%), followed by Siwalik and River valleys (29.9%); middle hills and River valleys, Trai and High mountain region. Table 3 presents the numbers of river segments in each of the physio-climatic region (In the attribute table of GIS, this classification represents by PHY_CLIM column).

Table 3. Nos of river segments according to the physio-climatic classification.

Region	Elevation (amsl)	Legends (Climate-Physiography)	Nos of River Segments	%
Terai	<200	31	3987	16.42
Siwalik & River Valleys	>200<1200	32	7259	29.90
Middle Hills & River Valleys	>1200<2500	22	4651	19.15
High Hills	>2500<4000	13	7394	30.45
High Mountains/Himalayas	>4000	14	990	4.08

5.2 Hydrologic Classification

Hydrologic classification of the provided river network is based on annual (mean in cubic meter per second) flow at each river reach which is available in GloRiC database. The attribute table of GloRiC data base was linked to the provided river network to have all the information in a single map layer (see the digital database: DIS_AV_CMS in the GIS attribute table). Hydrology of the river is source dependable. The reliable source of flow in the context of Nepal is snow while rain is equally important. River sources were identified based on the altitude such as the rivers located in higher altitude are snow fed rivers. These rivers are lower order in general. As river flows further downstream increased the order and the discharge.

This study attempted to classify the river by combining the sources, their power and variability in discharge. This classification is somehow related to hydrology and demonstrated 32 different classes of the rivers considering the following factors and named as Final_Clas in GIS attribute table:

- Sources
  - Snow Fed Rivers;
  - Snow dominated Rain Fed Rivers;
  - Rain Dominated Snow Fed Rivers, and
  - Rain Fed Rivers
- Discharge Variability
  - High variability, and
  - Low Variability
- Energy (i. e. Stream Power)
  - Very High Power (≥100 MW)
  - High Power (≥10 MW<100MW)
  - Medium Power (≥1 MW<10 MW) and
  - Low Power (<1 MW)

The classification is made in GIS platform and consistency has been maintained with the GloRIC classification framework.

5.3 Geomorphic Classification

River Gradient (Slope)

River gradient is defined as grade measured in by the ratio of drop in elevation of a stream per unit of horizontal distance (in other words, the "steepness" of a river). This study estimated the river gradient (i. e. slope in meter: RIV_SLOP_M in the GIS attribute table) from the elevation of upstream and downstream of the given river network extracted from the 30 m resolution DEM illustrated in figure 8.

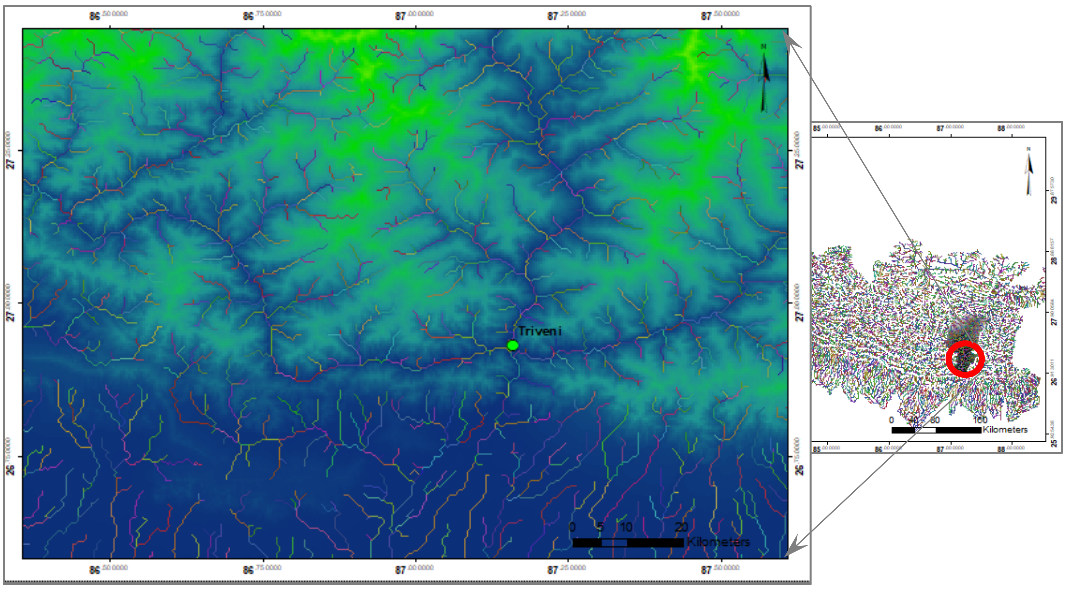

Figure 8.Example of river gradient of each river segments.

The study demonstrated that the given river network consisting of river gradient greater than 5% are estimated to be 13,665 out of 24,287 river segments. The higher gradient rivers were mostly located in the higher elevation zone (i. e. high mountain and the Himalaya) while the river segments consisting of less than 1% gradient are 5,280 all through the low land areas and northern part of the Himalaya.

The Himalayan rivers mostly contain high degree of slope gradient until they reach to the Terai.

Estimation of Stream Power

Stream Power (SP) is the rate of energy dissipation against the bed and banks of a river or stream per unit downstream length. SP usually measures in Watt was calculated utilizing the annual (mean) discharge discussed earlier at the designated river reach/section. This study estimated SP of the given river network at all the river reach (i.e. at each confluence of the river system). The GloRiC mean annual discharge estimated slope was used to estimate the SP. The calculated minimum and maximum SP were 0 and 1.75×10^9 watt, respectively.

Stream Order (Strahler)

The top-down approach of stream order demonstrated that the lower most order starts from one on the top of watershed (**Figure 9**). As the river travel further down number tributaries contributes to increase the river order. The highest river order observed in the study was seven (In the attribute table the column STRM_ORD represent this classification).

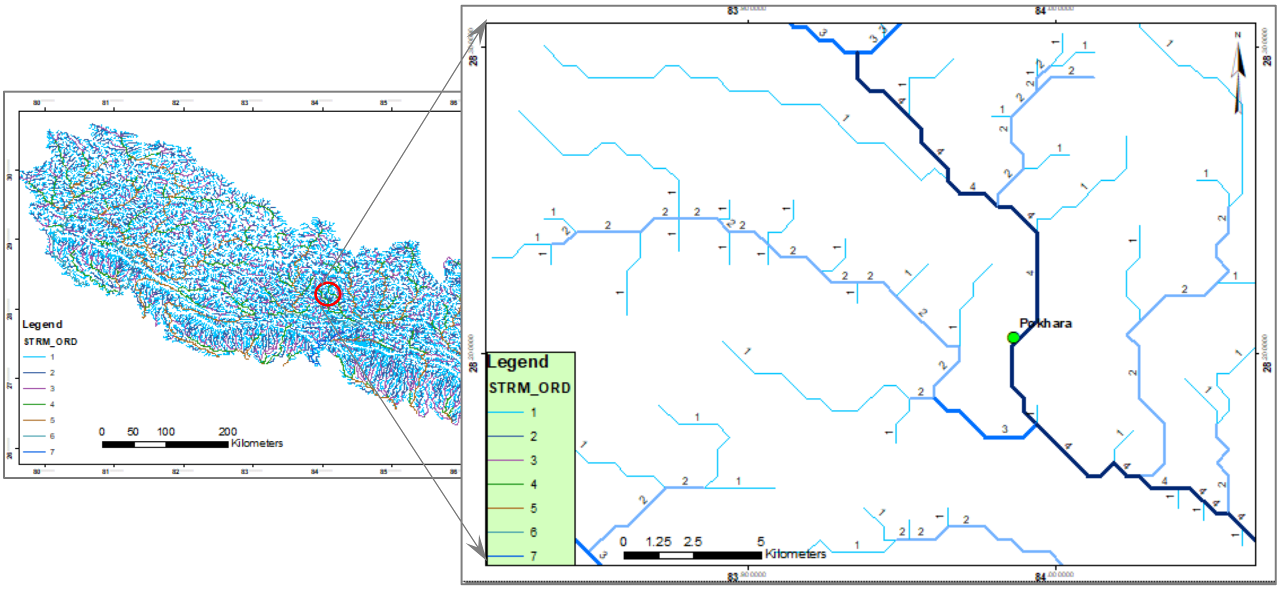

Figure 9. Example view of River/Stream order (Top-Down approach).

The database has been maintained in the GIS platform, that allows to select and visualize river reach using the select by attribute or make separate layer of the particular type of river.

Section 6: **Concluding Remarks**

Rivers can be classified based on different parameters and factors, including by their physical morphology, climate, discharge, shape etc. River classifications provide opportunities to better understand river ecosystems and their function, highlight similarities or differences between climatic or physiographic regions. Hydrologic classification is the process of systematically arranging streams, rivers or catchments into groups that are most similar with respect to characteristics of their flow regime.

Variety of classification techniques have been used in the past to derive hydrological classifications and regionalization. This study has illustrated simple but highly useful river classification in the data scarce situation. However, this study has used secondary data of mean annual discharge of the river under consideration.

Most of the river segments are observed in the high-hill region (30.45%), followed by Siwalik and River valleys (29.9%); middle hills and River valleys. Similarly, river gradient greater than 5% are estimated to be 13,665 out of 24,287 river segments. The higher gradient rivers were mostly located in the higher elevation zone (i. e. high mountain and the Himalaya) while the river segments consisting of less than 1% gradient are 5,280 all through the low land areas and northen part of the Himalaya. The GloRiC mean annual discharge was used for the calculation. The calculated minimum and maximum SP are 0 and 1.75×10^9 watt, respectively. Stream ordering assigns a numeric order to links in a stream network, which demonstrated the maximum of seven orders river in Nepal.

Additionally, the rivers are classified according to the sources and contributing factors such as Snow Fed, Snow dominated-Rain Fed, Rain dominated-Snow Fed and Rain Fed rivers. Altogather four different types of sources and contributing factors have been identified in this study. The river located above 4000 masl are said to be high land river (≥4000masl), follwed by high-hill (≥2500<4000 masl), mid-hill (≥1200 <2500 masl), siwalik and inland river valleys (≥200<1200 masl) and terai (<200 masl) rivers.

The final classification was made considering the river source, energy (or stream power) and discharge variability. This classification leads theoritically 32 different classes.

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