Abbreviation and Acronyms

AHEP	:	Available Gross Hydroelectricity Potential
ASTER	:	Advance Spaceborne Thermal Emission and Reflection Radiometer
AMF	:	Average Monthly Flow
APHRODITE	:	Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation
B	:	Breadth
BCDP	:	Building Code Development Project
B/C	:	Benefit-Cost Ratio
BoQ	:	Bill of Quantities
CAR	:	Catchment Area Ratio
CCT	:	Central Churia Thrust
CFRD	:	Concrete Faced Rock Fill Dam
COD	:	Commercial Operation Date
DCF	:	Discounted Cash Flow
DEM	:	Digital Elevation Model
DHM	:	Department of Hydrology & Meteorology
DMG	:	Department of Mines & Geology
DoED	:	Department of Electricity Development
d/s	:	Downstream
E	:	East
EIA	:	Environmental Impact Assessment
EMI	:	Equal Monthly Installment
ESA	:	European Space Agency
ESRI	:	Environmental System Research Institute
EU-DEM	:	European Union Digital Elevation Model
FDC	:	Flow Duration Curve

GHEP	:	Gross Hydroelectricity Potential
GIS	:	Geographic Information System
GLOF	:	Glacial Lake Outburst Flood
GoN	:	Government of Nepal
GPS	:	Global Positioning System
GWh	:	Giga Watt-Hour
H	:	Height
ha	:	Hectares
HEC-HMS	:	Hydrologic Engineering Center-Hydrologic Modeling System
HFL	:	High Flood Level
HFT	:	Himalayan Frontal Thrust
HPP	:	Hydropower Project
HRU	:	Hydrological Response Unit
ICOLD	:	International Commission on Large Dams
ICIMOD	:	International Center for Integrated Mountain Development
IDC	:	Interest During Construction
IDW	:	Inverse Distance Weighting
IEE	:	Initial Environmental Examination
IHA	:	International Hydropower Association
INPS	:	Integrated Nepal Power System
IPPs	:	Independent Power Producers
IRR	:	Internal Rate of Return
IS	:	Indian Standards
IVF	:	Index of Volumetric Fit
JICA	:	Japan International Cooperation Agency
J/V	:	Joint Venture
km	:	Kilometer
kV	:	Kilo Volt

kW	:	Kilo Watt
kWh	:	Kilo Watt-Hour
L	:	Length
m	:	Meter
MAE	:	Mean Absolute Error
masl	:	Meters above Sea Level
MATLAB	:	Matrix Labooratory
MBT	:	Main Boundary Thrust
MCT	:	Main Central Thrust
MDT	:	Main Dun Thrust
MFT	:	Main Frontal Thrust
MHEP	:	Maximum Hydroelectricity Potential
mm	:	Millimeter
MSE	:	Mean Square Error
MT	:	Mahabharta Thrust
MTF	:	Monthly Turbine Flow
MW	:	Mega Watt
N	:	North
NEA	:	Nepal Electricity Authority
NEIC	:	National Earthquake Information Center
NGDC	:	National Geological Data Center
NPV	:	Net Present Value
NPR.	:	Nepalese Rupees
NRMSE	:	Normalized Root Mean Square Error
NSE	:	Nash-Sutcliffe Coefficient of Efficiency
O&M	:	Operation and Maintainance
PBIAS	:	Percentage BIAS
PERT	:	Program Evaluation and Review Technique

PGA	:	Peak Ground Acceleration
PSO	:	Particle Swarm Optimization
Q	:	River Discharge
QCBS	:	Quality and Cost-Based Selection
RoR	:	Run-of-the-River
rpm	:	Revolutions per Minute
RMSE	:	Root Mean Square Error
s	:	Second
S	:	South
SAE	:	Standard Deviation Absolute Error
SNRTP	:	Strengthening National Rural Transport Programme
SOTER	:	Soil and Terrain Database Programme
SRTM	:	Shuttle Radar Topography Mission
STDS	:	South Tibetean Detachment System
TL	:	Transmission Line
ToR	:	Terms of Reference
u/s	:	Upstream
USDA	:	United States Department of Agriculture
USGS	:	United Stated Geological Survey
US$	:	United States Dollars
UTM	:	Universal Transverse Mercator
VB	:	Volume Bias
VDC	:	Village Development Committee
W	:	West
WECS	:	Water and Energy Commission Secretariat
yr	:	Year

Table of Contents

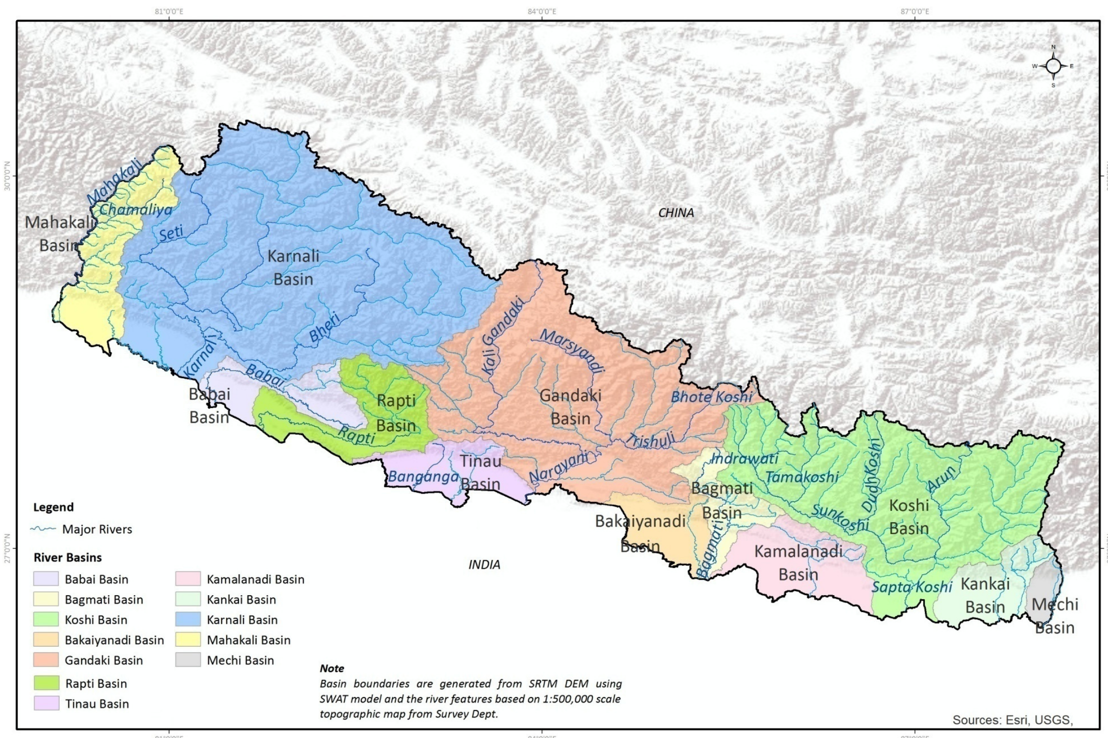
List of Figures

List of Tables

1. INTRODUCTION

1.1. **Background**

With an average rainfall of about 1530 mm over the country (WECS, 2005), Nepal is generously endowed by nature in water resources. There are about 6000 big and small rivers in the three main river systems Koshi, Gandaki and Karnali including some southern rivers and the two border rivers – Mechi in the east and Mahakali in the west (WECS, 2011). While some of the major rivers originate in the High Himalaya in Nepal, some others originate in the Tibet. Yet another group of rivers, such as Kankai, Kamala, Bagmati, Rapti and Bheri originate in the Mahabharata ranges. Numerous small streams start from the churia ranges of hills; these are principally rain fed and are, therefore, seasonal. The rivers network is shown in



Nepal receives 60-90% of the total annual precipitation during monsoon (June-September) period. About 55 – 80% of the total run-off occurs during this period, while the rest is conserved as snow and ground water which drains into the rivers during the dry season (Hannah et al., 2005). The total run-off per year from Nepal, including run-off from the Tibetian catchment is estimated to be about 225 billion cubic meters (WECS, 2011).

Nepal has longitudinal (east-west) extension of 885 km and lateral (north-south) extension of 145-248 km. Within relatively short lateral extension topographic elevation varies from 60 masl to 8848 masl, providing steep topographic gradient for potential hydropower generation. Based on that, an old study reveals that Nepal has a gross hydropower potential of 83,500 MW (Shrestha, 1966) and an economically viable potential of about 45,610 MW (Pradhan, 2009; WECS, 2011) - estimated as the combined capacity of 114 projects identified by

Shrestha [1966]. More recent study has estimated run-off-the-river (ROR) hydropower potential of 53,836 MW at 40% dependable flow (Jha, 2010).

Nepal's hydropower potential estimated by Shrestha [1966] was 5 decades ago. During this intervening period, much data has become available and rapid advancement in Geographical Information System (GIS) and hydro-meteorological modeling has allowed developing tools providing automatization and more accurate assessments of hydropower potential. So, critics have continuously pointed out the need to verify and update these figures. Re-estimation of hydropower potential, using the fast growing information and computing technologies, are also carried out in different countries around the world (Arefiev et al., 2015a). On the other hand, although figures estimated by Jha [2010] are computed using recent data and GIS tools, it needs to be verified and assessed in more detail. Therefore, it becomes sensible that Nepal's hydropower potential be assessed again in depth with the help of more recent data and modeling tools.

Realizing this need, Water and Energy Commission Secretariat (WECS) of the government of Nepal has allocated fund to carry out a study on the 'Assessment of Hydropower Potential of Nepal' (the Study) in the present context. Accordingly, an agreement was signed between WECS (the Client) and SILT-CEMAT-DSC JV (the Consultant) on 21st August 2015 to carry out the Study.

1.2. **Objectives**

The overall objective of the work outlined in the ToR are as follows:

- To carry out the assessment of gross ROR hydropower potential of rivers in Nepal and arrive at a techno-economically viable potential.
- To identify and assess the potential of reservoir type projects with installed capacity of 100 MW or more and run-off river projects with installed capacity 300 MW or more.

1.3. **Scope of Work**

The scope of the proposed work includes, but is not limited to, the following:

- To evaluate gross ROR hydropower potential in the major river basins: Sapta koshi, Sapta Gandaki and Karnali.
- To evaluate gross ROR hydropower potential of two boundary river basins: Mechi & Mahakali
- To evaluate gross ROR hydropower potential of rivers originating from middle mountains of Nepal: Kankai, Kamala, Bagmati, Bakaiyanadi, Tinu, Rapti and Babai

- To evaluate techno-economical ROR hydropower potential in the major river basins, boundary river basins and basins of the rivers originating from middle mountains of Nepal

- To identify the possibility of reservoir type of projects with an installed capacity of 100 MW or more and depict in the topo map.

- To identify potential sites for ROR projects having installed capacity 300 MW or more in the basis of 40% dependable flow as design discharge and depict in the topo map.

- To analyse environmental & social viability including techno-economical viability for identified projects.

- To prepare maps and depict the identified projects in the maps separately for basins, regions and districts.

1.4 Structure of the report:

The report is presented in two volumes. Volume – I presents the main report and its chapters are outlined as follows:

Chapter 2 describes different data - GIS, hydro-metrological, geological and hydropower data - collected to carry out this study.

Chapter 3 describes methodologies adopted to process geospatial data required to carry out hydrological study and hydropower potential computation.

Chapter 4 describes different methodologies adopted to process hydro-metrological data and compute design discharge and long-term average monthly discharge for river reaches.

Chapter 5 describes geology of Nepal and the river basins, at a catchment scale.

Chapter 6 describes the economics and financial analysis

Chapter 7 describes the estimation of the theoretical hydropower potential of Nepal

Chapter 8 describes the estimation of the RoR techno-economical potential of Nepal

Chapter 9 describes the identifications of RoR projects with installed capacity > 300 MW

Chapter 10 describes the identifications of reservoir projects with installed capacity > 100 MW

Chapter 11 provides the conclusion and discussion of the study

Volume II presents the Appendices containing some of the results of the analysis and the supporting information's for the analysis carried out in the study. The Appendices are presented as follows:

Volume-II (Appendices)

Appendix-A: List of Project Details

Appendix-B: Geospatial data

Appendix-C: Hydrological Analysis

Appendix-D: Results of Hydropower Potential

Appendix-E: Run-of-the River Projects Details

Appendix-F: Storage Project Details

2. DATA COLLECTION

2.1. Hydrological & Meteorological data

In the context of Nepal, the Department of Hydrology and Meteorology (DHM), the sole government authority responsible for the collection, analysis and dissemination of hydro-meteorological data, is collecting hydrological data of different rivers of Nepal since the early 1960s. Currently the DHM collects processes and publishes river flow data of around 100 river stations. Given that Nepal has around 6000 channelized water flows which can be classified as rivers or rivulets, the number of hydrometric station is very low. Moreover, the distribution of the river gauging stations is not uniform; majority of the gauging stations are concentrated in the mid-hill portion of Nepal. The high Himalayan region is too inaccessible to operate and maintain regular gauging stations, and the river flow channel in the flatter Terai region changes too frequently. Similarly, the DHM collects meteorological data, like precipitation, air temperature, solar radiation, humidity, and wind speed, from about 300 stations, the spatial distribution of which is more uniform compared to river gauging stations.

For our study the average monthly rainfall data and average monthly discharge data both are collected from DHM.

2.1.1 Collection of Average Monthly Rainfall Data

Monsoon is the wettest season and is the main source of rainfall in Nepal. The monsoon (rainy season) normally starts in the second week of June and continues until the fourth week of September and contributes an average 79.58% of the total annual rainfall in the country. The large amount of rainfall within a short period causes flash floods, massive landslides, soil erosion and sedimentation in hilly and mountainous regions, and inundation of the plains areas. The study of the rainfall pattern is very important for the hydrological study and climate change impacts on water resources. The available average monthly rainfall data of the 281 existing meteorological stations of Nepal from their opened date to December 2014 was collected for the study. The lists of meteorological stations are presented in Appendix A-1.

2.1.2 Collection of Average Monthly Discharge Data

One of the major hydrological parameters associated with the generation of hydropower is the average monthly river flow. The DHM has monthly river flow fluctuations data at different rivers in Nepal. In the gauged catchments with long time-series daily discharge data, the monthly river flow is calculated as arithmetic average discharge for a particular month. The monthly available water flow determines the amount of water that can be diverted from a river, in case of an ROR type HPP and stored in case of a reservoir type HPP. The available average monthly discharge data of existing 99 hydrological stations of Nepal from their opened date to December 2014 was collected for the study. The list of hydrological stations is presented in Appendix A-2.

2.2. Data on Geographical Information Systems (GIS)

Digital Elevation Model (DEM) is used as the primary spatial data for modelling and assessment of the hydropower potentials at river basin level. Freely available ASTER Global Digital Elevation Model (GDEM) with 30m spatial resolution was used for sub-watershed level hydrological modelling in GIS environment. ASTER GDEM was used considering its free availability, wall-to-wall coverage of entire territory of Nepal and regions beyond, which is required for sub-catchment level modelling for HP potential assessment. Additionally land cover data of 2010 (i.e. dense forest, light forest, shrub land, pasture/grazing, agriculture, settlement, bare soil, snow/glacier, water) prepared by ICIMOD has been used to analyze land cover in each delineated sub-watersheds.

Similarly the following GIS based data were also collected to generate thematic maps:

1. Road networks of Nepal (SNRTP project)
2. Substation and transmission line map at the scale of 1:1,000,000 (NEA, 2017)
3. Seismic hazard map of Nepal showing Peak Ground Acceleration (PGA) value with 10% probability of exceedance in 50 years at the scale of 1: 100,000,000 (Thapa and Wang, 2013)
4. Glacial lake inventory (ICIMOD, 2011)
5. Regional geological map at the scale of 1:1,000,000 (DMG, 1994)
6. Major active faults in Nepal (Upreti et al., 2007)
7. Provincial capital location prepared by department of survey

2.3. Data on Hydropower Project Studies

Any studies relating to the Hydropower projects could be the references for this study about the assessment of total hydropower potential of the country. So, all the earlier studies of any type of Hydropower projects ie RoR type, Storage Projects in all the rivers basins are collected and presented according to basins and project types. They are described briefly below here.

2.3.1 Koshi Basin Master Plan Study

Japan International Cooperation Agency (JICA) had prepared Mater Plan Study on the Koshi River Water Resources development Final report in March 1985.The study identified all potential hydropower sites and listed the sites in terms of priority for formulation of the Koshi River Water Resources Development. Potential hydropower sites in Sun Kosi river, Dudhkosi River , Likhu Khola, Malung Khola, Tama Kosi, Khimti Khola, Bhote Koshi , Balephi Khola, Rosi Khola , Indrawati, Tamur, Kabeli Nadi, Arun, etc were found and analysis was carried out on analysis of existing data , hydrology, geology, topography, etc and site reconnaissance, field investigation, surveying and drilling investigations of provisional priority sites. Total 52 potential projects had been identified in this study and details of projects are presented in Appendix A-3.

2.3.2 Gandaki River Basin Power Study

The Gandaki River Basin Power Study was carried by Snowy Mountains Corporation in association with Environmental Planning Associates for Government of Nepal in July 1979. Gandaki basin is located in central Nepal and study covers the potential sites in tributaries of Gandaki river systems namely Seti, Marsyangdi, Budhi Gandaki, Trishuli, Kaligandaki etc. The 'Master Plan of Hydroelectric power Development in Nepal' prepared with the assistance of the Japan International Co-Operation Agency (JICA) reports that theoretical power potential of Gandaki Basin is 21000 MW. This study have identified 42 different Run of river schemes and storage schemes to suit the varying topographic, hydrologic and geological conditions in Nepal. List and locations of potential projects identified are presented in Appendix A-4.

2.3.3 Mahakali & Karnali Basin Master Plan Study

The study was carried out over the period November 1991 to October 1993. Investigation was carried out for hydropower, irrigation, domestic water supply, flood mitigation and watershed management. This study consists of the area the Upper Karnali Basin upstream of full supply level of Karnali Multi Purpose Project and Mahakali River Basin within territory of Nepal. Total 38 hydropower potential schemes were identified (23 hydropower potential sites including Pancheswor and Karnali (Chisapani) and 15 newly identified schemes). List and locations of potential projects identified are presented in Appendix A-5.

2.3.4 Storage Project Master Plan Study

Japan International Cooperation Agency conducted "Nationwide Master Plan Study on Storage-type Hydroelectric Power Development in Nepal" in February 2014. Altogether 61 storage type projects were considered for the long list of inventory of potential sites for the preliminary screening. After all the investigations and analysis 10 projects were selected as the promising projects. The long list of Inventory as well as promising projects is listed in Appendix A-6.

2.3.5 Projects Identified by Independent Power Producers (IPPs)

Since the government opened the Hydropower policy in 1990, the private sector were found interested for the development of Hydropower projects. Details of the projects listed in the web page of Department of Electricity Development, Ministry of Energy, Water Resources and Irrigation of the Government of Nepal (GON), up to 25th Feb 2019, are provided in the Table 2-1, Table 2-2, Table 2-3 and Table 2-4.

Table 2-1: Details of survey license issued by GON

S. No.	Range of Capacity	Nos. of Projects	Total capacity (MW)	Remarks
1	Below 1 MW	18	13.37	
2	1 to 25 MW	202	2105.83	
3	25 to 100 MW	50	2707.67	
4	Above 100 MW	5	27506.02	
Total			25496.33	

Table 2-2: List of Project application by Independent Power Producers (IPPs)

S. No.	Range of Capacity	Nos. of Projects	Total capacity (MW)	Remarks
1	Below 1 MW	10	6.84	
2	1 to 25 MW	5	32.53	
3	25 to 100 MW	2	91.2	
4	Above 100 MW	6	1232	
5	License for Generation	27	1682.08	
Total			3044.65	

Table 2-3: List of Project in GON reserved list

S. No.	Range of Capacity	Nos. of Projects	Total capacity (MW)	Remarks
1	GON basket projects	104	2779.6	
2	GON studied projects	6	1272.21	
3	GON under study projects	2	7976.18	
Total			12028	

Table 2-4: List of Project in operation

S. No.	Range of Capacity	Nos. of Projects	Total capacity (MW)	Remarks
1	Below 1 MW	15	11.24	
2	Above 1 MW	75	1004.84	
Total			1016.08	

3. GIS Analysis

3.1 Preparation of Topographic Terrain Data

Digital Elevation Model (DEM) is used as the primary spatial data for modelling and assessment of the hydropower potentials at river basin level. Freely available ASTER Global Digital Elevation Model (GDEM) [1] version 2 with 30m spatial resolution was used to derive topographical and hydrological features of the river basins in GIS environment. ASTER GDEM was used considering its free availability, wall-to-wall coverage of entire territory of Nepal and regions beyond, which is required for sub-catchment level modelling for HP potential assessment. Coverage of ASTER GDEM map is shown in Figure 3-1. The DEM is processed using following methodological steps:

- Processing of DEM for correcting sink/gap/and other anomalies using ArcSWAT and ArcHydro tools in ArcGIS
- Generation of hydrologically correct DEM
- Generation of slope, aspect, flow accumulation, flow directions from the terrain required for delineation of catchments and sub-catchments throughout the country.

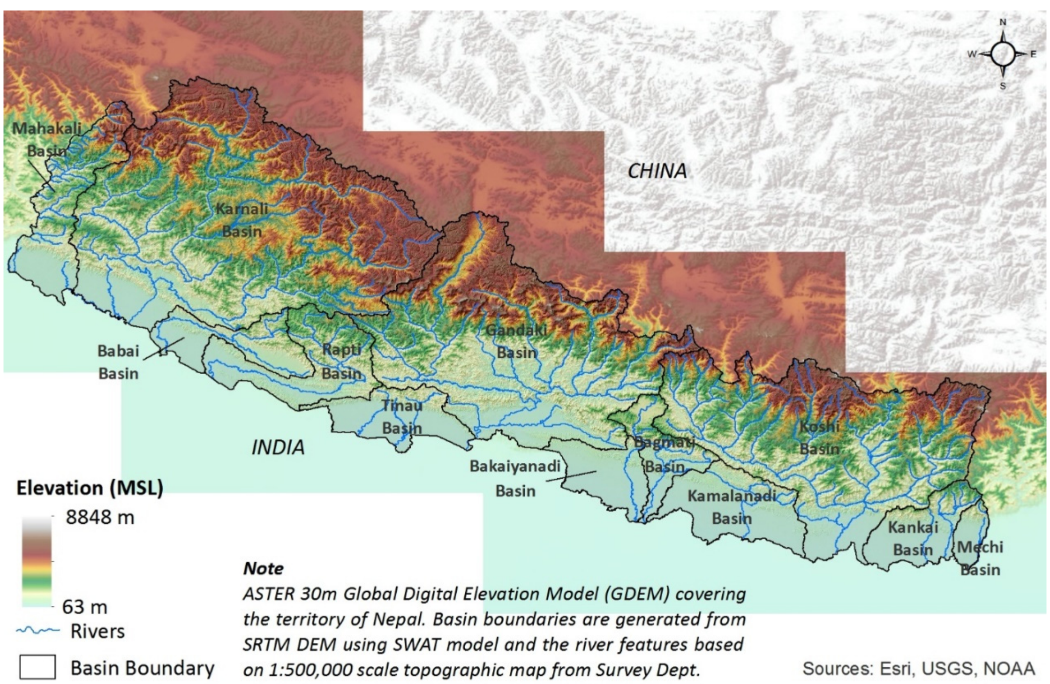


Figure 3-1: Aster GDEM covering Nepal

[1] http://gdem.ersdac.jspacesystems.or.jp/download.jsp

The processing of ASTER GDEM for entire territory of Nepal required considerable computing resources (using Intel Xeon 24 Core processor with 48 GB RAM workstation). Therefore, sub-catchment analysis was done at the river basins level.

3.2 Delineation of Sub-Catchments

Within a river basin, sub-catchments of minimum area 15 km2 area were delineated using GIS based SWAT modelling tool ArcSWAT using the GDEM. Hydrologically connected sub-catchments are delineated considering the critical source area (stream area threshold) as 1000 ha (10km2) that defines the minimum drainage area required to form the origin of stream in a sub-catchment. Streams and sub-catchment outlets are created with the above threshold. The ArcSWAT model delineates the streams (reaches) and locates drainage outlets at the downstream confluence. These outlets are the points in the drainage network of a sub-catchment where stream flow exits the sub-catchment area.

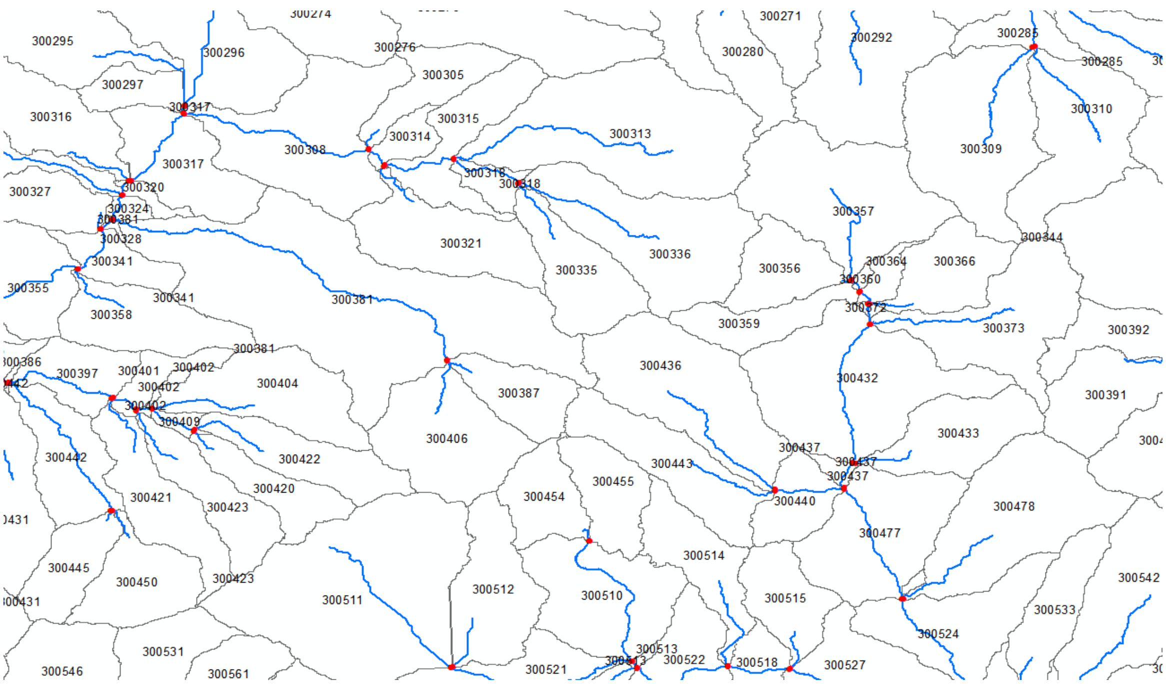


Figure 3-2: Illustration of delineated streams, outlets and sub-catchments

The outlets, streams and basins are uniquely numbered in 6 digit long integer values starting from 100001, 200001 and 300001 respectively and its database is created Figure 3-2. Each outlet is uniquely associated with a stream which is then uniquely associated with a basin. Thus river basins in this study were sub divided into a total number of 10,505 basins/ reach / outlets.

3.3 Analysis of Physiographic Variables for Sub-Catchments

Various physiographic variables are analyzed at the sub-catchment level to be used for different hydrological calculations. These physiographic variables include terrain elevation range (hypsometric ranges), slope, land cover, maximum and minimum elevations of stream, catchment area ratio and others. Following analysis were done extracting physiographic variables in the delineated sub-catchments:

- Elevation range analysis and analysis of sub-catchment areas within different elevation ranges (<1000m , 1000-2000m, 2000-3000m, 3000-4000m, and >5000m)
- Analysis of sub-catchment areas within different land cover zones (dense forest, light forest, shrub land, pasture/grazing, agriculture, settlement, bare soil, snow/glacier, water)
- Analysis of sub-catchment areas within different terrain slopes ($>10^{o}$, 10^{o}-20^{o}, 20^{o}-30^{o} and $>30^{o}$)
- Analysis of minimum, average and maximum slopes within each sub-catchment
- Analysis of catchment area ratio for each sub-catchment with respect to the DHM hydrological stations' catchment area

3.4 Analysis of Gross Heads

Gross heads available for power generation is computed as the elevation difference between the outlet of the sub-catchment under consideration and the outlet of the immediate downstream sub-catchment. Negative gross heads were obtained at several locations due to error present in the digital elevation model (DEM). The negative gross heads were then rectified using the spot elevation derived from the topographic map published by Survey Department of the Government of Nepal.

3.5 Validation of gross heads

The global vertical accuracy of ASTER-GDEM version 2 is reported as 8.5 m at 95% confidence interval (Mukherjee et al., 2012; Tachikawa et al., 2011). Based on the validation in Himalayan region, Mukherjee et al., (2012) show that the vertical accuracy of the ASTER-GDEM is affected by the terrain morphology and terrain roughness. The error in elevation is observed to increase in the terrain with topographic elevation greater than 600 m and the topographic slope greater than 10%. Nepal has very high topographic variation within a short spatial extent. So, it is pre-requisite to validate the ASTER-GDEM before its application to the study.

The validation is performed based on the relative elevation difference between headworks and powerhouse of 29 operating run-off-river hydropower plants in Nepal. The hydropower plants covered a range of gross heads between 50 m and 840 m (Figure 3-3). Actual gross heads of the plants were collected from the available study reports and various other sources. Then the headworks and powerhouse were located on Google Earth and saved as *.kml file. The file was imported to GIS platform to extract elevation from ASTER-GDEM at the headwork and powerhouse points. In the case of peaking run-off-river plants dam height was further added to the elevation at headwork. The gross-head was then computed by subtracting the elevation of powerhouse from that of headwork. The computed gross head was compared with the actual gross head to compute the percentage of error. Taking into consideration the large scale of the study and others existing source of uncertainty (e.g. hydrology) in power computation, 20% of deviation in the gross-head was deemed to be acceptable. The error in the computed gross head was found to be within the limit in 93% of the cases (Figure 3-4). The details of the validation is presented in Appendix B.

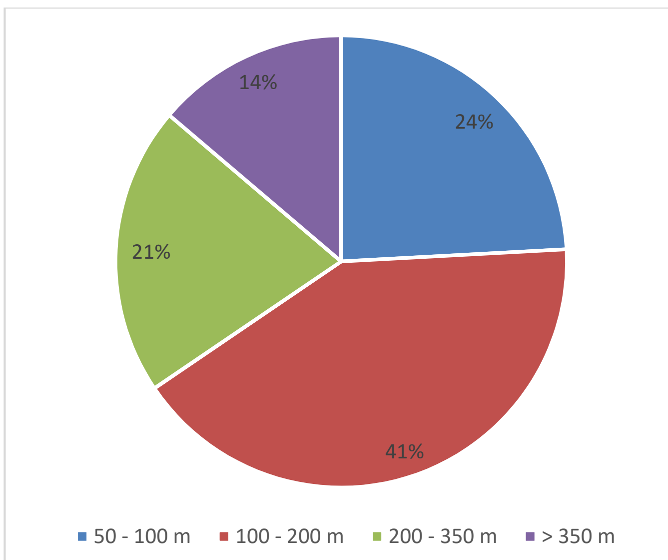


Figure 3-3: Distribution of gross head range of existing hydropower plants considered for DEM validation. Legend: ranges of gross-head

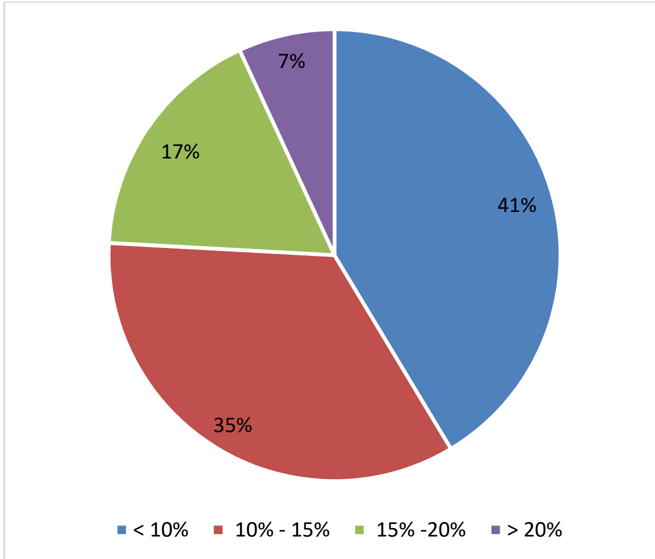


Figure 3-4: Error range observed in gross head during DEM validation. Legend: error range

3.6 Thematic map preparation

Several geospatial data were processed to obtain thematic data for the multi-criteria evaluation tool. The inventory of glacial lakes and glaciers (ICIMOD, 2011), which included shapefiles (four in total) for glaciers and glacial lakes as per 2001 and 2010 research. This was spatially joined into the sub-basins of Koshi, Gandaki and Karnali catchments.

The Peak Ground Acceleration (PGA) maps at probability of exceedance of 63% from Thapa and Wang (2013) was digitized and rasterized according to the PGA value classes. Similarly map of major faults in Nepal (Upreti et al., 2007) was digitized. A buffer map was created with 5km interval till 100 km distance, and then at 10 km interval beyond 100 km.

The A1 Size hardcopy Geological map of Nepal was scanned and digitized. The geological features were digitized and saved as two shape files: polygon features and line features. The polygon features which represented rock type have been rasterized.

The locations of the metropolitan and sub-metropolitan cities are plotted in map. These represent the nearest market for the procurement of construction materials. Buffer zones are created at an interval of 5 km till 100 km and then at an interval of 10 km beyond 100 km.

The grid substations were obtained from Power Development Map of Nepal and digitized. Attributes added include grid capacity and grid station name. A buffer raster was obtained from the grid point data at an interval of 5 km till 100 km and at 10 km interval beyond 100 km.

4. Hydrological Analysis

The hydropower (HP) potential of a river section is basically a function of available river discharge and net head so the discharge time series data is essential at the river reach for assessing its hydropower potential. In the river basins of Nepal few gauging stations are installed along the major tributaries. It is necessary to generate time series of discharge at un-gauged locations within a gauged basin or within a completely un-gauged basin for assessing the hydropower potential of the river basin. This chapter describes empirical and hydrological modelling methods used for the assessment of available river discharge used to compute run-of-river (ROR) hydropower potential in all the 12 major river basins of Nepal, namely the Babai, Bagmati, Bakaiya, Gandaki, Kamala, Kankai, Karnali, Koshi, Mahakali, Mechi, Rapti, and Tinau, in alphabetic order. The analyses were carried out using both empirical and modelling approach to determine the following hydrological parameters associated with power and energy generations for ROR type hydropower projects.

Average Monthly Flow (AMF)

Average monthly flow is the long-term average monthly discharge of the river computed at each potential headwork and powerhouse site. It determines the amount of monthly discharge available in the river to generate hydropower. It is used to compute the hydro-electric energy potential of the reach. The average monthly flow computation at each of the identified potential hydropower generation site.

Flow Duration Curve (FDC)

FDC provides a basis for the selection of design discharge of the HP generation at identified potential sites. Based on the calculated AMF, FDC values at each of the potential site were developed by using the Weibull Plotting Position method[2], and the 40% dependable flow (Q40) was interpolated from the FDC. The ToR of the current study requires the hydropower potential of major river basins of Nepal to be estimated at Q40 discharge value. However, the Government of Nepal (GON) has recently issued a directive to design ROR type of hydropower projects (HPP) with Q45 (45% dependable flow) as the design discharge.

[2] The Weibull's plotting position method is the most widely used method for estimating hydro-meteorological parameters, like extremes of precipitation and flood (Cunnane, 1989)

Since the purpose of this study is to assess the theoretical potential of hydropower, all the water flow in the river (below Q40) is considered as available for power generation; no downstream release and other environmental flow is considered.

Monthly Turbine Flow (MTF)

In a RoR type of hydropower projects, the total AMF is not tapped during the wet season. The river discharge above the design discharge flows downstream of the intake site above the weir. However, during the dry season, the average monthly discharge in the river is lower than the design discharge. The monthly discharge diverted from the river to generate hydropower is called the monthly turbine flow (MTF). As such, the actual river flow reaching the turbine of an HPP in each month (MTF) varies. For each month, the following relation is used to calculate the MTF.

a) If the design discharge is more than the AMF, the MTF = AMF
b) If the design discharge is equal to or less than the AMF, the MTF = design discharge

The design discharge is set as the Q40 value. The MTF for each month at each of the sub-basin is set as the average monthly flow or Q40 value, whichever is higher.

4.1 Empirical Assessment

There are all together 10,505 outlets where the discharge needs to be estimated to assess the power potential. Due to the steep topography of Nepal the hydrological characteristics of the rivers are strongly influenced by physiographic regions in which they flow; transposing hydrological data from one station to another is highly challenging. Evaluation of the hydropower potential of all the rivers and rivulets of Nepal, in the background of very low hydrometric station density necessitates transposition of hydrological data. Based on the literature, experience of dealing with hydrological data, lessons learned from previous studies, and discussion with various DHM officials, a Catchment Area Ratio method was used to transpose hydrological data from the gauged stations to un-gauged rivers sections of Nepal, for estimating average monthly flow, which is a major component of hydropower and energy potential of the rivers from Nepal. The latest available processed data from the DHM was used for this purpose.

4.1.1 Methodology

The hydrological data transposition process, from gauged to un-gauged sections of a river system, was carried out based on the Catchment Area Ratio (CAR) method. The CAR method estimates the flow at the un-gauged basin with respect to gauged basin in proportion to area, assuming that both basins/ catchments have similar characteristics (Emerson et al., 2005). Different CAR methods were applied for gauged and un-gauged catchments which are described as follows:

a) Gauged catchments

Since Nepal has very high variation in topography, the CAR method based on specific discharge yield is more reliable. Similar method was also used by Jha (2010) to estimate hydropower potential of Nepal. If a basin is gauged at point A and B (Figure **4-1**), then discharges at points X, X1 and X2 can be estimated by using equations 4-1, 4-2 and 4-3 respectively.

$$Q_x \approx \frac{Q_a}{A_a} \times A_x \qquad (4\text{-}1)$$

$$Q_{x1} \approx \left(\frac{Q_b - Q_a}{A_b - A_a}\right) \times A_{x1} \qquad (4\text{-}2)$$

$$Q_{x2} \approx Q_a + \left(\frac{Q_b - Q_a}{A_b - A_a}\right) \times (A_{x2} - A_a) \qquad (4\text{-}3)$$

where, Qx, Qx1, Qx2 are discharges at points X, X1 and X2 respectively. Qa and Qb are discharges measured at gauge stations A and B respectively. Similarly Aa, Ab, Ax, Ax1 and Ax2 are catchment areas at points A, B, X, X1 and X2 in the catchment.

The following steps were adopted to estimate discharge at the un-gauged outlets with respect to the gauged outlet.

- Average monthly flow (m3/s) was determined at a gauged location based on the available DHM data.
- The catchments of gauged locations were drawn and their upstream and downstream linkages were determined using GIS software Figure 4-2:.
- Sub basin outlets lying in the catchment of gauged locations were extracted using GIS software.
- The specific discharge was computed, by dividing the net discharge from the catchment by the catchment area contributing to the discharge, for each gauged locations for every months.
- The computed specific discharge was then used to transpose discharge to the outlets.
- The transposed average monthly flows were then used to determine the flow duration curve and Q40.

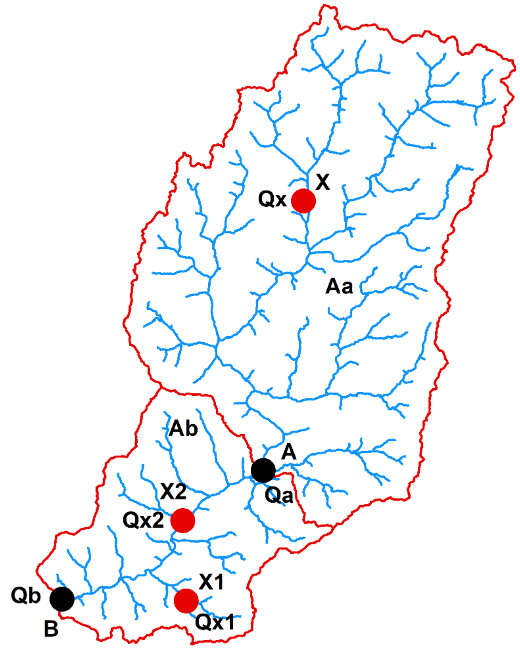


Figure 4-1: Figure elaborating CAR method based on specific discharge

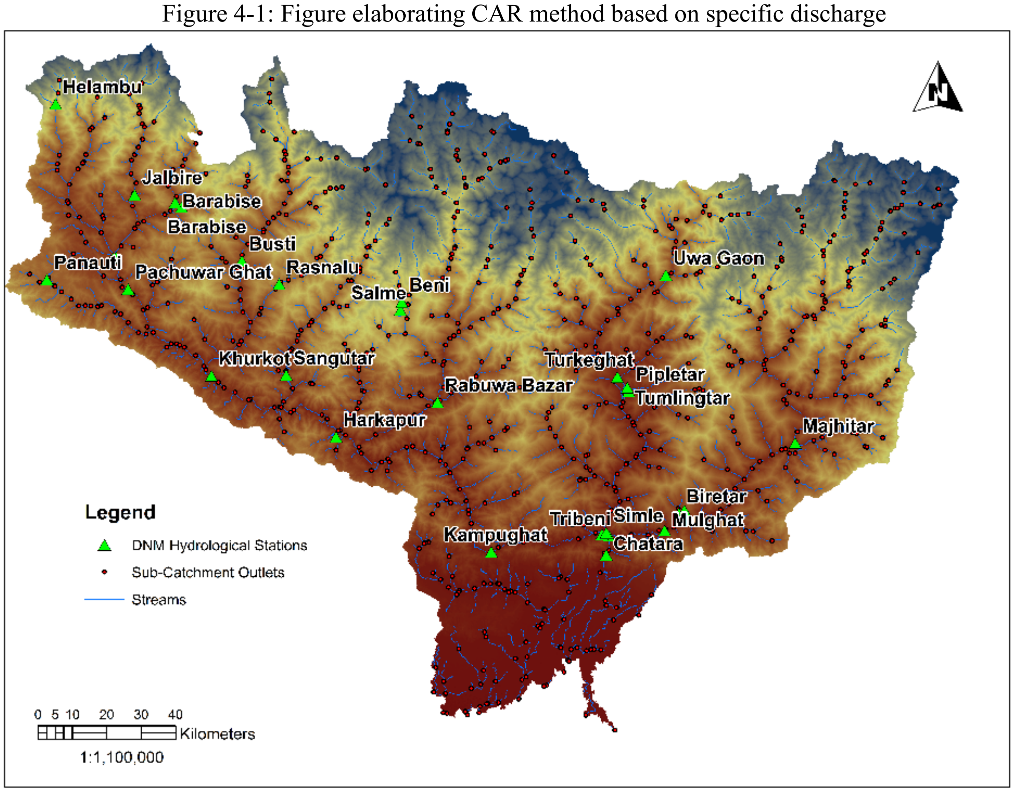


Figure 4-2: Hydrological stations located in the Koshi River basin

The mean monthly discharge observed at Hydrological stations, used for the analysis, is presented in Appendix C-3.

b) Un-gauged catchments

Smaller southern rivers such as Mechi and Bakaiya are un-gauged. The flow was transposed from the nearest similar catchment, based on CAR method using equation 4-4.

$$Q_x \approx \frac{Q_a}{A_a} \times A_x \qquad (4\text{-}4)$$

where, Qa is the discharge of the gauged catchment, m3/s; Aa is the area of the gauged catchment, km2; Qx is the discharge at the point of interest in the un-gauged catchment, m3/s; and Ax is the catchment area at the point of interest, km2.

Maikhola at Rajdwali and Kankai at Mainachuli were considered as the nearest gauged catchments for estimating flow in Mechi River whereas Bagmati River at Bhorleni and Karmaiya and Manahari Khola at Manahri were considered as the nearest gauged catchments for estimating flow in Bakaiya. The summary of the transposed average monthly river flow values at each of the potential hydropower generation site is provided in Appendix C-1.

4.1.2 Flood Flow

The flood flow values of specific return period is essential in the design aspects of a hydropower project. The potential inundation area in an upstream river stretch resulting from damming of flow in the downstream river section during a flood event determines the location of the hydropower sites in the upstream area. The annual instantaneous flood value of each of the DHM's stations was analysed to estimate the flood values of specific return periods using five different methods, namely the Gumbel, Extreme Value, Log Pearson Type III, Log Normal and the Weibull Plotting Position. The values from the different analytical methods were averaged to specific return period (100 and 1000 years). The flood magnitude in each of the potential hydropower development sites in each river basin is estimated for the return periods of 100 and 1000 years, using the relation provided in equation 4-5.

$$Q_x \approx \left(\frac{A_x}{A_a}\right)^n \times Q_a \qquad (4\text{-}5)$$

where, Qa is the instantaneous flood discharge of the DHM's gauged catchment, m3/s; Aa is the area of the gauged catchment, km2; Qx is the instantaneous flood discharge at the point of interest in the un-gauged catchment, m3/s; Ax is the catchment area at the point of interest, km2, and n is an exponent. The value of n is normally taken as 1 for transposing flow values of longer duration like annual flow and monthly flow; for transposing shorter duration flow values like instantaneous flood, the n value is taken anywhere between 0.5 to 0.75. To be on the safer side, for this study, the n value is taken as 0.5, which normally results in higher values of transposed instantaneous flood. The reference DHM hydrological station was selected by following the same procedure as for the average monthly flow transposition. The flood values for different return periods at each of the DHM station was calculated for this purpose and is presented in Appendix C-4. Similarly, the summary of the instantaneous flood values at each of the potential hydropower generation site is provided in Appendix C-4.

4.2 Hydrological modelling using HEC-HMS

HEC-HMS (Hydrologic Engineering Center-Hydrologic Modeling System), a semi-distributed model, was also used to determine hydrological parameters at an ungauged location within a gauged river basin. This model was developed by US Army Corps of Engineers. The model is open source, has many modules, user friendly and widely applied in many countries including Nepal.

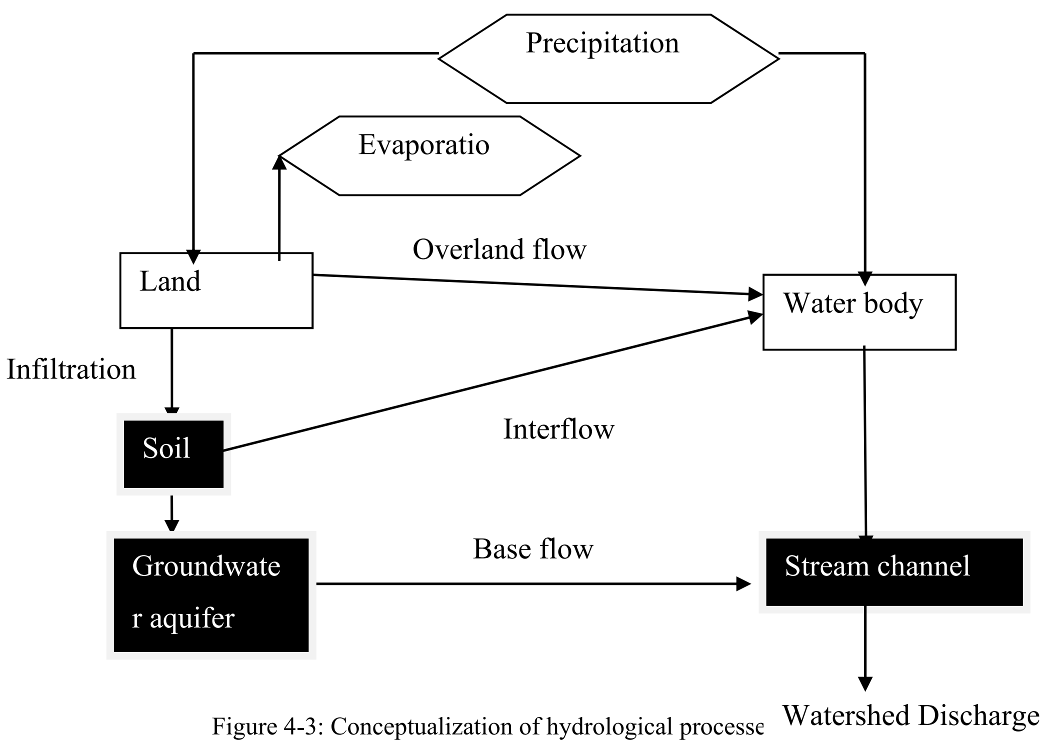


Figure 4-3: Conceptualization of hydrological processe

4.2.1 Modelling Approach

HEC-HMS is a conceptual model for representing the hydrological process of a basin. The model computes direct runoff and base flow, which is summed up to get total flow. The direct runoff is computed using loss module and runoff transform module. The runoff is routed through stream reach to consider the time of travel, for which routing module is applied. Several methods are implanted in HEC-HMS for each module. The conceptualization of hydrological processes in HEC-HMS model is shown in Figure 4-3:.

In this study, available historical rainfall and discharge data for gauged river basin, whose hydropower potential is to be assessed, was collected. Hydrological modelling was carried out in two different stages. In the first stage the model was setup for calibrating the parameters. For developing HEC-HMS model, the basin was divided into a number of sub-basins where the discharge measurements were available. Although HEC-HMS is a semi-distributed model, the rainfall within a sub-basin is lumped and considered to be uniform. The sub-basin rainfall was estimated by using Thiessen polygon technique. The parameters of HEC-HMS model were calibrated and validated using the available historical time series data of flow at gauging stations.

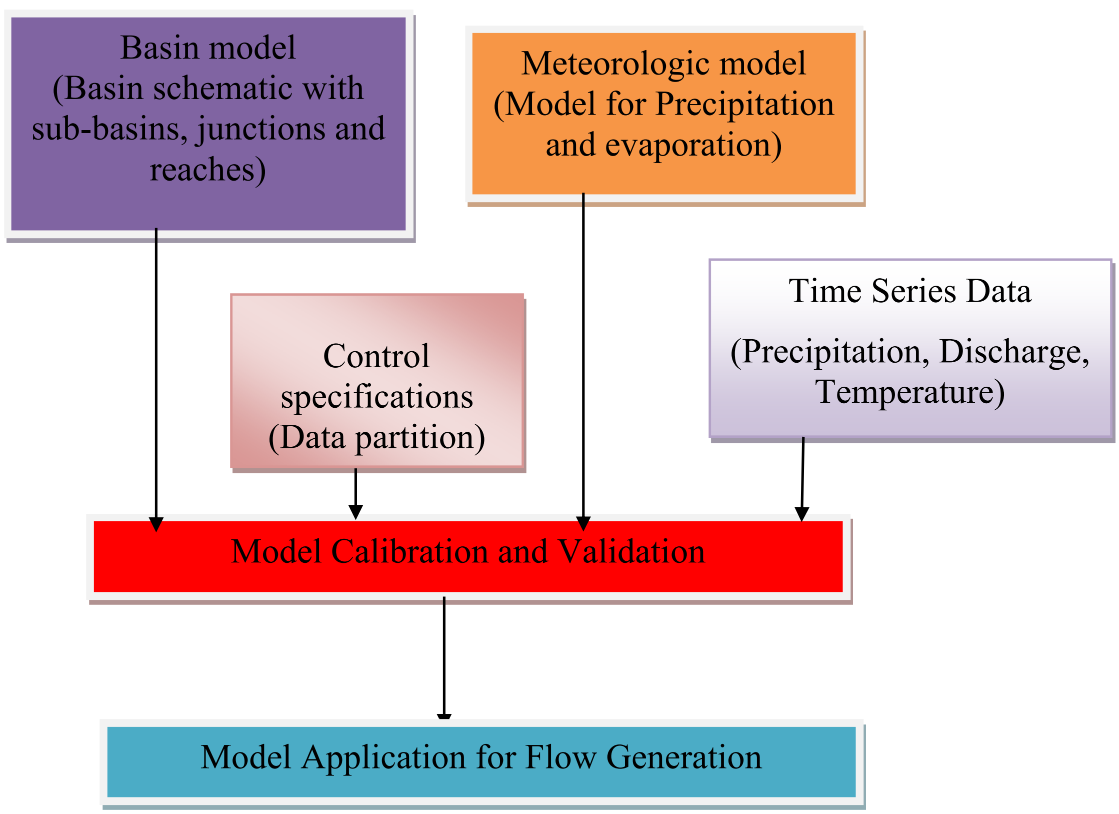


Figure 4-4: HEC-HMS Modelling sequences

In the second stage, a HEC-HMS model was setup for each sub basins taking into every sub-basins obtained from the GIS analysis to estimate discharges at each outlets. The calibrated parameters obtained from the first stage of modelling were used.

Modelling sequences adopted for each HEC-HMS model is described as follows and the schematic diagram is shown in

Figure 4-4.

- First of all, basin schematic is prepared, in which a basin is represented by sub-basins, junctions, reaches, source, sink etc. The type of model for each module is also selected.
- Meteorologic model is prepared, in which the type of model representing precipitation and evaporation is specified.
- Data is partitioned for simulation through control specifications.
- Time series data is loaded into the model through time series data manager.
- The model is calibrated (manually, automatically) and validated.
- Calibrated model is applied for study.

4.2.2 Model parameters

The following sub-model parameters were used for the model setup:

Sub model	**Type**	**Parameters**
Loss model	Deficit and constant loss	Initial loss rate Constant loss rate
Runoff transform model	Clark model	Time of concentration Storage coefficient
Base flow model	Monthly	Constant, monthly varying base flow
Routing model	Lag	Time lag

4.2.3 Model application and results

Rainfall data is prepared for 1990-2006 time period. Rainfall stations having continuous record during this period and possibility of filling few missing values are selected in the study. Some rainfall stations had to be discarded due to the unavailability of continuous data. The basin average precipitation is prepared by Thiessen polygon method. Discharge stations are also selected based on the availability of quality data. The latest available data after 1990 has been used for model calibration.

The model was run on daily resolution, from which long term mean monthly flow was computed. The model performance for mean monthly flow was assessed in terms of following statistical indicators:

- NRMSE = Normalized Root mean square error = Root mean square error/standard deviation of observed data
- NSE = Nash-Sutcliffe Coefficient of Efficiency
- VB = Volume bias

Model setup, calibration and validation of the river basins are presented as follows:

a) Koshi River Basin

The model schematic for Koshi basin to implement HEC-HMS model for calibration purpose is shown inFigure 4-5.

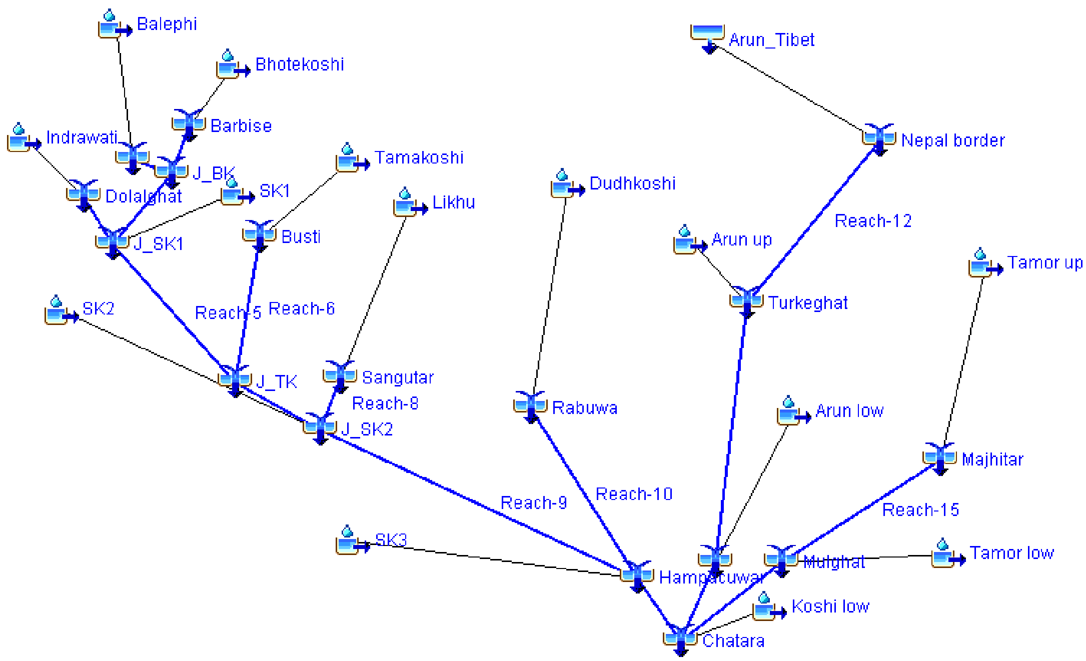


Figure 4-5: HEC-HMS set up for Koshi basin

The sub basins are considered based on the availability of stream gauging stations. The Koshi basin is a trans-boundary river. A large part of the Arun sub-basin lies in Tibet (China). The inflow from Arun at Tibet-Nepal border was taken directly from the output of another study (Bharati et al., 2016), in which global rainfall data (APHRODITE) was used. A source node was specified in this study for Tibetan part of Arun with of the time series of discharge shown in

Table 4-3. For other tributaries originating from Tibet, the cumulative area including Tibetan part is considered. The mean areal precipitation was computed from the rainfall stations in Nepal only. The parameters were calibrated from the observed discharge data in Nepal. The parameters are calibrated from the observed discharge data in Nepal. Hydrological and Metrological database used in the HEC-HMS model of the Koshi basin is presented in Table 4-1 and Table 4-2 respectively.

The upper part of the Koshi River basin has snow cover. To incorporate the effect of snow in discharge estimation a simple degree day method was used in the model. The degree day method relates the total daily snow melt with the temperature difference between the mean daily temperature and base temperature required for snow melt - 0 ^{o}C (USDA, 2004). The time series temperature data needed for the snowmelt model was supplied for the sub-basin having snowmelt contribution. Data from the temperature stations within Koshi basin: 1103, 1206, 1220, 1222, 1303, 1304, 1307, 1314, 1405, 1419 were used in the modelling.

Table 4-1: Hydrological database used for Koshi basin HEC-HMS model setup

Basin	Data	Hydrological stations	Hydrological station ID
Koshi	Calibration: 1990-1999 Validation: 2000-2006	Barbise, Jalbire, Dolalghat, Busti, Sangutar, Rabuwa, Hampachuwar, Turkeghat, Simle, Majhitar, Mulghat, Chatara	604.5, 606, 610, 620, 629.1, 647, 660, 670, 681, 684, 690, 695

Table 4-2: Meteorological database used for Koshi basin HEC-HMS model setup

Basin	Rainfall stations	No. of rainfall station
Koshi	1006, 1008, 1009, 1016, 1022, 1023, 1027, 1028, 1049, 1058, 1063, 1101, 1102, 1103, 1104, 1108, 1115, 1203, 1204, 1206, 1211, 1219, 1224, 1301, 1303, 1307, 1308, 1309, 1314, 1317, 1324, 1325, 1403, 1404, 1406, 1420	36

Table 4-3: Inflow from Arun at Nepal-Tibet border (m3/s) adopted from (Bharati et al, 2016)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
59.2	39.8	61.6	65.2	86	183.5	302.3	414.8	275.3	151.9	86.4	68.8

b) Gandaki River Basin

The model schematic for Gandaki basin up to Narayanghat to implement HEC-HMS model is shown in Figure 4-6. Similarly the schematic diagram of the East Rapti part is shown in Figure 4-7. The sub basins are considered, based on the availability of stream gauging stations. Part of some tributaries such as Trishuli and Budhi Gandaki basin lie in Tibet (China). The cumulative area at the discharge gauging station in Nepal including Tibetan part is considered in modeling. The mean rainfall is based on stations within Nepal. The parameters are calibrated from the observed discharge data in Nepal. Hydrological and Metrological database used in the HEC-HMS model of the Gandaki basin is presented in Table 4-4 and
Table 4-5 respectively.

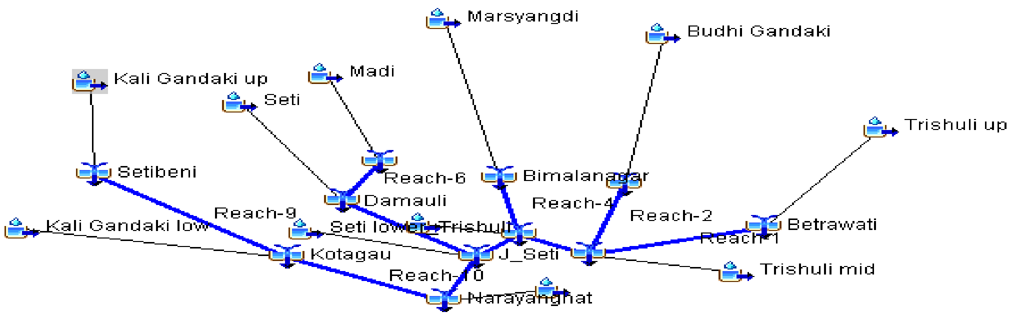


Figure 4-6: Schematic for Gandaki River basin up to Narayanghat in HEC-HMS

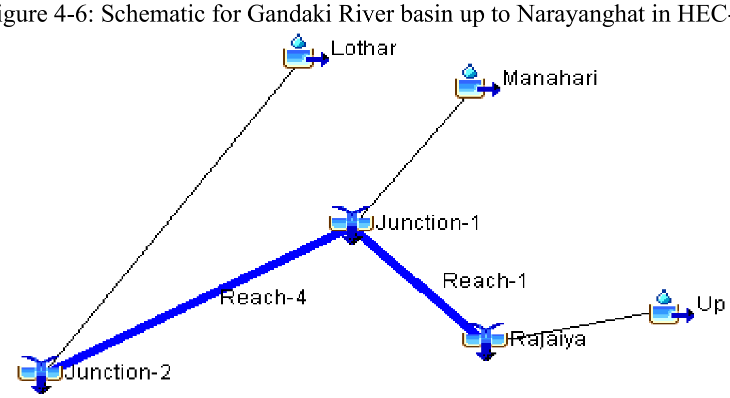


Figure 4-7: Schematic for Gandaki River basin in the East Rati part in HEC-HMS

Table 4-4: Hydrological database used for the Gandaki basin HEC-HMS model setup

Basin	**Data**	**Hydrological stations**	**Hydrological station ID**
Gandaki	Calibration: 1990-1999 Validation: 2000-2006	Betrawati, Arughat, Shisaghat, Bimalnagar, Setibeni, Kotagau, Narayanghat	410, 420, 438, 439.7, 445, 447, 450

Table 4-5: Meteorological database used for the Gandaki basin HEC-HMS model setup

Basin	**Rainfall stations**	**No. of rainfall station**
Gandaki	601, 610, 613, 619, 701, 722, 726, 801, 804, 806, 807, 809, 813, 815, 817, 820, 823, 824, 1002, 1004, 1005	21

c) Karnali River Basin

The model schematic for Koshi basin to implement in HEC-HMS model is shown in Figure 4-5. The sub basins are considered, based on the availability of stream gauging stations. Part of Humla Karnali basin lies in Tibet (China). The cumulative area at the confluence of Mugu Karnali including Tibetan part is considered in modeling. The mean rainfall is based on stations within Nepal. The parameters are calibrated from the observed discharge data in Nepal. Hydrological and Metrological database used in the HEC-HMS model of the Karnali basin is presented in Table 4-6 and Table 4-7 respectively.

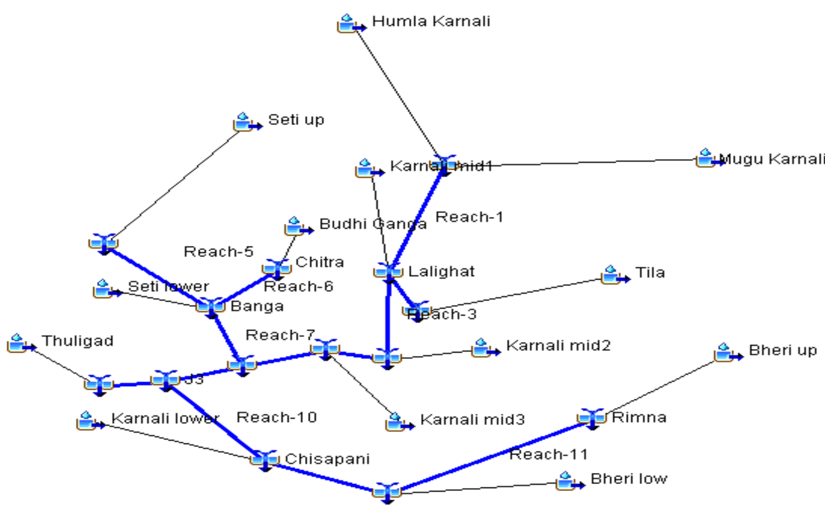


Figure 4-8: Schematic for Karnali River basin in HEC-HMS

Table 4-6: Hydrological database used for the Karnali basin HEC-HMS model setup

Basin	Data	Hydrological stations	Hydrological station ID
Karnali	Calibration: 1990-1999 Validation: 2000-2006	Lalighat, Nagma, Asaraghat, Benighat, Gopaghat, Banga, Khanaytal, Jamu, Chisapani	215, 220, 240, 250, 259.2, 260, 262, 270, 280

Table 4-7: Meteorological database used for the Karnali basin HEC-HMS model setup

Basin	Rainfall stations	No. of rainfall station
Karnali	202, 204, 205, 206, 214, 302, 303, 306, 308, 311, 312, 403, 404, 405, 406, 410, 418, 504	18

d) Kankai River Basin

The model schematic for Kankai basin to be used in HEC-HMS modelling is shown in Figure 4-9. The parameters are calibrated from the observed discharge data Mainachuli. Hydrological and Metrological database used in the HEC-HMS model of the Kankai basin is presented in Table 4-8 and Table 4-9 respectively.

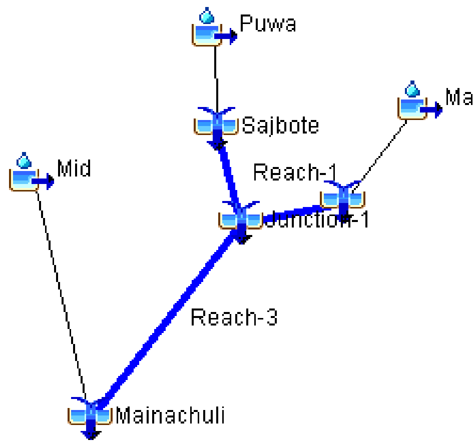


Figure 4-9: Schematic for Kankai River basin in HEC-HMS

Table 4-8: Hydrological database used for the Kankai basin HEC-HMS model setup

Basin	**Data**	**Hydrological stations**	**Hydrological station ID**
Kankai	Calibration: 1990-1999 Validation: 2000-2006	Mainachuli	795

Table 4-9: Meteorological database used for the Kankai basin HEC-HMS model setup

Basin	**Rainfall stations**	**No. of rainfall station**
Kankai	1407, 1410, 1421	3

e) Kamala River Basin

The model schematic for Kankai basin to be used in HEC-HMS modelling is shown in Figure 4-10. The parameters are calibrated from the observed discharge data at Chisapani. Hydrological and Metrological database used in the HEC-HMS model of the Kamala basin is presented in Table 4-10 and Table 4-11 respectively.

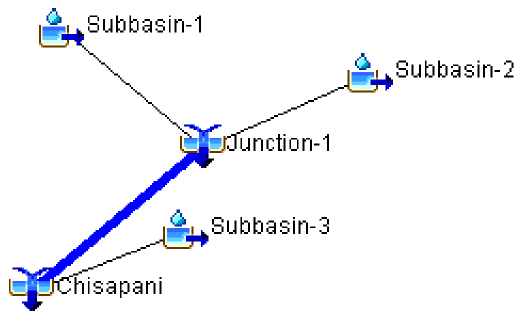


Figure 4-10: Schematic for Kamala River basin in HEC-HMS

Table 4-10: Hydrological database used for the Kamala basin HEC-HMS model setup

Basin	Data	Hydrological stations	Hydrological station ID
Kamala	Calibration: 2000-2001 Validation: 2002	Chisapani	598

Table 4-11: Meteorological database used for the Kamala basin HEC-HMS model setup

Basin	Rainfall stations	No. of rainfall station
Kamala	1107, 1108, 1112, 1213, 1216	5

f) Bagmati River Basin

The model schematic for Bagmati basin to be used in HEC-HMS modelling is shown in Figure 4-11. The parameters are calibrated from the observed discharge data at Pandheradovan. Hydrological and Metrological database used in the HEC-HMS model of the Bagmati basin is presented in Table 4-12 and Table 4-13 respectively.

Figure 4-11: Schematic for Bagmati River basin in HEC-HMS

Table 4-12: Hydrological database used for the Bagmati basin HEC-HMS model setup

Basin	Data	Hydrological stations	Hydrological station ID
Bagmati	Calibration: 1990-1999 Validation: 2000-2006	Khokhana, Pandheradovan	550.5, 589

Table 4-13: Meteorological database used for the Bagmati basin HEC-HMS model setup

Basin	Rainfall stations	No. of rainfall station
Bagmati	905, 912, 915, 1030, 1043, 1060, 1117	7

g) Tinau River Basin

The model schematic for Tinau basin to be used in HEC-HMS modelling is shown in Figure 4-12. Only one sub-basin up to Butwal was considered in the model. Hydrological and Metrological database used in the HEC-HMS model of the Tinau basin is presented in Table 4-14 and Table 4-15 respectively.

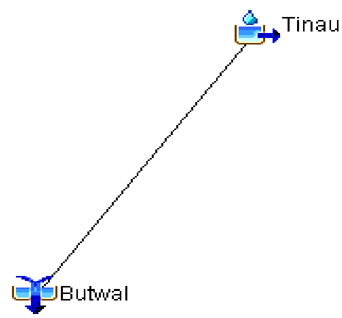


Figure 4-12: Schematic for Tinau River basin in HEC-HMS

Table 4-14: Hydrological database used for the Tinau basin HEC-HMS model setup

Basin	Data	Hydrological stations	Hydrological station ID
Tinau	Calibration: 1990-1999 Validation: 2000-2006	Butwal	390

Table 4-15: Meteorological database used for the Tinau basin HEC-HMS model setup

Basin	Rainfall stations	No. of rainfall station
Tinau	702, 703	2

h) West Rapti River Basin

The model schematic for Bagmati basin to be used in HEC-HMS modelling is shown in Figure 4-13. The parameters are calibrated from the observed discharge data at Jalkundi. Hydrological and Metrological database used in the HEC-HMS model of the West Rapti basin is presented in Table 4-16 and Table 4-17 respectively.

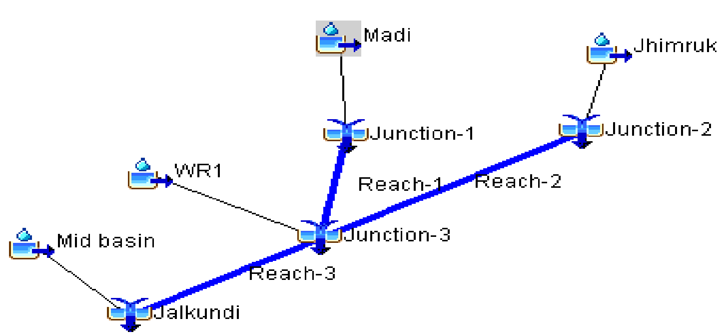


Figure 4-13: Schematic for West Rapti River basin in HEC-HMS

Table 4-16: Hydrological database used for the West Rapti basin HEC-HMS model setup

Basin	**Data**	**Hydrological stations**	**Hydrological station ID**
West Rapti	Calibration: 1990-1999 Validation: 2000-2006	Nayagaon, Jalkundi	330, 360

Table 4-17: Meteorological database used for the West Rapti basin HEC-HMS model setup

Basin	**Rainfall stations**	**No. of rainfall station**
West Rapti	504, 505, 510, 715, 407	5

i) Babai River Basin

The model schematic for Bagmati basin to be used in HEC-HMS modelling is shown in Figure 4-14. The model parameters are calibrated from the observed discharge data at Chepang. Hydrological and Metrological database used in the HEC-HMS model of the Babai basin is presented in Table 4-18 and Table 4-19 respectively.

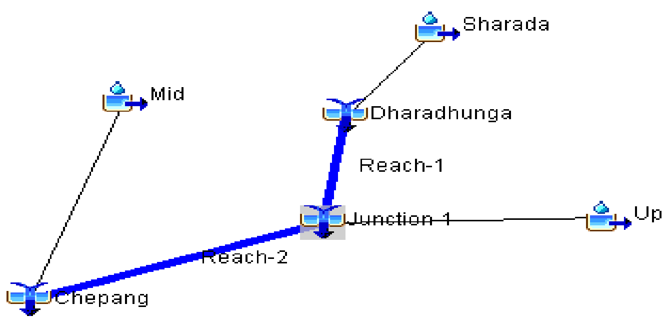


Figure 4-14: Schematic for Babai River basin in HEC-HMS

Table 4-18: Hydrological database used for the Babai basin HEC-HMS model setup

Basin	**Data**	**Hydrological stations**	**Hydrological station ID**
Babai	Calibration: 1990-1999 Validation: 2000-2006	Dharadhunga, Chepang	286, 289.5

Table 4-19: Meteorological database used for the West Rapti basin HEC-HMS model setup

Basin	**Rainfall stations**	**No. of rainfall station**
Babai	508, 511, 512, 413	4

4.2.4 Calibration and validation

The period from 1990 to 1999 was considered as calibration period for all river basins except for Kamala basin. Whereas the period between 2000 and 2006 is considered as the validation period. A continuous gauged flow of Kamala is available at Chisapani only between 2000 and 2002. So, in the case of Kamala River the period between 2000 and 2001 is considered as calibration whereas the the year 2002 is considered for the validation. The performance of the model calibration and validation was assessed by comparing the observed and simulated hydrographs, and computing some statistical performance indicators. The indicators considered are: Normalized Root mean square error (NRMSE), Nash-Sutcliffe Coefficient of Efficiency (NSE) and Volume Bias (VB).

The performance of HEC-HMS model for calibration and validation for mean monthly flow of all river basins is provided in Table 4-20. The calibration result shows that the NSE is above 0.8 for all stations, which is an indication of good performance. Similarly, the NSE in validation results are also above 0.8 in most of the cases. The comparison between the observed and the simulated mean monthly hydrographs for different stations considered in a respective river basins are presented in Appendix C-2.

The discrepancy between the observed and predicted flow occurs due to several factors. The main factors are:

- Uncertainty in data: The model was calibrated and validated sub-basin wise with limited number of rainfall stations. Many rainfall stations were discarded due to the long gaps in the data. The available rainfall data is not sufficient to represent spatial and temporal variability, which has the effect of over and underestimation. The discharge data (taken as observed) which was used for calibration and validation is estimated from water level data using rating curve, which also has uncertainties.
- Uncertainty in parameters: There is uncertainty in parameters as they are estimated/calibrated using observed data.
- Uncertainty in model: The hydrological model is a conceptual representation of the process. As HEC-HMS is a lumped model sub-basin wise, there is uncertainty in model representing the hydrological processes within basin.

Table 4-20: Model performance for HEC-HMS in different river basin

Basin	Sub-basin	Calibration			Validation		
		NRMSE	NSE	VB	NRMSE	NSE	VB
Koshi	Balefi at Jalbire	0.4	0.86	-0.1	0.2	0.94	-0.1
	Dudhkoshi at Rabuwabazar	0.3	0.91	-0.09	0.4	0.84	-0.27
	Sunkoshi at Hampachuwar	0.3	0.91	0.13	0.1	0.98	0.06
	Arun at Turkeghat	0.2	0.95	0.004	0.3	0.9	-0.13
	Arun at Simle	0.3	0.91	0.13	0.5	0.73	0.2
	Tamor at Majhitar	0.1	0.99	0.01	0.4	0.8	0.2
	Tamor at Mulghat	0.1	0.98	-0.01	0.2	0.94	-0.12
	Saptakoshi at Chatara	0.3	0.9	0.18	0.3	0.92	0.21

Basin	Sub-basin	Calibration			Validation		
		NRMSE	NSE	VB	NRMSE	NSE	VB
Gandaki	Trishuli at Betrawati	0.1	0.98	-0.02	0.3	0.88	-0.15
	BudhiGandaki at Arughat	0.3	0.9	-0.07	0.2	0.95	0.08
	Marsyangdi at Bimalnagar	0.2	0.97	0.14	0.1	0.98	0.07
	Madi at Shisaghat	0.2	0.95	-0.07	0.4	0.8	-0.22
	Kali Gandaki at Kotagau	0.3	0.91	0.19	0.5	0.75	0.3
	Narayani at Narayanghat	0.2	0.97	0.05	0.2	0.95	0.06
	Rapti at Rajaiya	0.1	0.98	-0.03	0.3	0.93	-0.09
Karnali	Tila at Nagma	0.4	0.84	-0.13	0.5	0.75	-0.18
	Karnali at Lalighat	0.2	0.93	0.03	0.2	0.95	0.07
	Karnali at Asaraghat	0.1	0.98	-0.004	0.3	0.91	0.02
	Karnali at Benighat	0.2	0.95	0.05	0.3	0.91	0.06
	Seti at Gopaghat	0.4	0.79	-0.08	0.4	0.83	-0.14
	Seti at Banga	0.4	0.83	-0.1	0.3	0.89	-0.06
	Bheri at Jamu	0.3	0.91	0.09	0.3	0.91	0.005
	Karnali at Chisapani	0.3	0.92	-0.05	0.3	0.9	-0.08
Kankai	Kankai at Mainachuli	0.3	0.93	0.13	0.2	0.96	-0.08
Kamala	Kamala at Chisapani	0.3	0.92	0.04	0.2	0.94	-0.01
West Rapti	West Rapti at Jalkundi	0.2	0.95	-0.01	0.3	0.92	0.08
	Mari Khola at Nayagaon	0.4	0.9	-0.02	0.5	0.88	0.2
Babai	Sharada at Dharadhunga	0.3	0.99	-0.1	0.5	0.98	-0.2
	Babai at Chepang	0.3	0.91	0.12	0.4	0.83	0.17

4.2.5 Flow computation

HEC-HMS was calibrated and validated with the stream gauging station, which is taken as the outlet of a sub-basin. The sub-basin is a combination of a number of smaller watersheds, whose flow at outlet is required to assess the hydropower potential. The HEC-HMS model was set up for each watershed within the sub-basin. The calibrated parameters of sub-basin scale were transferred to each watershed and the flow was computed at the outlet of each watershed from the HEC-HMS. For the ungaued part in the Terai, the model parameters of the most downstream calibrated sub basin was used. The number of outlets nodes where the discharge were estimated using HEC-HMS model is shown in Table 4-21.

Table 4-21: Number of discharge estimation outlets in each river basins

River Basin	Koshi	Gandaki	Karnali	Kankai	Kamala	Bagmati	West Rapti	Babai
Nodes	1315	2181	2350	157	218	165	252	192

5. Geology and Geomorphology

5.1 General

Geological studies in hydropower development are important. Sustainability of the hydropower projects depend on geology of the project area. Hence, alignment and location of hydropower project components rely on geology of the project area. Hydropower potential computed in this study does not take into account geology of the project sites. However, this chapter is presented to give an overview of the general geological settings of Nepal and its river basins. Geological aspects will only be taken into account while computing the techno-economical hydropower potential of Nepal.

5.2 Geology of Nepal Himalaya

The Nepal Himalaya is situated in the central part of the Himalayan arc and has covered about one third part (about 800 km in length). The Nepal Himalaya is located between the Kumaon Himalaya, in the west, and the Sikkim-Bhutan Himalaya, in the east. The Nepal Himalaya is subdivided into the following five major tectonic zones from south to north (Upreti and Le Fort, 1999) which is also shown in Figure 5-1.

Indo-Gangetic Plain (Terai)

---- ***Himalayan Frontal Thrust (HFT)*** ----

Sub-Himalaya (Siwalik or Churia Group)

---- ***Main Boundary Thrust (MBT)*** ----

Lesser Himalaya

---- ***Main Central Thrust (MCT) ----***

Higher Himalaya

---- ***South Tibetan Detachment System (STDS) ----***

Tibetan-Tethys Himalaya

5.2.1 Indo-Gangetic Plain (Terai)

This zone represents the northern edge of the Indo-Gangetic Plain and forms the southernmost tectonic division of the Nepal Himalaya. It represents Pleistocene to Recent in age and has an average thickness of about 1,500 m. This zone is basically composed of materials varying between clay to boulder. The uppermost part of the Indo-Gangetic Plain, the Bhabhar zone, is composed of materials varying between boulder and pebble. The Middle part, Marshy zone, is composed of sand whereas clay is dominant in the southern Terai.

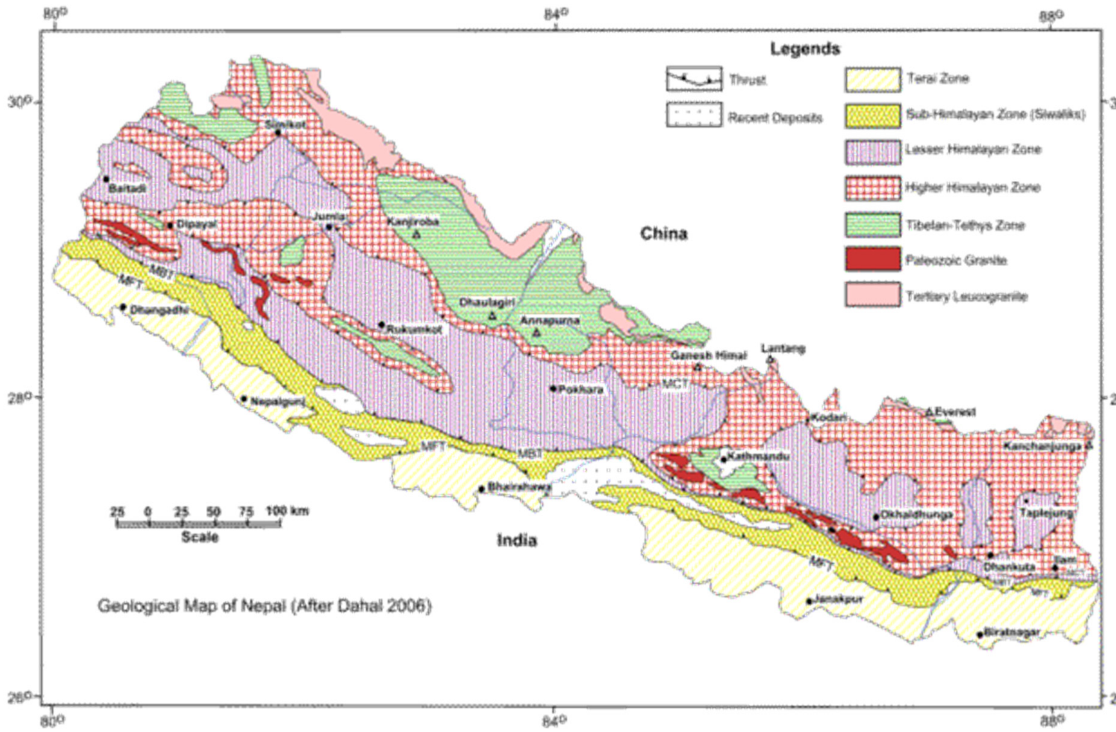


Figure 5-1: Geological Map of Nepal Himalaya

5.2.2 Sub-Himalaya (Siwaliks or Churia Group)

The Sub-Himalaya (Siwaliks or Churia Group) is located in the southern part of the country, between Indo-Gangetic plain and Lesser Himalaya, and is represented by low hills of the Churia Range. The Siwalik Group of Nepal is composed of 5-6 km thick fluvial sediments of the middle Miocene to early Pleistocene age. The sediments are generally layers of mudstone, sandstone and conglomerate. Based on lithology and increasing grain size, the Siwalik Group is divided into Lower, Middle and Upper Siwaliks, from south to north. The Lower Siwalik is comprised of mudstone and sandstone, whereas the Middle Siwalik is represented by thick-bedded, coarse-grained, "pepper and salt" appearance sandstone. The Upper Siwalik is identified by the presence of conglomerate with lenses of mud and sand.

5.2.3 Lesser Himalaya

The Lesser Himalaya lies in between the Sub-Himalaya (Siwalik Group), in the south, and Higher Himalaya, in the north. Both the southern and northern limits of this zone are represented by thrusts. The Main Boundary Thrust (MBT) is the southern boundary and the Main Central

Thrust (MCT) is the northern boundary. Tectonically, the entire Lesser Himalaya consists of allochthonous and para-autochthonous rocks. Rock sequences have developed nappes, klippes and tectonic windows, which have complicated geological features. The Lesser Himalaya is mostly made up of un-fossiliferous sedimentary and metasedimentary rocks, consisting of quartzite, phyllite, slate and limestone, ranging in age from Pre-Cambrian to Miocene. Some area of Lesser Himalayan terrain are covered by high-grade metamorphic rocks.

5.2.4 Higher Himalaya

Higher Himalaya is well defined geologically as well as morphologically and consists of a huge pile of highly metamorphosed rocks. It is situated between the Lesser Himalaya, in the south and the Tibetan-Tethys Himalaya, in the north. MCT and STDS serve as the southern and northern boundary of the region respectively. This zone is made up of oldest rocks of the Pre-Cambrian metamorphic and the granitic gneiss. The north-south width of the unit varies from place to place. This zone consists of almost 10 km thick succession of the crystalline rocks also known as the Tibetan Slab (Le Fort, 1975). This sequence can be divided into four main units by Bordet [1969]. From bottom to top these units are: Kyanite-sillimanite gneiss (Formation I), Pyroxene, marble and banded gneiss (Formation II) and Augen gneiss (Formation III).

5.2.5 Tibetan-Tethys Himalaya

Rocks of the Tibetan-Tethys Himalaya zone are made up of thick pile of rich fossiliferous sediments. Their age ranges from early Paleozoic to middle Cretaceous era. This zone is about 40 km wide and composed of sedimentary rocks such as shale, limestone and sandstone. In Nepal, these fossiliferous rocks of the Tibetan-Tethys Himalaya are well developed in the Thak Khola (Mustang), Manang, Dolpa and Saipal area of Nepal.

5.3 Regional Geology

Nepal Himalaya has been divided into five zone based on the river boundary, from east to west direction.

5.3.1 Eastern Nepal Himalaya

The Eastern Nepal lies between the Mechi River, in the east, and the Koshi River, in the west. Rocks of the Siwalik Group, Lesser Himalaya and Higher Himalaya are exposed in the Eastern Nepal. DMG [1987] has prepared geological map of the Eastern Nepal. According to the map, the Siwalik Group has been subdivided into the Lower Middle and Upper Siwalik. The Lesser Himalaya has been subdivided into the Midland Group and Kathmandu Group. Similarly, the

Higher Himalaya has been subdivided into the Formation I, Formation II and Formation III. Rocks of the Tibetan-Tethys Himalaya are not exposed in Eastern Nepal.

Mechi Basin, Kankai Basin, eastern part of the Koshi Basin lies in the Eastern Nepal Himalaya.

5.3.2 Central Nepal Himalaya

The Central Nepal lies between the Koshi River, in the east, and the Gandaki River, in the west. Rocks of the Siwalik Group, Lesser Himalaya, Higher Himalaya, Tibetan-,Tethys Himalaya are exposed in the region. Rocks of the Lower, Middle and Upper Siwaliks are exposed in southern part. Rocks of the Midland Group, Kathmadhu Group are observed in the Lesser Himalaya. Similarly, the rocks of the Higher Himalaya are observed in the northern part of the Central Nepal.

The Bagmati basin, western part of the Koshi basin, the Kamala basin, the Bakiya-Nadi basin and eastern part of the Gandaki basin fall in the Central Nepal Himalaya.

5.3.3 Western Nepal Himalaya

The Western Nepal lies between the Gandaki River, in the east, and the Bheri River, in the west. It is composed of same types of the rock sequences as the Eastern Nepal. The rocks of the Siwalik Group, the Lower, Middle and Upper Siwaliks, are exposed in the southern part of the zone. Similarly, the rocks of the Midland Group and Surkhet Group are also exposed in the western Nepal. The rocks of the Higher Himalaya and Tibetan-Tethys Himalaya are exposed in northern part of the zone.

Western part of the Gandaki basin, the Tinau Khola basin lie in the Western Nepal Himalaya.

5.3.4 Mid-Western Nepal Himalaya

The Mid-western Nepal lies between the Bheri River, in the east, and the Karnali River, in the west. The region is composed of Higher Himalaya, Lesser Himalaya and Siwaliks. The Higher Himalayan rocks are composed of high-grade metamorphic rock of gneiss, schist, banded gneiss and augen gneiss whereas the Lesser Himalaya has been composed low-grade metamorphic rocks and sedimentary rocks such as the quartzite, slate, phyllite and sandstone, limestone. The Siwalik Group is comprised of thick to thin beds of the sandstone and mudstone as well as conglomerate.

Eastern part of the Karnali River basin, the Babai Khola basin and the Rapti River basin lies in the Mid-western Nepal Himalaya.

5.3.5 Far-Western Nepal Himalaya

The Far-western Nepal lies between the Karnali River, in the east and the Mahakali River in the west. Geologically, the Tibetan-Tethys Himalaya, Higher Himalaya, Lesser Himalaya and Siwaliks are all included in the Far-western Nepal.

The Tibetan-Tethys Himalaya is composed of sedimentary rocks of shallow marine deposits such as the shale, sandstone, limestone. The Higher Himalaya is characterized by thick bedded gneiss and schist of the high-grade metamorphic rocks. Lesser Himalaya has represented by presence of low-grade metamorphic and sedimentary rocks of sandstone, shale, limestone, dolomite, quartzite, phyllite. The Siwalik has fragile geology and composed of sandstone and mudstone in varying ratio.

The Mahakali River basin, western part of the Karnali River basin lie in the Far-western Nepal.

5.4 Active faults and thrusts in the Nepal Himalaya

According to tectonic division of the Nepal Himalaya has been separated by several thrusts extending in the east-west direction. The Main Frontal Thrust (MFT) separates the Siwalik Group from the Ganetic Plain. The former lying in north and latter lying in south. The MFT is located southernmost part of the Himalaya. The Main Dun Thrust (Central Churia Thrust) lies in the Siwalik zone. It separates the northern and southern Siwalik belt. The Main Boundary Thrust (MBT) is other important thrust in Himalaya. The thrust is initiated in Himalaya 11 million years ago. This thrust separates the Lesser Himalayan rocks, in the north, from the Siwalik rocks, in the south. The Main Central Thrust (MCT) lies between the Lesser Himalayan rocks and the Higher Himalayan rocks. The thrust was developed 25 million year ago in the Himalaya. The South Tibetan Detachment System (STDS) is seen in between the Higher Himalaya in the south and Tethys Himalaya in north (Figure 5-2 and Table 5-1).

Besides the above mentioned thrust, many thrust are observed within the Lesser Himalaya. The Barigad Thrust in western Nepal Himalaya, Mahabharta Thrust (MT) in Central Nepal, Simikot Thrust, Budhiganga Thrust in Mid-western Nepal Himalaya. Many active faults are seen in the Lesser Himalaya, Siwaliks and Tibetan-Tethys Himalaya.

Some of the thrust extends upto the Siwalik zone because of nappe and klippe formation in the Himalaya in geological past. For example, the Arun Window, Taplejung Window in eastern Nepal, Kathmandu Nappe, Okhaldhunga Window in Central Nepal, Palpa Klippe in the Testern Nepal, Bhajang Window in Far-western Nepal.

These active thrusts/faults cross different river basins of Nepal and have created the problem in the Hydropower development in Nepal because of the activation of the thrust. The MBT and MDT and MFT are still active in Nepal Himalaya.

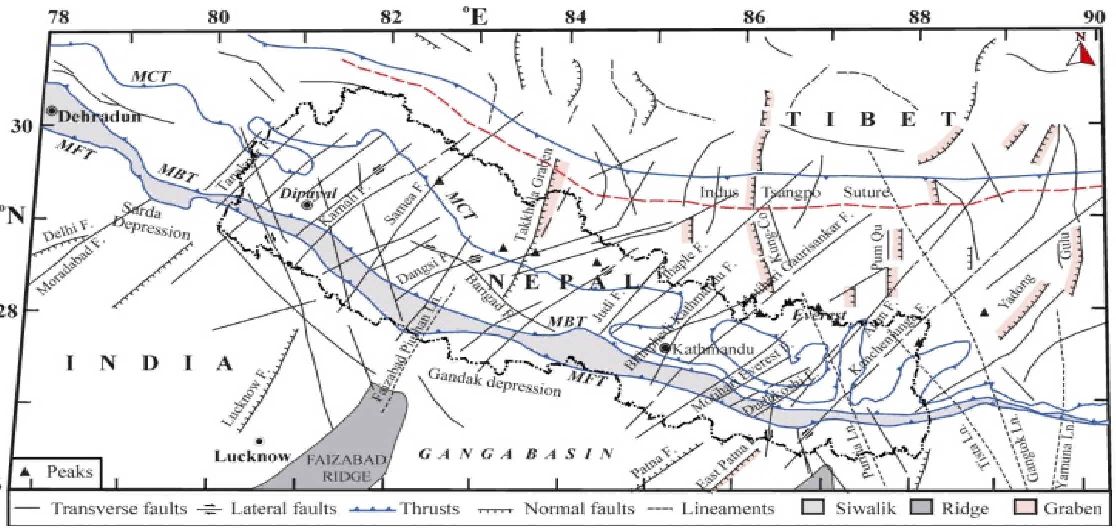


Figure 5-2: Active faults of Nepal Himalaya

Table 5-1: Frequency of different types of fault-plane solutions observed in four delineated seismogenic regions in the Nepal Himalaya and its vicinity.

Seismogenic Regions	Nunber of fault-plane solutions	Frequency of different types of fault-plane solutions				
		Thrusts	Strike-slip+Thrusts	Strike-slips	Normal[3]	Strike-slip+ Normal
Western Nepal(Region A)	24	18	4	--	(2)	-
Central Nepal(Region B)	14	11	1	1	(1)	-
Eastern Nepal(Region C)	22	2	14	1	1(3)	1
South Central Tibet(Region D)	23	--	1	2	17	3
Total solutions	83	31	20	4	24	4

[3] Please note that the numbers shown within parentheses under normal column (6th column) are the earthquakes actually located in the Tibetan part, north of the Himalayan thrust belt though they are falling in the delineated regions A, B, and C. This statistics are established considering 83 fault-plane solutions

5.5 Geology of the river basins

The study covers entire Nepal Himalaya and is divided into twelve river basins: the Koshi basin, the Gandaki basin, the Karnali basin, the Mahakali basin, the Mechi basin, the Kankai-Nadi basin, the Kamala-Nadi basin, the Babai basin, the Rapti basin, the Bagmati basin and the Bakiya-Nadi Basin (Figure 1-1).

5.5.1 Major River Basins

5.5.1.1 Koshi River Basin

Koshi River Basin extends within the Central and Eastern Nepal Himalaya. The Koshi River Basin is covered by Higher Himalayan rocks in northern part whereas the middle part is covered by Lesser Himalaya rocks and southern part is covered by Siwalik rocks.

The Main Central Thrust (MCT) and Main Boundary Thrust (MBT) are the main tectonic feature of the Koshi River basin. MCT and MBT are exposed in southern part of the basin. Some active faults and unnamed thrusts are also observed in the basin. Most of the basin area is covered by high-grade metamorphic rocks.

5.5.1.2 Gandaki River Basin

This basin lies within the Western and Central Nepal Himalaya. The basin geologically belongs to the Tibetan-Tethys Himalaya (sedimentary rocks), Higher Himalaya (metamorphic rocks), Lesser Himalaya (metasedimentary rocks and sedimentary rocks) and Siwaliks. Northern part of the basin is covered by the Tethys Himalayan rocks, middle part of the basin is covered by Higher Himalayan and Lesser Himalayan rocks whereas the southern part of the basin is covered by sedimentary rocks of the Siwaliks.

The Gandaki basin also passes through the South Tibetan Detachment System (STDS) in northern part of the basin. MCT and MBT passes in the southern part of the Basin. Other unnamed thrusts and fault can be seen within the Lesser Himalaya zone of the basin. These faults and thrusts are active as well as passive in movement. Ramdi Fault, Barigad Fault and Karewa Fault are the example of the active fault in the Gandaki Basin. The Main Boundary Thrust (MBT) is also considered as active in Gandaki Basin. Active fault of Budhiganga also passes in the Mid-western Nepal.

5.5.1.3 Karnali River Basin

The Karnali basin is located in the Mid-western Nepal and the Far western Nepal. Geologically the basin belongs to the Tethys Himalaya, Higher Himalaya, Lesser Himalaya and Siwaliks. Northern part of the Karnali River Basin is covered by the Tibetan-Tethys Himalaya. The Tethys Himalaya is composed of sedimentary rocks of limestone, sandstone and shale. The Higher Himalaya is composed of thick gneiss and schist (Formation I, Formation II and Formation III). Northern part of the basin is also covered by the rocks of the Higher Himalaya. Middle part of the basin is composed of the Lesser Himalayan rocks (quartzite, dolomite, slate). The southern part of the basin is covered by sedimentary rocks of the Siwalik Group.

Within the basin, the MCT, MBT, MFT and MDT can be observed. The Karnali River passes through the recognized thrust and some active fault and unnamed thrust. MCT is seen in the northern part of the basin whereas the MBT and MFT are seen in the southern part of the basin. The Bajhang Window has also developed in the Karnali Basin.

5.5.2 Boarder River Basin

5.5.2.1 Mechi River Basin

The Mechi Khola Basin limits between the Lesser Himalaya in north and Gangetic Plain in south and located in the eastern Nepal Himalaya. The Lesser Himalaya is composed of low to high-grade metamorphic rocks (gneiss and schist as well as slate, quartzite). The Siwalik is distributed in the middle part and southern part of the basin which is covered by thick loose sediments of the Gangetic Plain.

5.5.2.2 Mahakali River Basin

The Mahakali River Basin is located in the Far western Nepal Himalaya. The basin is composed of the Higher Himalaya, Lesser Himalaya and Siwalik rocks. The Higher Himalayan rocks are seen in northern part of the basin and composed of high grade metamorphic rocks of gneiss and schist. The Lesser Himalayan rocks, comprised of metasedimentary to sedimentary rocks like sandstone, quartzite, and slate, are distributed in the middle part of the basin. The southern part of the basin is covered by thick sedimentary rocks of the Siwalik.

This basin also include the MCT, MBT and MFT and some active faults and thrust within the Lesser Himalaya.

5.5.3 Rivers originating from the middle mountains

5.5.3.1 Kankai River Basin

The Kankai River Basin lies in the Eastern Nepal Himalaya and starts from the Lesser Himalaya and extends upto Gangetic Plain. The rocks of the Lesser Himalaya are composed of gneiss and schist as well as quartzite. The Siwalik rocks, composed of mudstone and sandstone, are observed in the central part of the basin. The southern part of the basin is covered by thick and loose sediments of the Gangetic Plain.

The Main Boundary Thrust (MBT), Main Central Thrust (MCT) and Main Frontal Thrust (MFT) are observed in the basin. Due to the extension of the window the MCT has seen in the norther part of basin.

5.5.3.2 Kamala River Basin

Kamala basin is located in the Central Nepal Himalaya. The basin starts from the Siwalik range in north and extends upto the Gangetic Plain. The Siwalik range is composed of sedimentary rocks like conglomerate, mudstone and sandstone with fragile geology. The Gangetic Plain covers the southern part of the basin.

Main Boundary Thrust (MBT) and Main Frontal Thrust are main feature of the basin. The main Dun Thrust (MDT) or Central Churia Thrust (CCT) are another active thrust of the basin.

5.5.3.3 Bagmati River Basin

Bagmati River originates from the Lesser Himalaya and the basin lies in the Central Nepal Himalaya. The basin is composed of metasedimentary to metarophic rock of the Lesser Himalaya and extends upto the Gangetic Plain passing through the Siwalik Group. The basin passes the Main Boutdary Thrust (MBT), Mahabharta Thrust (MT), Central Churia Thrust (CCT) and Main Frontal Thrust (MFT).

Mahabharta Thrust is considered as the part of the Main Central Thrust (MCT). The Main Dun Thrust (MDT), developed within the Siwalik, represents an active thrust of the basin. These above mentioned thrusts extend nearly east-west in direction.

5.5.3.4 Bakaiya-Nadi River Basin

The Bakiyanadi Basin is located in the Central Nepal Himalaya. The basin originated from the Lesser Himalaya and extend upto the Gangetic Plain passing through the Siwalik rocks. The Lesser Himalaya is seen in northern part of the basin just north of the Main Boundary Thrust

(MBT). The middle part of the basin is covered by Siwalik rocks whereas the southern part of the basin is covered by loose sediments of the Gangetic plain.

Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) are seen in the Bakiyanadi. Within the Siwaliks, the Main Dun Thrust (Centarl Churia Thrist) is also observed. The basin has step to gentle sloped area. Some active thrust like Mahabharat Thrust also passes through the basin.

5.5.3.5 Tinau-Khola River Basin

Headwaters of the Tinau Khola Basin lie on the Lesser Himalaya and the basin extends upto the Gangetic Palin by passing through the Siwalik range. The northern part of the basin is covered by metamorphic to sedimentary rocks of the

The basin has crossed the Main Boundary Thrust, the Main Frontal Thrust and the Main Dun Thrust or Central Churia Thrust (CCT). These thrust are active and extend nearly east-west direction. The basin has also crossed an active Klippe Thrust.

5.5.3.6 Rapti River Basin

The Rapti Basin is located in the Mid western Nepal Himalaya and extends between the Lesser Himalaya in north and Gangetic Plain in south. The Lesser Himalaya in northern part is covered by sedimentary and low-grade metamorphic rocks whereas the Siwalik rocks are covered in middle part of the basin and composed of sandstone and mudstone. The southern part of the basin is covered by loose sediments of the Gangetic Plain.

The MBT and the MFT passes through the Rapti River basin. The MBT lies in the northern part of the basin whereas the southern part is intersected by the MFT. Some thrusts of Dun valley (Silinig Khola Thrust, Sit Khola Thrust) are developed within the Siwaliks between the MBT and MFT.

5.5.3.7 Babai River Basin

The Babai Khola Basin is located in the Midwestern Nepal Himalaya and extends between the Siwalik ranges in north and Gangetic Plain in the south. The Siwalik range is composed of the mudstone, sandstone and conglomerate of the Siwalik and and passes thouth the Dun valley sediments within the Siwalik range whereas the southern part of the basin is covered by thick loose sediments of the Gangetic Plain.

Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) are seen in the basin. Some active thrusts are developed within the basin.

5.6 Seismicity

According to Bajracharya [1994] Nepal Himalaya has been seismically divided into five seismic zones (Zone1, Zone 2, Zone 3, Zone 4, Zone 5) and three seismic hazard zones (Low, Moderate and High).

The Koshi Basin and the Gandaki Basin are covered by high to moderate seismic hazard whereas the Karnali basin has low to moderate seismic hazard. Some part of the Karnili Basin is also covered by high seismic hazard. Mahakali Basin has covered by moderate to high seismicity. Mechi Basin is covered by moderate hazard. Kamalnadi Basin has covered by high seismic hazard. Similary the Bagamti Basin has moderate hazard, Tinau Khola, Babai Khola has also moderate seismic hazard (Figure 5-3)

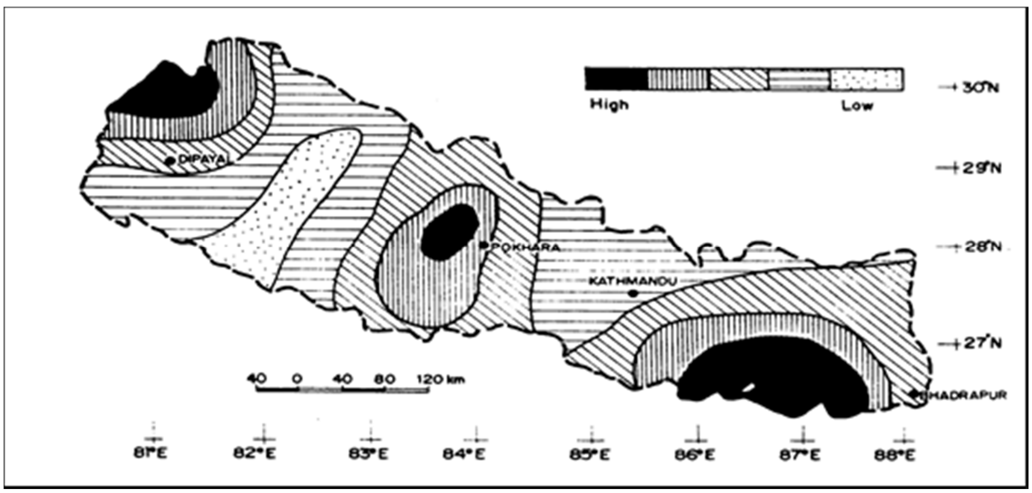


Figure 5-3: Simplified seismic risk map of Nepal (Bajracharya, 1994)

5.6.1 Historical Seismic Activity

The Nepal Himalaya has experienced several large earthquakes over the past centuries. The earthquakes of larger magnitudes that have occurred in Nepal Himalaya are summarized below in Table 5-2.

Table 5-2: Larger magnitude of earthquake occurred in Nepal Himalaya

S. N.	Location of Earthquake	Year	Magnitudes
1	Udayapur, Eastern Nepal	1988	6.6
2	Chainpur, Eastern Nepal	1934	8.3

S. N.	Location of Earthquake	Year	Magnitudes
3	Dolakha, Central Nepal	1934	8.0
4	Sindhupalchowk, Central Nepal	1833	8.0
5	Kaski, Central Nepal	1954	6.4
6	Myagdi, Central Nepal	1936	7.0
7	Bajhang, Far Central Nepal	1980	6.5
8	Dharchula, Far Central Nepal	1966	6.1
9	Dharchula, Far Central Nepal	1966	6.3
10	Dharchula, Far Central Nepal	1916	7.3
11	Gorkha, Central Nepal	2015	7.9
12	Dolkha, Central Nepal	2015	6.9

5.6.2 Earthquake Catalogue

The National Building Code Development Project (BCDP, 1994) has developed an earthquake catalogue using earthquake data catalogues of the US Geological Survey, The National Earthquake Information Center (NEIC), National Oceanic and Atmospheric Administration and National Geological Data Center (NGDC). The complete earthquake catalogue for the magnitudes M 4.5 and greater is given in Table 5-3.

Table 5-3: Instrumentally recorded earthquake

S. N.	Magnitudes	Catalogue Year
1	M 6.0 and greater than M 6.0	Catalogue complete for the period 1911 to 1992
2	M 5.5 and greater than M 5.5	Catalogue complete for the period 1925 to 1992
3	M 5.9 and greater than M 5.9	Catalogue complete for the period early 1960 to 1992
4	M 4.5 and greater than M 4.5	Catalogue complete for the period late 1970 to 1980s

5.7 GLOF

The rise in atmospheric temperature has resulted in melting of the glaciers and creation of meltwater lakes retained by the glacial moraine deposit dams. Such lakes are referred as the glacial lakes. Some of the glacial lakes have bursted (by outflanking or failure of the moraine dams) in the past causing a huge surge of water in the streams which they feed downstream. The event is referred as the Glacial Lake Outburst Floods (GLOFs). Hydropower plants located in the glacial fed rivers contain risks of damages from the GLOF events. So, it is important to assess the risks during the planning of the infrastructures. Mool et al., (2011) report 24 GLOF events in recent past in Nepal.

According to Glacier inventory published by ICIMOD in 2010, there are about 3,880 glaciers in Nepal located in the Koshi, Gandaki, Karnali and Mahakali basins, covering total area of 4,212 km2 (Table 5-4). The inventory data in GIS format was used for analysis in this study.

Table 5-4: Distribution of glaciers in catchments of Nepal (Source: Mool et al., 2011)

Basin	2001 glacier inventory			2010 glacier inventory			
	No.of glaciers	Total area	Mean area	No.of glaciers	Total area	Highest elevation	Lowest elevation
	[-]	[sq.km]	[sq.km]	[-]	[sq.km]	[m a.s.l]	[m a.s.l]
Koshi	779	1410	1.81	843	1180	8437	3962
Gandaki	1025	2030	1.98	1337	1800	8093	3273
Karnali	1361	1741	1.27	1461	1120	7515	3631
Mahakali	87	143	1.65	167	112	6850	3695
Total	3252	5324	6.71	3808	4212		

6. Economic Analysis

This section of the report analyses the methodology to be followed in estimating the economic viability of potential hydropower in Nepal. The technical potential of hydropower describes the energy capacity that is actually useable when technical, infrastructural, ecological and other conditions are taken into consideration. In this study, the technical hydropower potential is calculated for each grid point representing a river. Thus, each assessed river point forms the virtual intake and a powerhouse location. This assumption therefore creates a series of virtual hydropower projects along the considered rivers to ensure compatibility. The technical hydropower potential for every possible virtual project combination has been calculated elevation difference may be utilized resulting in a higher hydroelectric production capacity, but also increasing investment costs. Cost benefit technique is employed to establish both financial and economic viability of hydropower projects. This method may be fairly easy and straight forward in establishing financial and economic feasibility of hydropower projects as done in projects basis.

6.1 Estimation of Quantities

The cost estimation of RoR hydropower projects at the scale of this study is very challenging. The costs vary with the size and types of Hydropower Projects. In addition, the project features depend upon requirement of the site so cost of different components vary from projects to projects (Figure 6-1). It is important that the cost variations due to site conditions are well captured, which allows more realistic economical evaluation of the project. A standardization method (Andaroodi, 2006; Khatri et al., 2014; Singal et al., 2010) was used to estimate the cost in this study. In this method, the volume of the construction material is derived as the function of the design parameters for each project component. The cost are estimated for the Weir, desander, waterway (pipe/ tunnel), Penstock, Powerhouse and Electro-mechanical components. Other costs such as environmental costs and project developments costs, vary according to the projects so they are not included in the current analysis. Whereas, the financial costs are taken into account in during the analysis.

The cost estimation for the reservoir projects is discussed in the Chapter 10.

6.1.1 Weir

The weir is assumed as a gravity over flow weir with ogee shape spillway crest. Since, the valley cross-section cannot be accurately estimated, a 5 m high weir with cross-section fulfilling the stability criteria at specific discharge of 10 m3/s/m was assumed in the analysis. Under, this assumption the length of weir is allowed to vary as per the requirement to spill the design flood safely. Hence higher floods result in longer weirs. Only civil costs are estimated based on the items volume of concrete, weight of reinforcement. The relationship for the concrete volume and weight of reinforcement in Equations 6-1 and 6-2 were used for the estimation.

$$V_c \; @ \; 13.122 „ Q_f \; . \; 4 „ 10^{012} \qquad (6\text{-}1)$$

$$W_r \; @ \; 0.397 „ Q_f \; . \; 10^{013} \qquad (6\text{-}2)$$

Where, Vc is volume of concrete in m3; Wr is weight of reinforcement in metric ton; Qf is design flood discharge in m3/s.

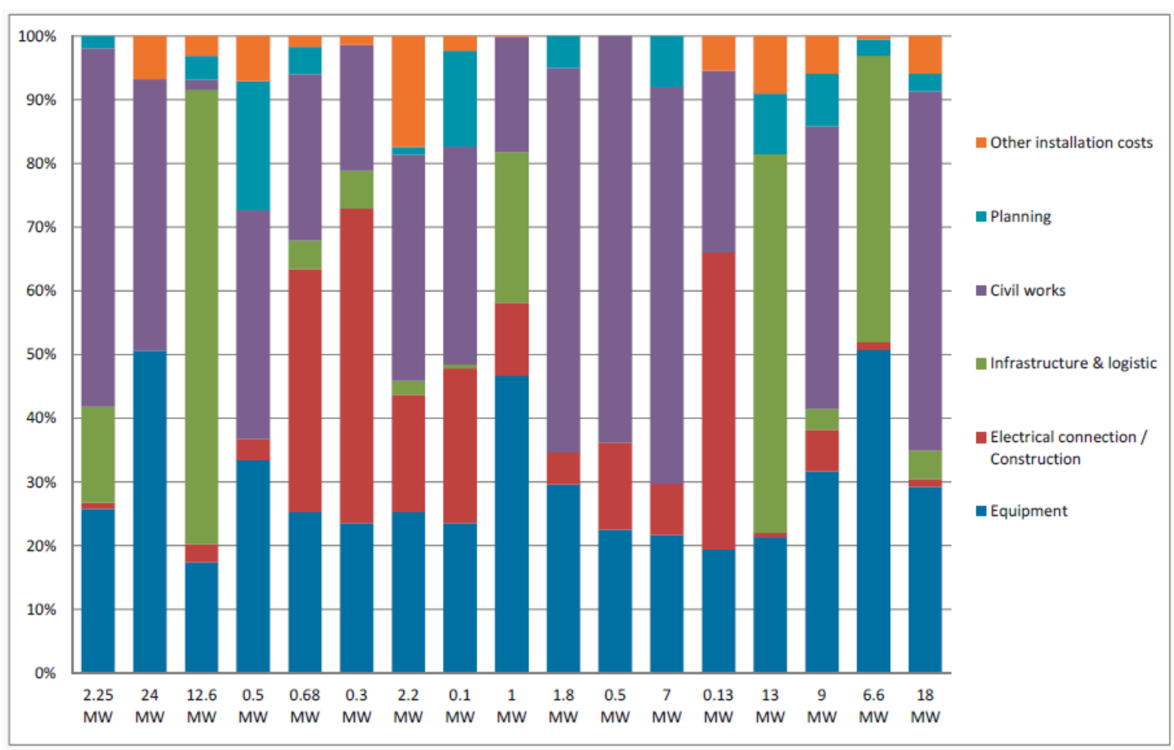


Figure 6-1: Cost breakdown for small hydropower in developing countries (Source: IRENA, 2012)

6.1.2 Settling basin

Settling basing is the structures to remove the suspended particles which are directed towards the power generating units. In which water turbulence is reduced and allows the particles to be settled and waste away at a minimum velocity. It is clear that finer particles require longer settling time, and water transit times. So, the size of the basin is the function of the diameter of the particle to be settled and the design discharge. Similarly, only civil costs are estimated based on the items volume of concrete, weight of reinforcement. The relationship provided from Equation 6-3 to 6-8 were used for the estimation.

For ds > 0.1 mm $$V_c \approx 38.538 \times Q^{1.1711} \quad (6\text{-}3)$$

For ds > 0.15 mm $$V_c \approx 16.823 \times Q^{1.2998} \quad (6\text{-}4)$$

For ds > 0.2 mm $$V_c \approx 19.8 \times Q^{1.2471} \quad (6\text{-}5)$$

For ds > 0.1 mm $$W_r \approx 1.9269 \times Q^{1.1711} \quad (6\text{-}6)$$

For ds > 0.15 mm $$W_r \approx 0.8411 \times Q^{1.2998} \quad (6\text{-}7)$$

For ds > 0.2 mm $$W_r \approx 0.99 \times Q^{1.2471} \quad (6\text{-}8)$$

Where, Vc is the volume of concrete in m3; Wr is the weight of reinforcement in metric ton; Q is design discharge in m3/s.

6.1.3 Waterway

Analyzing the current hydropower development, pipe and tunnels are assumed as waterways in this study. Tunnel is adopted where the topography permits and when design discharge is higher than 10 m3/s. For the rest of the scenarios, pipe is assumed as the water way. A penstock pipe is however provided to convey the design discharge from the tunnel outlet to the turbine units.

The cost of the waterway (both penstock and tunnel) is governed by the cross-section diameter. An analysis is carried out to determine the optimum diameter of tunnel, based on a tradeoff between the construction cost and the energy loss. The optimum penstock diameter was estimated using the relationship derived by Singhal and Kumar (2015) which is described in Equation 6-9 and 6-10.

In the case of pipe or penstock the cost estimated on the basis of the weight of the pipe. Whereas in the case of tunnel, the cost is estimated on the basis of volume of excavation, volume of concrete, weight of reinforcement, area of form work and area of shotcrete. The relationship described from Equation 6-11 to 6-15 were used for the estimations.

$$D = \left[\frac{2.36 \times 10^{6} \times Q^{3} \times n^{2} \times e \times pf \times C_{p}}{121 \times H \times C_{s} / \sigma \times P_{p}}\right]^{3/22} \quad (6\text{-}9)$$

$$C_{sp} = \frac{121 \times H \times D^{2} \times L_{p}}{\sigma} \quad (6\text{-}10)$$

$$V_{e} = 1.35Q^{0.775} \quad (6\text{-}11)$$

$$V_{c} = 5.711Q^{0.3877} \quad (6\text{-}12)$$

$$W_{r} = 0.1035Q^{0.3877} \quad (6\text{-}13)$$

$$A_{f} = 4.3931Q^{0.3877} \quad (6\text{-}14)$$

$$A_{s} = 4.3931Q^{0.3877} \quad (6\text{-}15)$$

Where, Csp is weight of penstock in kg; D is optimum diameter of penstock in m; n is manning coefficient in s/m1/3 (0.008 – 0.012); e is efficiency of power plant (0.85); pf is power factor (0.65- 0.7); Cp is cost of energy per kWh in NPR (6); Cs is cost of steel per kg in NPR; σ is permissible stress in steel MPA (183.33); H is hydraulic head in m; Lp is length of penstock in m; Pp is annual penstock cost factor (0.106); Q is design discharge in m3/s; Ve is volume of rock excavation in m3; Vc is volume of concrete in m3; Wr is weight of reinforcement in kg; Af is area of form work in m2; As is area of shotcrete in m2.

6.1.4 Powerhouse

Civil cost of powerhouse is governed by its type: surface or underground and type of turbine installation. The selection of powerhouse type depends on the space availability and other factors at the site and can be only decided during the field inception phase of the project. Since field details cannot be made available at the scale of this study, a surface type powerhouse is assumed in the analysis. The civil cost is divided into two components: a) foundation and b) super structure. The foundation is governed by the type of machinery. The machine foundation concrete volume relation derived by Gordon (1983) was used for the estimation. Similarly the volume of concrete required for the superstructure was also estimated and a relationship for the total powerhouse concrete was derived. The relationship for the powerhouse with Pelton and Francis turbines are presented in Equations 6-16 to 6-19 respectively:

For Pelton turbine

$$V_c \approx 89.81 \left(\frac{H \times MW}{RPM} \right)^{0.85} \quad (6\text{-}16)$$

$$W_r \approx 0.3522 \left(\frac{H \times MW}{RPM} \right)^{0.78} \quad (6\text{-}17)$$

For Francis turbine

$$V_c \approx 76.92 \times G^{2.28} \quad (6\text{-}18)$$

$$W_r \approx 0.76 \times G^{2.23} \quad (6\text{-}19)$$

Where, Vc is the volume of concrete in m3; Wr is the weight of reinforcement in metric tons; H in hydraulic head in m; MW is the capacity of machine in MW; RPM is the machine speed in number of revolution in minutes; G is the diameter of generator casing in m which can be estimated using the relationships defined by Equations 6-20 to 6-28.

For head at 20 m $$G \approx 0.7962 \times Q^{0.4858} \quad (6\text{-}20)$$

For head at 50 m $$G \approx 0.8826 \times Q^{0.4998} \quad (6\text{-}21)$$

For head at 100 m $$G \approx 1.046 \times Q^{0.4819} \quad (6\text{-}22)$$

For head at 200 m $$G \approx 1.2181 \times Q^{0.473} \quad (6\text{-}23)$$

For head at 300 m $$G \approx 1.4089 \times Q^{0.4562} \quad (6\text{-}24)$$

For head at 500 m $$G \approx 1.5005 \times Q^{0.4601} \quad (6\text{-}25)$$

For head at 750 m $$G \approx 1.6341 \times Q^{0.4554} \quad (6\text{-}26)$$

For head at 1000 m $$G \approx 1.7361 \times Q^{0.4521} \quad (6\text{-}27)$$

For head at 1500 m $$G \approx 1.8908 \times Q^{0.4474} \quad (6\text{-}28)$$

6.1.5 Electromechanical cost

The electromechanical cost is governed by the type and capacity of the turbine equipment. The cost of turbine varies among different manufacturers and types due to difference in the construction technologies. Hence, it is very difficult to obtain a single accurate relation for cost estimation of all turbine types and sizes. The cost of electromechanical equipment is estimated based on the relation derived by Alvarado-Ancieta (2009), presented in Equation 6-29, is used for the estimation. The study is based on the recent electromechanical costs collected from hydropower plants. The relation however, estimates the electromechanical cost of smaller installed capacity on the higher side. The relation estimates the prices with reference to December 2008. The cost may may have increased due to the escalation of the dollar but also may have decreased due to recent advances in the manufacturing technology and competition in the market. So, no adjustment are made to the costs computed by the relation.

$$C_{EM} \approx 1.1948 \times P^{0.7634} \qquad (6\text{-}29)$$

Where, CEM is electromechanical cost in million US$; P is the installed capacity in MW

6.2 Cost estimation

The estimated quantities were multiplied by the respective rates to estimate the cost of the projects. The rates used for the analysis is presented in Table 6-1.

Table 6-1: Unit rates of items used in the cost estimation

SN	Item	Unit	Rate (NPR)
1	Concrete	m 3	15000
2	Concrete for tunnel	m 3	22500
3	Reinforcement	Kg	103
4	Tunnel Excavation	m 3	5000
5	Tunnel formwork	m 2	1000
6	Shotcrete	m 2	5500
7	Penstock pipe	Kg	140

6.3 Analysis

The financial analysis is concerned with the estimation of the financial implications of a proposed projects. It is based on the use of real term monetary values of the cost & benefit and makes use of market prices and, therefore, includes any taxes or royalties which will be levied on the factors of production and any subsidies, capital or operating costs, which may be received as part of the development. All the costs are charged and all the revenues are credited to conduct analysis in the actual amounts expended or received. For the analysis, the financial rate of return and cash flow is assessed from the perspective of a utility owner/operator.

6.3.1 Basis for Analysis and Assumptions

The relevant specific parameters applied for the financial analysis in this study are as follows:

Power generation: The basis for analysis is primarily based on the energy generation of the project. The only income of this project is its income from energy sale.

Analysis Period: The construction of the project is assumed as four years. The duration of commercial operation is considered as 30 years, with reference to current provision by Ministry of Energy of the Government of Nepal.

Reference Date: The reference date for determining the costs and exchange rate is the year 2018.

Operation & Maintenance Costs: Annual operation and maintenance cost of the Project for the first year of commercial operation have been assumed to be 1.25 percent of the total project cost.

Energy Price: The energy is assumed to be sold to Nepal Electricity Authority (NEA) at the rate of Rs. 4.80 for the wet months and Rs. 8.40 for the dry months. This is the latest rate adopted by Nepal Electricity Authority for small hydropower projects. There is an escalation of three percent from the date of commercial operation for the first nine years.

Royalty: The Government of Nepal imposes different rates of capacity and energy royalty on the operating plant. The tariffs also vary between the first 15 years and the remaining 15 years of generation. The details of which are presented in Table 6-2.

Table 6-2: Royalty for the Hydropower project

SN	Installed Capacity	1 – 15 years		16 – 30 years	
		Capacity Royalty	Revenue Royalty	Capacity Royalty	Revenue Royalty
[-]	[MW]	[NPR/KW]	[%]	[NPR/KW]	[%]
1	< or = 1	-	-	-	-
2	1 – 10	100	1.75 %	1000	10
3	10 – 100	150	1.85 %	1200	10
4	>100	200	2	1500	10

Depreciation: Straight line method has been applied for depreciation calculation.

Tax Rate: As stipulated in the Income Tax Act 2058, the applicable corporate tax rate for enterprises undertaking electricity generation is 20 percent. Corporate tax is waved for the first 10 years of generation.

Financing Mix: The Project is assumed to be constructed through 70 percent Bank Loan and 30 percent Equity. The long term loan is assumed to carry an annual interest rate of 12 percent. The repayment period for long term debt shall be 10 years following commercial operation of the project. Interest during construction (IDC) has been capitalized as mentioned in the previous chapter.

Loan Repayment Model: Equal Monthly Installment (EMI) model shall be adopted to calculate the installments. The interest rate shall be 12 percent.

Discount Rate: The discount rate shall be 12%. This rate shall be used to calculate Net Present Value, Discounted Payback Period, Annuity and Benefit Cost Ratio of the project. Commercial Operation Date (COD) shall be taken as the reference year to calculate discounted cash flow.

Net Cash Flow: While calculating the net cash flow in order to calculate IRR, B/C Ratio, NPV, Simple and Discounted PBP, the total cash inflow is deducted from the total cash outflow every year. Thus, the cash inflow represents only the income from energy sale. On the other hand, cash outflow is the sum of O&M cost, Interest on Bank Loan, Staff Bonus and tax.

Exchange Rate: Fixed exchange rate of Nepali rupee with Indian Rupee at NRs. 1.60 and US Dollar at NRs. 108 are assumed.

Unit Energy Cost: Since O&M cost of the Project increases every year, the average O&M cost of the entire 30 years has been considered while calculating the unit energy cost.

6.3.2 Computation of financial indicators

The financial analysis is carried out by the usual discounted cash flow technique. Analysis has been done by calculating net present value, internal rate of return and benefit cost ratio. The projected income statement and the cash flow from the project for the next 30 years are analyzed. The analysis is carried out in Nepalese Rupees (NPR) assuming the energy from the project is sold to Nepal Electricity Authority (NEA) at the present prescribed rates and the project will be developed in NPR.

6.3.2.1 The Annuity Equation

Annuity is a stream of equal cash flows for a specified number of periods. There are two types of annuity, Ordinary (Deferred) annuity and Annuity Due. Generally, annuity refers to Ordinary (Deferred) annuity. Annuity method is widely used in the analysis of hydropower projects because they yield a fixed income over the life. The general equation of the present value of an annuity are presented in Equation 6-30 to 6-34

$$PVA_n = PMT\left[\frac{1}{1+i}\right]^1 + PMT\left[\frac{1}{1+i}\right]^2 + \dots + PMT\left[\frac{1}{1+i}\right]^n \tag{6-30}$$

$$= PMT\left\{\sum_{i=1}^{n}\left[\frac{1}{1+i}\right]^{i}\right\} \tag{6-31}$$

$$= PMT\left(PVIFA_{i,n}\right) \tag{6-32}$$

$$PMT = \left[\frac{PVA_n}{PVIFA_{i,n}}\right] \tag{6-33}$$

$$= \frac{PVA_n \times i(1+i)^n}{(1+i)^n - 1} \tag{6-34}$$

Where, PVAn is present value if an annuity for period is n; PMT is series of payment of an equal amount of money for period n; n is specified number of period in years; I is the discount rate; PVIFA is present value of interest factor of an annuity.

6.3.2.2 Time Value of Money

A rational individual would not value the opportunity to receive a specific amount of money in future if he/she can have same amount of money today. Most individuals value the opportunity to receive money now rather than waiting for some period of time to receive the same amount. This phenomenon is referred as an individual's time preference for money. Thus, an individual's preference for possessions of a given amount of cash today, rather than in future is called 'time preference for money' or 'Time Value of Money'. The time value of money is generally expressed by an interest rate or discount rate.

Capital has an alternative use. So the opportunity cost of capital should also be considered while evaluating the investment proposals. The opportunity cost may be defined as the rate or return on the best available alternative investment of equal risk. Commercial banks in Nepal charge 11 to 13 percent interest on project loan. The interest rate on bank loan for this project is assumed to be 12 percent. So we have chosen 12 percent as discount rate for this project. The discount factor for a lump sum payment is calculated by using Equations 6-35 to 6-37.

$$DF = \left[\frac{1}{1+i}\right]^n \tag{6-35}$$

$$DF = \sum_{t=1}^{n} \frac{1}{(1+i)^t} \quad (6\text{-}36)$$

$$= \frac{(1+i)^n - 1}{i(1+i)^n} \quad (6\text{-}37)$$

Where, DF is discount factor; i is discount rate; n is number of years;

… Net Present Value

Net Present Value (NPV) method is the classic economic method of evaluating the investment proposals. It is one of the discounted cash flow (DCF) techniques explicitly recognizing the time value of money. Net Present Value may be defined as the excess of the present value of cash inflows over the present value of cash out flows. To calculate Net Present Value, first an appropriate rate of interest shall be selected to discount the cash flows. Then, the present value of investment (i.e. cash inflows) and the present value of investment outlay (i.e. cash outflows) shall be computed using interest rate as the discounting rate. Finally, the net present value shall be found out by subtracting the present value of cash outflows from the present value of cash inflows. Net Present Value can be calculated by using the Equation 6-38 and 6-39.

	$NPV = CF_0 + \frac{CF_1}{(1+i)^1} + \frac{CF_2}{(1+i)^2} + \dots + \frac{CF_n}{(1+i)^n}$	(6-38)
	$= \sum_{t=0}^{n} \frac{CF}{(1+i)^t}$	(6-39)

Where, i is interest rate; n is project life in years (30).

A project is said to be financially viable if it provides positive Net Present Value (NPV).

… Internal Rate of Return

The internal rate of return (IRR) method is another discounted cash flow technique which takes account of the magnitude and timing of cash flows. This technique is also known as yield on investment, marginal efficiency of capital, marginal productivity of capital, rate of return, time adjusted rate of return and so on. It is a method of evaluating investment proposals using the rate of return on an asset investment, which is calculated by finding the discount rate that equates the present value of future cash flows to the investment's cost. Thus, IRR is that discount rate which equates the present value of cash inflows with the present value of cash outflows. The Equations 6-40 and 6-41 were used to calculate the IRR of the projects.

	$Cf_0 + \frac{Cf_1}{(1+IRR)^1} + \frac{Cf_2}{(1+IRR)^2} + \dots + \frac{Cf_n}{(1+IRR)^n} = 0$	(6-40)
	$\sum_{t=0}^{n} \frac{Cf_t}{(1+IRR)^t} = 0$	(6-41)

… Benefit/Cost ratio or Profitability Index (PI) of the Project

Another time-adjusted method for evaluating the investment proposals is the Benefit/Cost (BC) ratio or profitability index (PI). It is the ratio of the present value of future values (NPV + the Initial Investment), divided by the Initial Investment. If BC>1, the project is financially viable and if BC is < 1 the project is deemed financially viable.

7. HYDROPOWER POTENTIAL

7.1 General

Hydropower is power derived from the energy of water moving from higher to lower elevation. Use of hydropower in economic activities can be observed as early as second century BC in China. However, hydropower was first used to generate electricity, in England, in 1878 AD (IHA, 2016a). By 20th century, use of hydropower to generate electricity spread all over the globe. The first hydropower plant in Nepal was installed at Pharping in 1911 AD, with an installed capacity of 500 KW (Pradhan, 2009).

At present, total global hydropower installed capacity is 1,212 GW (IHA, 2016b) which comprises of about 17 % of global electricity generation and 70% of renewable energy production (REN21, 2016). Energy productions and uses, mostly from fossil fuel sources, have contributed significantly to the historic increase in greenhouse gas concentration in the atmosphere (Edenhofer et al., 2011). It continues to contribute about 67% of the present global greenhouse gas production (IEA, 2015a). With implementation of climate change mitigation measures, stake of renewable energy in the future global energy production is expected to increase substantially under most ambitious mitigation scenarios (Edenhofer et al., 2011). Renewable energy is projected to be the largest source of global electricity generation by early 2030's (IEA, 2015b). Hydropower is widely considered as clean source of energy, although reservoirs contribute to some amount of greenhouse gas emission (Varis et al., 2012). Hydropower contributes to highest share of renewable energy production and hence has a great importance in global context in adopting climate change mitigation measures.

In Nepal, more than 90% of electricity generation comes from hydropower (NEA, 2017). Earlier studies have estimated Nepal's hydropower potential as 83,500 MW (Shrestha, 1966), 53,836 MW (Jha, 2010). Nepal being abundant in water resources and so much dependent on hydropower for electricity generation, it becomes evident that more accurate figures of hydropower potential should be estimated using state-of-the-art GIS and hydrological modelling tools (refer 3.1 to 3.5 and 4.3).

Gross hydropower potential is defined as the maximum theoretically possible amount of energy stored in a stream (Arefiev et al., 2015a). As such, maximum hydropower potential establishes the theoretical top of energy that the study basin can produce assuming that all water resources are used to produce energy, which in real life application does not occur, because of environmental flows, other water uses and economic cost/benefit analysis (Palomino Cuya et al., 2013). Similarly, available hydropower potential is the part of the gross hydropower potential after deducting the hydropower potential of the restricted reaches due to environmental, economic or other restrictions (Arefiev et al., 2015a; Hall et al., 2004). Finally techno economical hydropower potential is the part of the available hydropower potential which can be developed based on existing bylaws, present infrastructure and construction technologies and experience in hydropower development (Arefiev et al., 2015a). The relation between different hydropower potentials is presented in Figure 7-1.

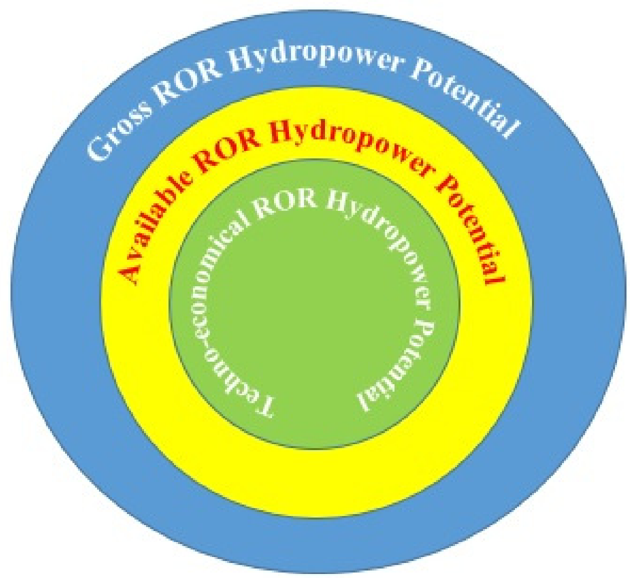


Figure 7-1: Relation between different hydropower potentials

7.2 Methodology

Hydropower is a function of discharge and head (elevation difference). Literature survey, on hydropower potential estimation using GIS technologies, were reviewed to adopt widely used methods to assess hydropower potential in this study. Most of the previous studies assessing the hydropower potential of Nepal (Bajracharya, 2015; Jha, 2010; Prajapati, 2015; Shrestha, 1966) are found to be inconsistent and different compared to the worldwide common practices in calculating hydropower potential. Methods used to compute hydropower potential in this study is described in Figure 7-2.

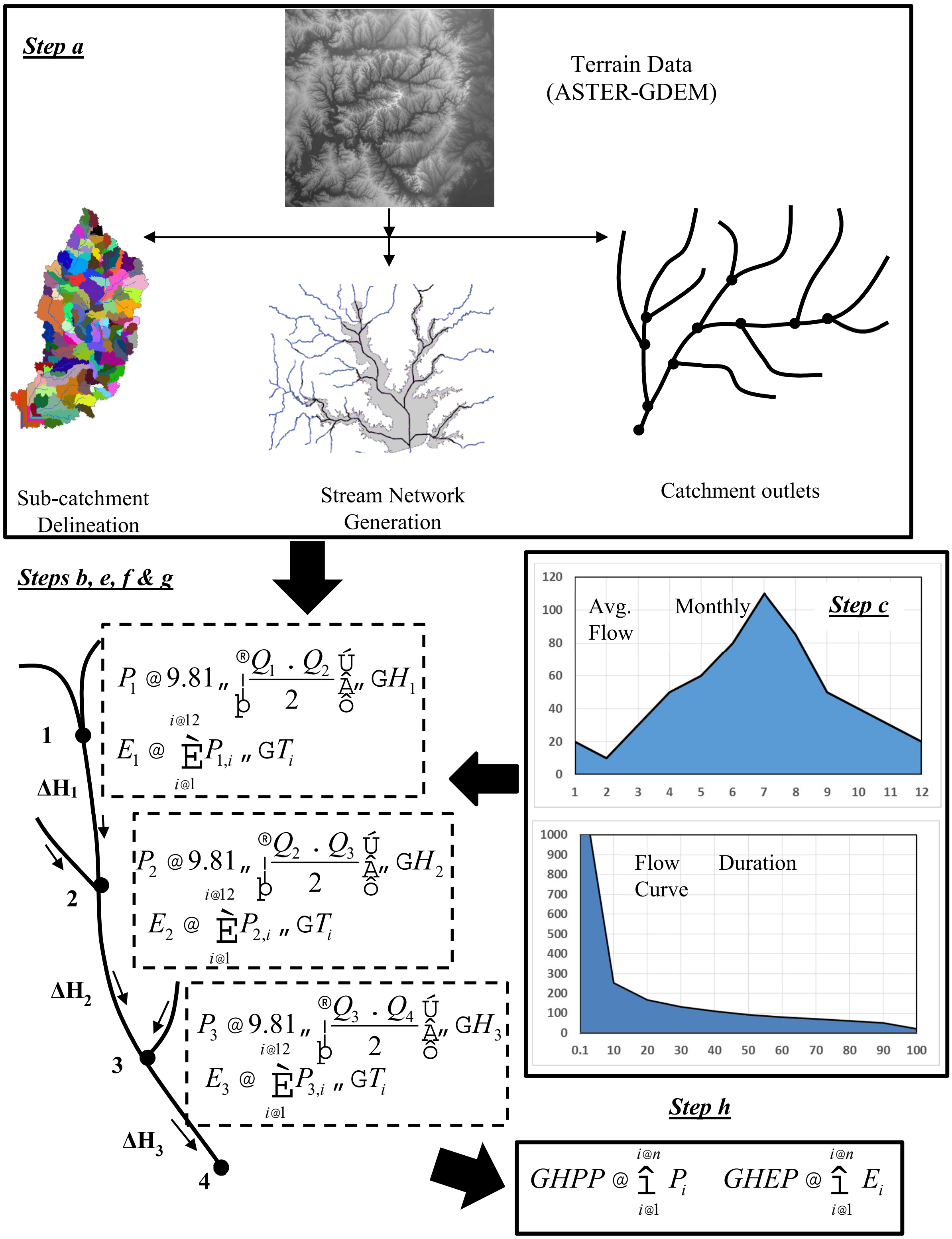


Figure 7-2: General methodology adopted to compute theoretical hydropower potential

7.2.1 Computation approach

Two types of computation approaches – continuous and discrete approaches – have been used to compute hydropower potential. A continuous approach computes hydropower potential on pixel by pixel basis in river. Whereas, discrete approach computes hydropower potential considering certain reach of a river. A river reach consists of several pixels. Most of the studies (e.g. Alterach et al., 2009; Arefiev et al., 2015a, 2015b; Bajracharya, 2015; Hall et al., 2004; Jha, 2010; Palomino Cuya et al., 2013; Prajapati, 2015; Punys et al., 2011) used discrete approach to compute the hydropower potential. Thus it is also adopted in this study. However, definition and length of a river reach varied among different studies. Stretch of a river between two adjacent confluences is adopted as a river reach to compute hydropower potential in this study. Similar definition is also adopted by Hall et al. [2004].

7.2.2 Discharge

According to TOR of the study, hydropower potential will be computed at 40% dependable flow. Discharge at the start of the river reach contributes most to the hydropower potential of a river reach. However, catchment between headwork and powerhouse also yields discharge in a dewatered zone which also contain a hydropower potential. Most of the discrete approaches (e.g. Arefiev et al., 2015a, 2015b; Hall et al., 2004; Jha, 2010; Palomino Cuya et al., 2013) also take into account contribution of discharge of dewatered zone – river reach between headwork and powerhouse- to the hydropower potential of a river reach. Discharge in a dewatered zone is computed as a difference between discharges at upstream and downstream end of a river reach.

7.2.3 Head

Gross-head defines total potential energy stored in water and is computed as an elevation difference between static water level at the upstream and downstream end of a river reach. Whereas net head defines remaining potential energy stored in water considering loss of energy used to overcome friction force when water moves from headwork to powerhouse. Net head depends upon properties of the waterway (type, construction material and length). Since, gross hydropower potential denotes the theoretical maximum potential energy stored in a stream, gross head is used for the computation (e.g. Alterach et al., 2009; Arefiev et al., 2015a, 2015b; Bajracharya, 2015; Ballance et al., 2000; Feizizadeh and Haslauer, 2012; Hall et al., 2004; Jha, 2010; Palomino Cuya et al., 2013; Punys et al., 2011; Setiawan, 2015). Net head will be taken into account while computing techno-economical hydropower potential.

7.2.4 Electro-mechanical efficiency

The energy of moving water rotates turbine which rotates generator to generate electricity. The energy of moving water cannot be entirely converted into electrical energy due to friction and other losses occurring in turbine, generator and transformer. So electro-mechanical efficiency - combined efficiency of turbine, generator and transformer - are taken into account while computing the electricity output. Since, gross hydropower potential denotes the theoretical maximum potential energy stored in a stream, electro-mechanical efficiency is not taken into account in the computation (e.g. Arefiev et al., 2015a, 2015b; Bajracharya, 2015; Ballance et al., 2000; Punys et al., 2011; Setiawan, 2015). However, hydropower potential of river basins in Nepal estimated by Jha [2010] and Prajapati [2015] take into account electro-mechanical efficiency. Electro-mechanical efficiency will be taken into account while computing techno-economical hydropower potential.

7.2.5 Hydropower potential

Gross hydropower potential of a river reach has two components (equation 7-1). The first component is contribution from flow that enters upstream end of the reach (headwork) and leaves at downstream end of the reach (powerhouse), transiting the river reach. Gross head for this component will be total gross head of the reach which is computed simply as elevation difference between upstream and downstream end of the reach. The second component is a contribution from discharge generated by catchment of the dewatered zone (local catchment of the river reach). Gross head of this contribution varies between zero to total gross head of the river reach. So, gross head for the second component is considered as half of total gross head of the river reach.

Gross hydropower potential of a river reach is computed as:

$$P_i = \overbrace{9.81 \times Q_i \times \Delta H_i}^{component\ 01} + \overbrace{9.81 \times (Q_{i+1} - Q_i) \times \frac{\Delta H_i}{2}}^{component\ 02} \qquad (7\text{-}1)$$

Where, Pi is the gross hydropower potential of the ith reach, MW; Qi is the 40% dependable flow at upstream end of the ith reach, m3/s; Qi+1 is the 40% dependable flow at downstream end of the ith reach (m3/s); ΔHi is the total gross head of the ith reach, m.

The equation can be algebraically rearranged as:

$$P_i = 9.81 \times \frac{Q_i + Q_{i+1}}{2} \times \Delta H_i \qquad (7\text{-}2)$$

Total gross hydropower potential of a basin is then computed as:

$$GHPP = \sum_{i=1}^{1=n} P_i \qquad (7\text{-}3)$$

Where, GHPP is the gross hydropower potential of a basin, MW; n is the number of river reaches in a river basin.

7.2.6 Hydroelectric Energy Potential

Monthly hydroelectric energy production varies due to monthly variation of river discharge. So, hydroelectric energy potential is computed, using equation 5-4, by integrating energy produced in each month of a year.

$$HEP = \sum_{i=1}^{i=12} P_i \times \Delta T_i \qquad (7\text{-}4)$$

Where, HEP is the hydroelectric potential of the basin, MWh; Pi is the monthly power generation,MW; ΔTi is the duration of the power produced in ith month, h;

Total maximum hydroelectric energy potential (MHEP) is computed taking into account all average monthly discharge available in river for electricity generation. Whereas, gross hydroelectric energy potential (GHEP) is computed taking into account only the monthly turbine flow (MTF – Section 4) for electricity generation. Finally available gross hydroelectric energy potential (AHEP) is obtained after deducting gross hydroelectric energy potential of excluded river reaches from the total gross hydroelectric energy potential of river basin.

7.3 Assumptions

Following assumptions were made while computing gross and available hydropower potential:

- Area above permanent snow line (elevation > 5000m) does not have hydropower potential.
- Catchment area below 15 km^2 do not collect sufficient perennial discharge to compute hydropower potential
- River reach, lying in the head waters of the catchment (stream order <3), with hydraulic head < 15m have negligible hydropower potential
- River reaches of the main river and major tributaries (stream order >3) having hydraulic head <5m have negligible hydropower potential

7.4 Results

7.4.1 Basin Wise Hydropower Potential

Gross hydropower potential were computed in the three major river basins: the Koshi, the Gandaki and the Karnali, the southern river basins: Rapti, Babai, Kamala, Kankai, Bagmati, Bakaiya, and Tinau, and the boundary river basins: Mahakali and Mechi. Thus the gross hydropower potential of Nepal at 40% of flow exceedance is estimated as 72,544 MW. The results are presented in Table 7-1 and Figure 7-3. In the boundary river basins, only half of the gross hydropower potential of the stream which lies in the international border is considered. The gross hydropower potential was analyzed all together in 3712 river reaches of different river basins mentioned above (Table 7-2). The potential of these river reaches, within different river basin, are presented in Appendix D.

Hydropower potential of different basins were assessed for discharges computed using different methods are presented in Table 7-1. Discharges were estimated based on Empirical methods (Catchment Area Ratio method) and Hydrological modelling using HEC-HMS software. HEC-HMS model is based on established hydrological principles and takes into account the spatial heterogeneity of the catchment for discharge estimation, compared to the empirical methods. Hence the discharge estimated from hydrological modelling is adopted for Gross Hydropower Potential estimation in the gauged river basins. The calibration and validation results of the model shows a good performance of the model in gauged basins.

For the ungauged basins Bakaiya and Mechi, the power calculated based on the discharge estimated by Empirical method are adopted. Hydrological model could not be used in the Mahakali basin because there are not sufficient gauging stations available to estimate the flow in the basin. So, the discharges estimated by Empirical methods were used to estimate the power potential of the Mahakali basin. It should be noted that the power potential of the river reach (Mechi and Mahakali) which is an international border is considered only half of the calculated value.

The three major rivers basins constitute of 93.7% of the total gross hydropower potential of Nepal. Whereas the southern river basins and the boundary river basins represent only 3.3% and 3% respectively (Figure 7-4). Among the three major river basins, the Koshi, the Gandaki and the Karnali represent 38.3%, 27.3% and 28.1% of the total gross hydropower potential of Nepal respectively. Koshi River basin has the highest potential, 27805 MW, and the Mechi River has the lowest potential, 62 MW.

Table 7-1: Gross Hydropower Potential in different river basins of Nepal

SN	River basin	Empirical	HEC-HMS	Adopted
1	Koshi	21940	27805	27805
2	Gandaki	19385	19803	19803
3	Karnali	21306	20385	20385
4	Rapti	595	745	745
5	Bagmati	638	437	437
6	Babai	174	264	264
7	Kankai	463	394	394
8	Kamala	209	261	261
9	Tinau	101	184	184
10	Bakaiya	84		84
11	Mechi	62		62
12	Mahakali	2120		2120
			Total	**72,544**

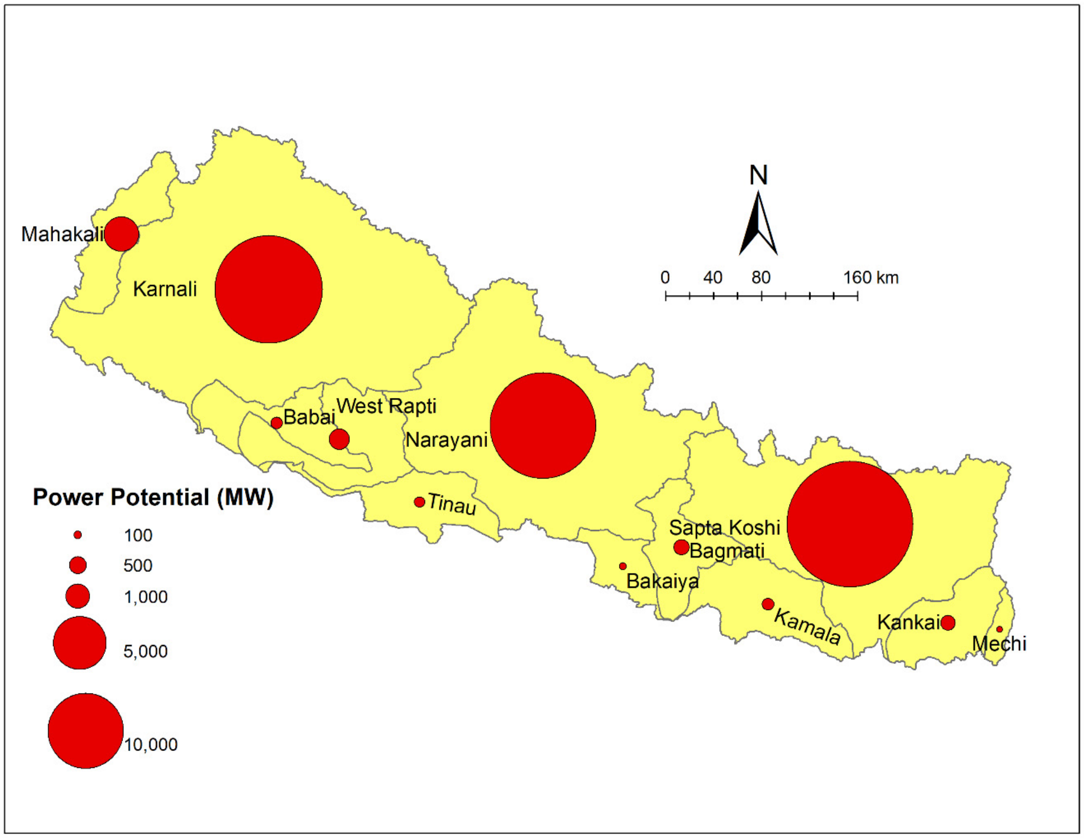


Figure 7-3**:** Gross Hydropower Potential in different river basins of Nepal

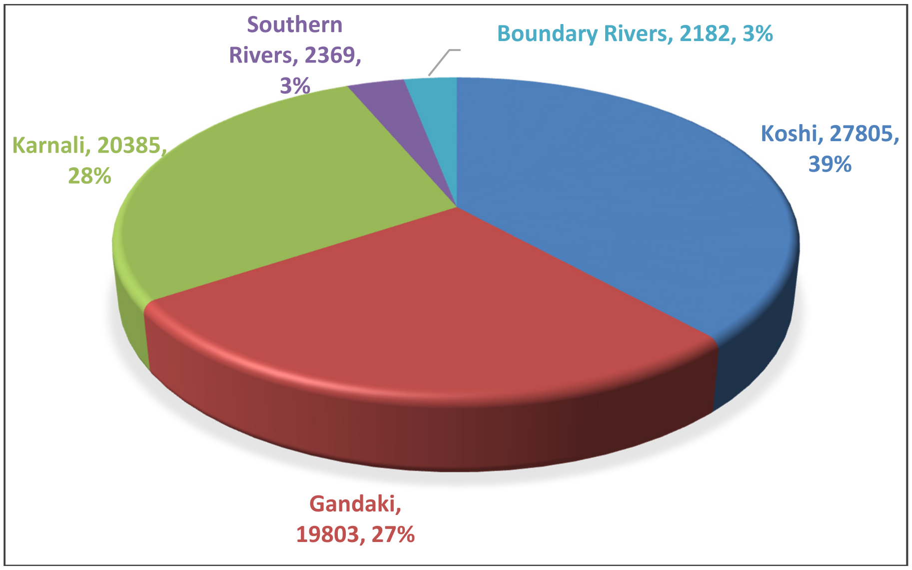


Figure 7-4**:** Gross Hydropower Potential distribution among different river basins of Nepal

Table 7-2: Number of river reaches used to estimate gross hydropower potential in river basins

River Basins	Number of river reaches
Koshi	650
Gandaki	1361
Karnali	1248
Kankai	46
Kamala	62
Bagmati	50
Bakaiya	35
Tinau	20
Rapti	55
Babai	51
Mechi	12
Mahakali	122
Total	**3712**

7.4.2 Gross hydropower distributions in major basins

Distribution of gross hydropower potential within major tributaries of the three major river basins were also analyzed. The results are presented below

Koshi river basin

The power potential of major tributaries of the Koshi river basin are presented in

Table 7-3 and Figure 7-8. Arun River (39.18%) contributes the highest amount of the power potential to the Koshi River basin followed by Tamor (22.83%), Dudhkoshi (13.15%), Tamakoshi (11.16%), Sunkoshi (9.60%), Indrawati (1.99%), Likhu (1.97%) and Southern part (0.12%) respectively. Power potential of Sunkoshi Basin includes those of Bhotekoshi, Balephi and Sunkoshi river basin.

Table 7-3: Gross Hydropower Potential of major tributaries in the Koshi Basin

SN	Tributary Basin	Power Potential (MW)	% of Basin Potential
1	Indrawati	554	1.99
2	Likhu	547	1.97
3	Arun	10,893	39.18
4	Dudhkoshi	3,657	13.15
5	Sunkoshi	2,670	9.60
6	Tamakoshi	3,103	11.16
7	Tamor	6,348	22.83
8	Southern	33	0.12
	Total	**27805**	**100**

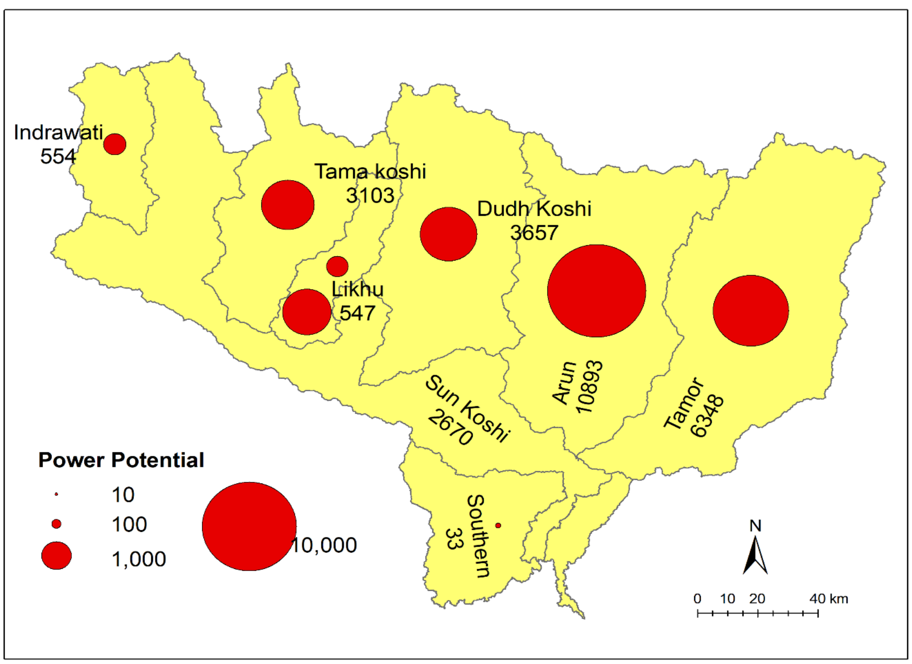


Figure 7-5: Gross Hydropower Potential in different different tributary of Koshi River basin

Gandaki river basin

The power potential of major tributaries of the Gandaki river basin are presented in Table 7-4 and Figure 7-6 . Kaligandaki (28.96%) contributes the highest amount of power potential to the Gandaki River basin followed by Marshynagdi (23.3%), Budhi Gandaki (20.41%), Trishuli (16.71%), Seti (4.67%), Madi (2.51%), Madi (2.51%), Naryani (2.19%) and Rapti (1.24 %) respectively. Narayani includes the main channel part of Sapta Gandaki River downstream of Naryanghat.

Table 7-4: Gross Hydropower Potential of major tributaries in the Gandaki Basin

SN	Tributary Basin	Power Potential (MW)	% of Basin Potential
1	Kali Gandaki	5735	28.96
2	Marshyangdi	4614	23.30
3	Budhi Gandaki	4042	20.41
4	Trishuli	3309	16.71
5	Seti	926	4.67
6	Madi	498	2.51
7	Narayani	433	2.19
8	Rapti	246	1.24
	Total	**19803**	**100**

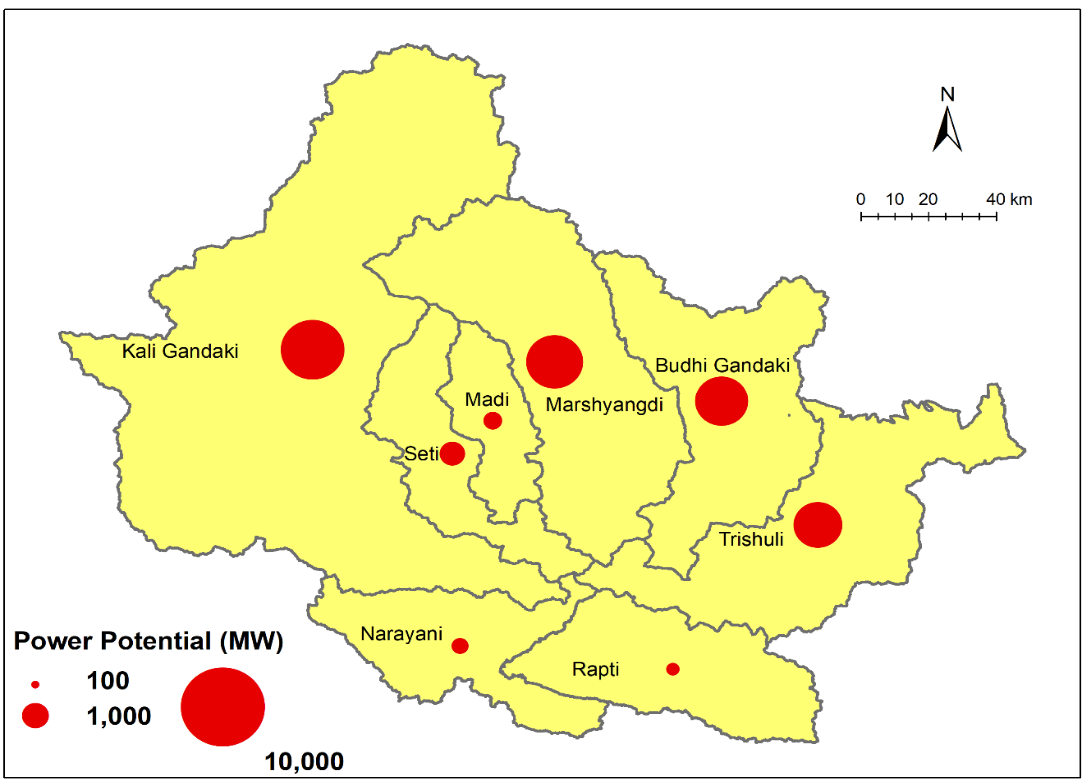


Figure 7-6**:** Gross Hydropower Potential in different different tributary of Gandaki River basin

Karnali River Basin

The power potential of major tributaries of the Karnali river basin are presented in Table 7-5 and Figure 7-7. Bheri (39.21%) contributes the highest amount of power potential to the Karnali River basin followed by West Seti (18.8%), Karnali Main (16.68%), Humla Karnali (11.26%), Mugu Karnali (9.87%) Tila (3.97%) and the Southern tributaries (0.21%) respectively.

Table 7-5: Gross Hydropower Potential of major tributaries in the Karnali Basin

SN	Tributary Basin	Power Potential (MW)	% of Basin Potential
1	Bheri	7993	39.21
2	West Seti	3833	18.80
3	Karnali Main	3401	16.68
4	Humla Karnali	2296	11.26
5	Mugu Karnali	2011	9.87
6	Tila	809	3.97
7	Southern part	43	0.21
	Total	**20385**	**100**

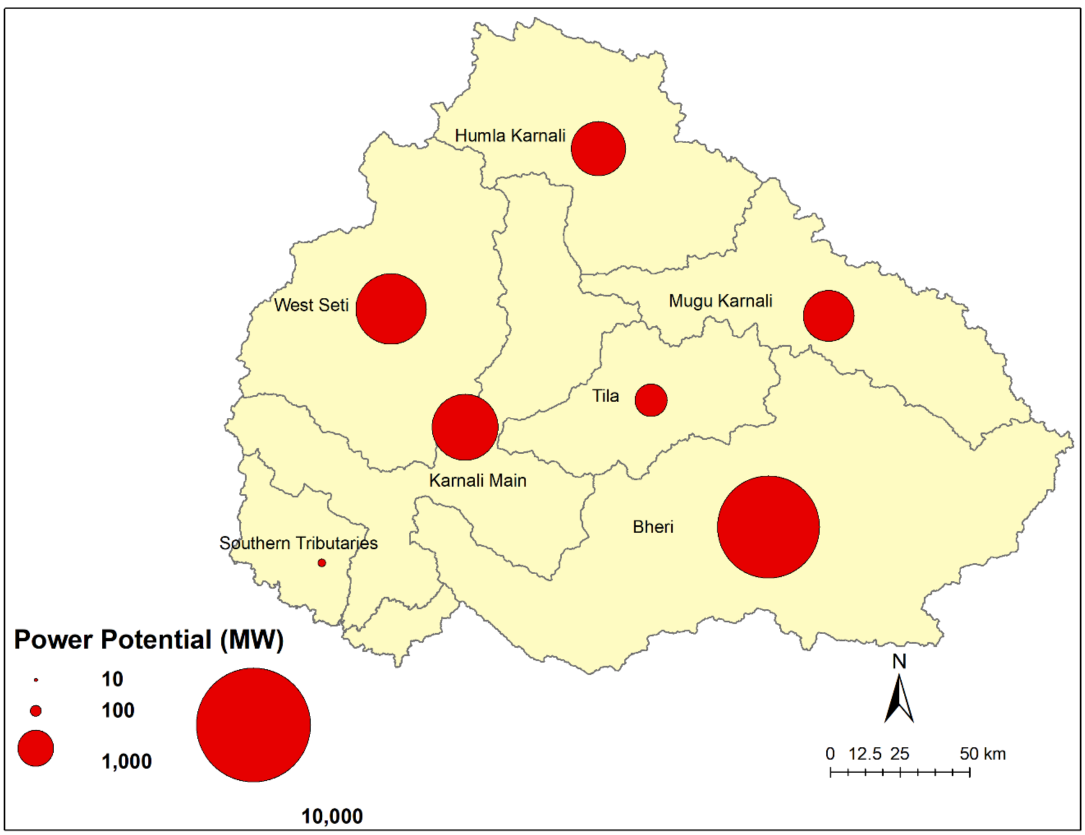


Figure 7-7**:** Gross Hydropower Potential in different different tributary of Karnali River basin

7.4.3 Gross hydropower potential distributions in provinces

The hydropower potential of Nepal is shared among seven provinces. The distribution of the potential within the provinces are shown in Table 7-6, Figure 7-8 and Figure 7-9. Province-1, which includes most of the Koshi basin incorporates highest hydropower potential (22,619 MW)-which is 31.2% of total hydropower potential. Province-2 incorporates the lowest hydropower potential (275 MW)-which is 0.4% of total potential. Similarly Province-3, Proovince-4, Province-5, Province-6 and Province-7 incorporate 14.6%, 20.7%, 3.7%, 18.9% and 10.6% of the total potential respectively.

Table 7-6: Distribution of gross hydropower potential among different provinces

SN	Province	Power Potential (MW)	% of Basin Potential (MW)
1	Province 1	22,619	31.2
2	Province 2	275	0.4
3	Province 3	10,568	14.6
4	Province 4	14,981	20.7
5	Province 5	2,677	3.7
6	Province 6	13,702	18.9
7	Province 7	7,722	10.6
	Total	**72,544**	**100**

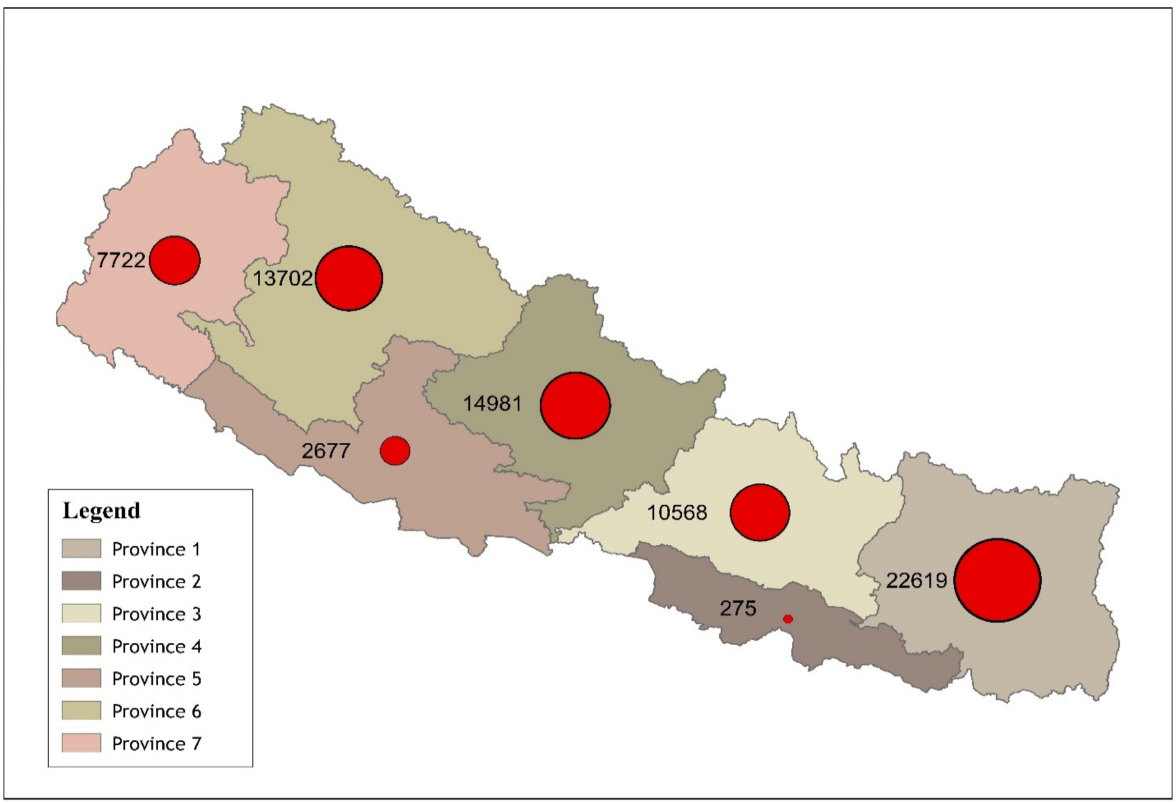


Figure 7-8**:** Distribution of gross hydropower potential among different provinces

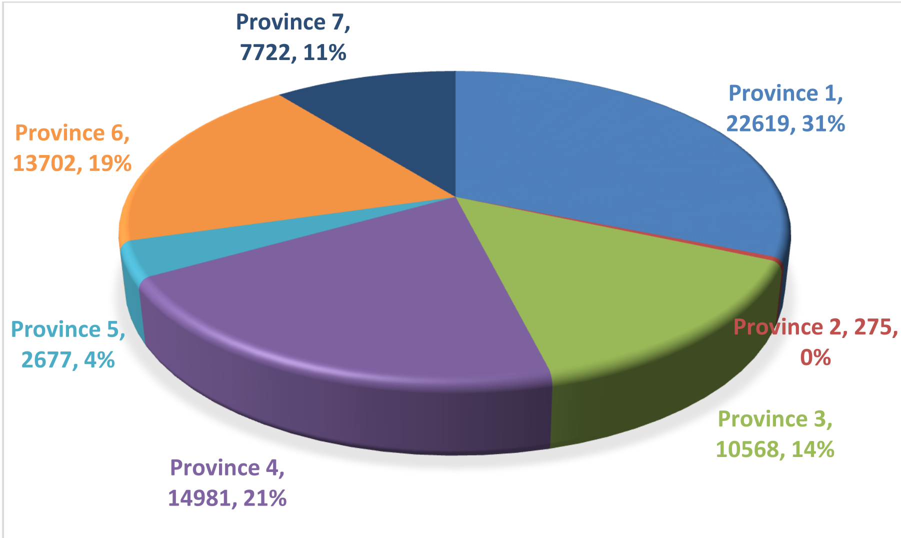


Figure 7-9: Percentage distribution of gross hydropower potential among different provinces

7.4.4 Hydro-electric energy potential

Gross Hydro-electric energy potential (GHEP) and Maximum Hydro-electric energy potential (MHEP) were computed for the Koshi, the Karnali, Rapti, Mahakali, Mechi, Babai, Kamala, Kankai, Bagmati, Bakaiya, and Tinau river basins. In boundary river basins, Mechi and Mahakali, the hydro-electric energy potential (both GHEP and MHEP) of the stream, which lies in the international border, is halved. GHEP is computed as the annual hydro-electric that can be generated at an installed capacity of Gross Hydropower Potential. Whereas, MHEP is computed as the maximum energy that can be generated utilizing all of the discharge in streams at available topographic head. The results are presented in Table 7-7 and Figure 7-10.

GHEP of the Koshi, Gandaki and the Karnali River basin were determined as 153,836 GWh, 119,384 GWh and 138,149 GWh respectively. Gross Hydro-electric Energy potential of remaining river basins were computed as 30,738 GWh.

Similarly the Maximum Hydro-electric Energy Potential (MHEP) of the Koshi, the Gandaki, the Karnali and the remaining river basins were determined as 282,797 GWh, 223,806 GWh, 224,197 and 70,392 GWh respectively.

Table 7-7:: Hydro-electric Energy Potential in different basins of Nepal

Basins	Gross Hydro-electric Energy Potential (GHEP) - GWh	Maximum Hydro-electric Energy Potential (MHEP) - GWh
Koshi	153,836	282,797
Gandaki	119,384	223,806

Karnali	138,149	224,197
Rapti	4,099	8,169
Bagmati	2,427	7,025
Babai	1,407	2,939
Kankai	2,133	4,461
Kamala	1,320	2,698
Tinau	956	2,299
Bakaiya	466	1,036
Mechi	343	536
Mahakali	17,587	41,229
Total	**442,107**	**801,192**

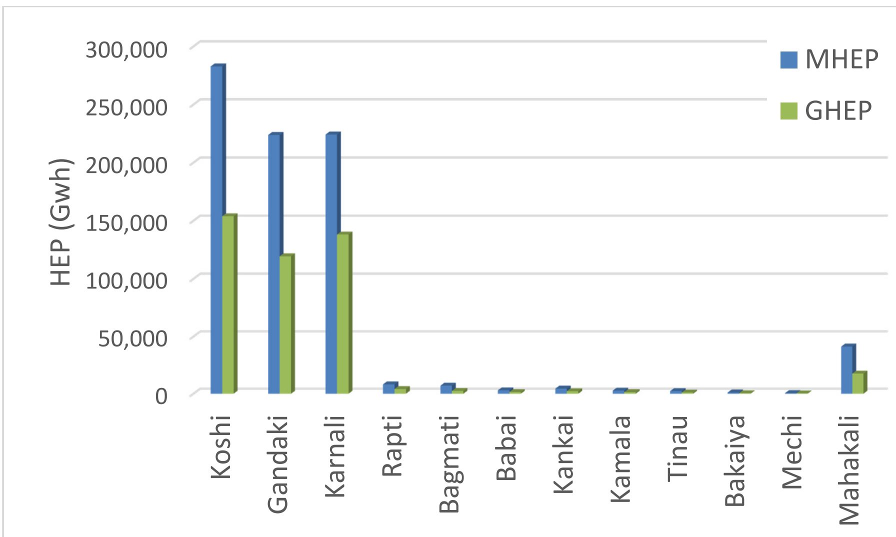


Figure 7-10: Hydro-electric Energy Potential in different River basins of Nepal

7.5 Limitations of current assessment

Errors in estimation of discharge and gross head lead to uncertainties in the calculation of hydropower potential which are described as follows:

7.5.1 Hydrological uncertainties

Gross hydropower potential estimation requires estimation of discharge at several reaches along rivers. However, discharge measuring stations - hydrological stations - are located sparsely in large rivers and some of the tributaries. The majority of river reaches are without hydrological stations, so discharge at the reaches are estimated using hydrological model or transferring measured discharge from hydrological stations using Catchment Area Ratio (CAR) method.

Discharge in the three major basins- the Koshi, the Gandaki and the Karnali - were estimated using HEC-HMS, a semi-lumped, hydrological model. In semi lumped models, hydrological properties are lumped over the sub basin and the specific yield of discharge (discharge yield per unit area of catchment) is assumed uniform in that sub basin. Since discharge yields varies in basin due to spatial variation of land use, geology, soil type etc., such assumptions lead to some error in discharge estimation of river reaches at a scale smaller than the sub basin.

CAR method was used to estimate discharge at the river reaches of the southern and the boundary river basins. In this method the measured flow at nearest hydrological station is transferred to the desired location in proportion to catchment area. The CAR method also assumes a constant specific yield of discharge within a basin which leads to some error in discharge estimation of river reaches in the basin.

Rainfall/ precipitation is a key input to the hydrological model. It is extremely variable in time and space in mountainous regions. The spatial variability of rainfall is very often identified as the major source of error in rainfall-runoff hydrological modelling. Detailed information on spatial variability of rainfall becomes relevant while modelling small catchments and runoff process which directly depend on precipitation. Since, 83% of Nepal's territory consists of hills and mountains a dense network of rainfall station is required to capture well the spatial variability of rainfall. Unfortunately, the network of rainfall stations is very sparse. The network become even sparser in the high altitude – Himalayan – region. The area covered by Theissen polygons are large in the regions with sparsely located rainfall stations, which could not capture the spatial variation of rainfall thus leading to errors in estimating discharge in hydrological models.

A hydrological model with more distributed features may improve the hydrological estimations of the study. The use of such models may be challenging using hydro-metrological database with poor spatial and temporal resolution. However the use of available gridded metrological data in combination with ground measured data can overcome such challenges and improve the results of the distributed hydrological models.

Parts of basin areas of three major rivers: the Koshi, the Gandaki and the Karnali also lie in Tibet. This study incorporates the flow generated by the Tibetan part of catchment in Koshi Basin. Long-term flow generated by the Tibetan catchment of Arun River, assessed by previous studies, was provided as an inflow to the Koshi basin at the international boundary.

In cases of the Gandaki and the Karnali basin, the precipitation computed in the higher regions of the catchment were also applied to the Tibetan parts of their respective catchment. Since the Tibetan part receives less amount of rainfall compared to the Nepalese territory, it may result in estimation of higher flows in the upper reaches of the catchment. A hydrological modelling taking into consideration spatial variability of rainfall in Tibetan part of the catchment would provide more realistic results.

7.5.2 Uncertainties in terrain data processing

The data used, its scale, inherent anomalies were the major sources of uncertainties and potential errors of GIS based Digital Elevation Modeling analysis. Following points are highlighted, this may have attributed to certain uncertainties and potential errors in calculations:

ASTER satellite based GDEM Ver. 2 dataset has inherent anomalies, especially in the regions of high terrain profiles and narrow gorges, which has attributed to certain errors in delineating the sub-catchment boundaries and generation of stream networks.

Due to inherent errors in certain pixel elevations the calculation of elevation differences (head) was obtained erroneous. Such errors were rectified using secondary DEM generated using the contours and spot levels from the National Topographical Maps. Narrow and deep valleys are very common in high altitude regions. The resolution of ASTER-GDEM (30 m) was too low to represent these topographical features leading to error in estimation of gross heads. The use of higher resolution data (Lidar, etc.) can greatly reduce errors in estimation of gross heads in those areas.

Coverage (contributing areas) of terrain parameters such as slope and aspect; and bio-physical parameters such as land cover were spatially analyzed using 30m derived raster datasets. The resolution of the raster dataset may have introduced certain generalizations, and therefore some variations in calculations of the coverage of these parameters in each of the sub-catchments. However, at the national/basin levels, this generalization may not attribute to significant errors.

8. TECHNOECONOMICAL HYDROPOWER POTENTIAL

It is not realistic to assume that all of the gross hydropower potential will be developed in the short medium or even in the long term. The technical potential of hydropower describes the energy capacity that is actually useable when technical, infrastructural, ecological and other conditions are taken into consideration. Thus projects with realistic features have to be identified to determine their techno-economical potential. So, this chapter describes the methodology employed to compute the techno-economical potential of Run-off-River projects.

8.1 General Methodology

The techno-economical hydropower potential is calculated as follows:

Step-1: Screening the river reaches on the basis of gross hydropower potential computed in Chapter 7.

Step-2: Spotting the headwork and power house location using automated tool developed in the GIS platform. Compute the length of the waterway.

Step-3: Determining the design plant discharge, average monthly discharge and flood discharge at the headwork site.

Step-4: Design the size of the project components from the known discharge, gross-head.

Step-5: Determine the cost of the project cost based on the size of the project components, using standardized tool.

Step-6: Determine project benefits from the monthly energy generation

Step-7: Carry out economic analysis based on the project costs and benefit. Screen the projects that are economically feasible.

Step-8: Determine the geological, environmental setting of the project site and extract required parameters to carry out multi-criteria analysis.

Step-9: Screen the economically feasible projects with technical multi-criteria screening tool.

Step-10: Select the techno-economically feasible projects on the basis of score and sum their installed capacity to determine the techno-economic hydropower potential of Nepal.

The economical components are determined by assessing the project costs and benefits. While the risk factors affecting the technical as well economic component of the project are incorporated in the multi-criteria evaluation tools by appropriate scoring.

8.2 Spotting of potential RoR Projects

In this study, the algorithm was developed to identify the potential headwork and powerhouse sites for run-of-river hydropower projects along the river stream and tributaries networks in watershed. The process of involved in algorithm are shown in Figure 8-1. The framework is developed in MATLAB platform to identify powerhouses' sites for selected headworks. ArcView 10. 2 GIS software is used to generate GIS data for river stream and tributaries networks within the selected watershed. The delineated watershed of DEM transfer into MATLAB to extract the hydropower attributes and further analysis. Validation is done with comparing existing hydropower locations in catchment. The spotting of the hydropower potential site only uses the GIS data to locate the possible potential alternatives of powerhouses and headworks based on stream gradient index. The processes involved in the algorithm are described in detail as follows (Figure 8-1):

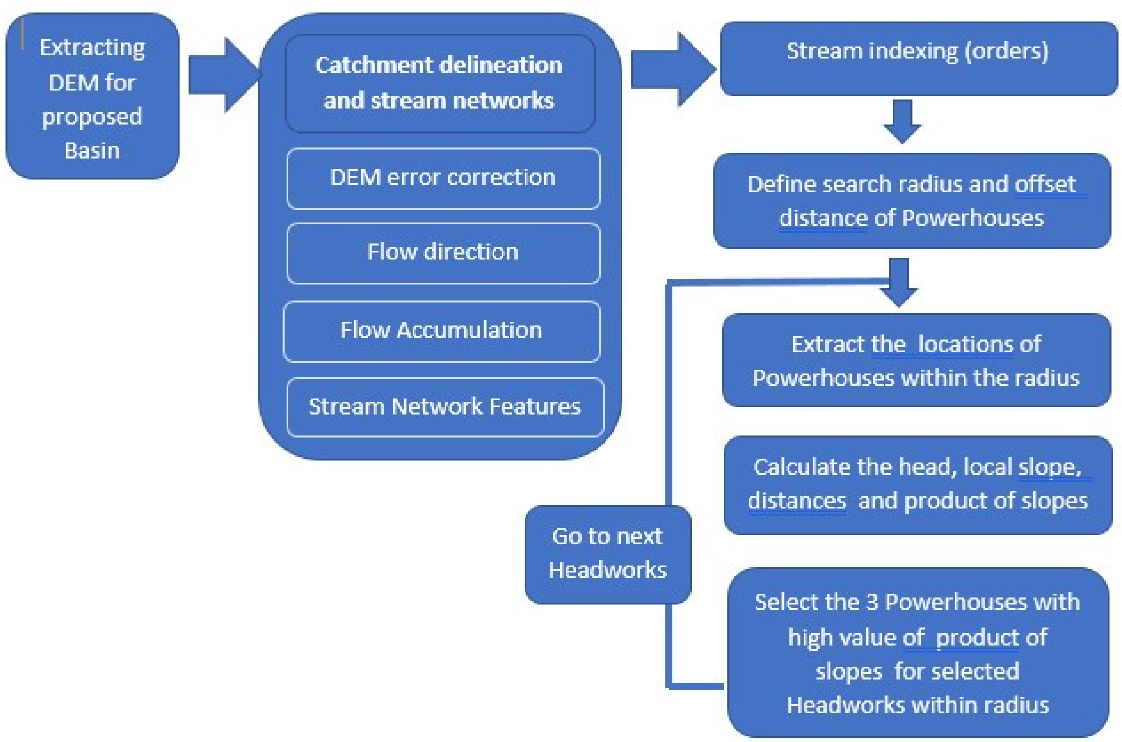


Figure 8-1: Analytical framework of algorithm

8.2.1 Data Set Selection

The first step is to select spatially covered data sets for selected area. A primary assessment of hydropower potential requires boundaries, topography, geometric information on stream networks, and hydrologic information on watershed. These attributes can efficiently derive from DEMs using widely available GIS applications, which allow calculate the location of sites for hydropower plant development. DEM are freely available in online, (e.g. SRTM, ASTER GDEM, EU-DEM). ASTER GDEM is used in this study.

8.2.2 Catchment delineation

Catchment delineation is done to create boundary area and drainage networks of watershed, which is usually extract from DEM by creating boundary that represents contributing the area upstream from a specified outlet point in ArcGIS Desktop software. The Spatial analyst tools are used to derive attributes of stream network (position and length), sub-catchments and drainage patterns of the basin. Geo-processing analysis is performed to fill sinks and pits in cells and to generate flow direction, flow accumulation, streams, stream segments, and watersheds on data. These data then used to develop a vector representation of catchments and drainage lines from selected points. The size and number of sub-basins are defined in catchment depending on study, but it should capture enough spatial variability. In practice, the catchment delineation process is often quite difficult when delineation of headwater streams with valley width is less than DEM resolution. Furthermore, the vertical accuracy of DEMs often causes problems in flat regions and complications in an interpretation of hydrology due to water transfer and changes in underlying geology, which may lead to the delineated watershed, not coincide with the real watershed.

8.2.3 DEM errors

DEMs are not free from error. Such error is stem from uncertainties in data acquisition, spatial resolution and interpolation techniques used for their preprocessing (Purinton and Bookhagen, 2017) . Usually, in studies of GIS based hydropower survey, the solution of error referred to remove the artefacts and pits. This solution improves the representation of shapes and elevation grid of streams that used in watershed for the hydrological analysis. The quality of DEM and appropriate processing tools are required to obtain adequate results. Only small segments of the cells are overlaying for stream network in a DEM compare to whole watershed. However, this portion is particularly tending errors in elevation grid that turn out inaccurate in representation of streams topography (Schwanghart and Scherler. 2017). The elevation grid with filled spurious sinks in DEMs is always prerequisite for carryout hydrological analysis successfully and also for generating meaningful geographical and flow related information.

Filling of sinks remove any imperfections of grid cell in DEM (Figure 8-2). Each cell of DEM has at least one neighboring cell with equal or lower value of elevation. If cell with higher value surrounded a cell the water is trapped in that cell and cannot flow. Sometimes filling large sinks may produce a large flat area that leads to unrealistic gradient in stream networks. In such case, carefully make a choice of approach that solves these problems. To eliminate this problem the modified value of elevation calculated at several neighboring (up and down segments) may need to be averaged for smoothing.

The hydrologically corrected flow profile of streams by filling spurious sinks in DEMs is often hard to validate with real topography, however visualization of data may interpret the results.

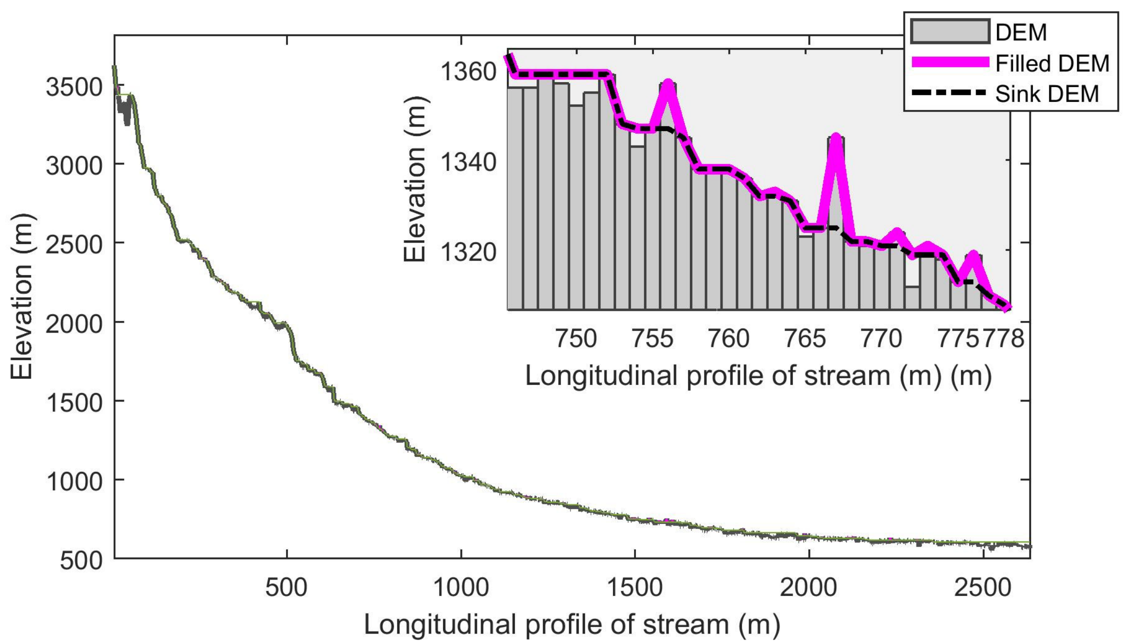


Figure 8-2: Corrected by filling and cutting of DEM

8.2.4 Stream network features

Each sub-basin contains of stream that could be mainstream or tributary and these all are connected one to another based on flow direction. The flow accumulation gives the number of cells (or area) that drain to a particular cell to define a stream. It assumed that a stream is formed when a certain area (threshold) drains to a point. This threshold can be defined by using the number of cells in the flow accumulation grid. For example, If assume an area of 30 km as the threshold to create a stream, the number of cells corresponding to this threshold area will be 33,333 (30000000/(30*30)). To create stream raster, the stream cells corresponding select raster threshold area of 30km will includes cells that have pixel value greater than 33,333. Streams are linked by assigning a unique number to each link (or segment) in the stream raster. Then create the stream order for the stream network from flow direction and converts stream raster to a polyline feature.

8.2.5 Stream indexing

Stream indexing is essential to identify source to mouth direction of stream networks within the watershed. It facilitates to represent longitudinal profile and search descending order for proposed algorithm. Each sub-basin contains stream (both end connected with other neighboring streams) or tributary (one end connected with another stream) and these all are connected one to another. Stream indexing arranges by orders the stream network through starting at the origin and run down the network incrementing the order of the polyline feature. The indexing is done by repeating this process for each source.

8.2.6 Search radius and intervals

The locations of headwork and powerhouse site are placed in equal intervals from upstream to downstream in each stretch of perennial streams. Then, the radius is defined to calculate the numbers of possible powerhouses in downstream (mainstreams or/and tributaries) within circular area for that particular headwork (this will be center of circle) as shown in Figure 8-3. It assumed that for each headwork have several possible powerhouses in downstream in equal distances in each search. The distance between headwork site and powerhouse location (preferably not more than 500m) should be shorter that search radius (select with reasonable distance or not more than 10 km). The process continues (iterative) to calculate one after another headwork following to downstream in each stream with selected radius. The information extracted from each circular area used to estimate further identifying potentially good locations for powerhouse sites.

Searching algorithm runs from source of stream to downstream base on indexed stream. The circular area centering it headwork passes down one after another. The search is terminating when point is an outlet of watershed.

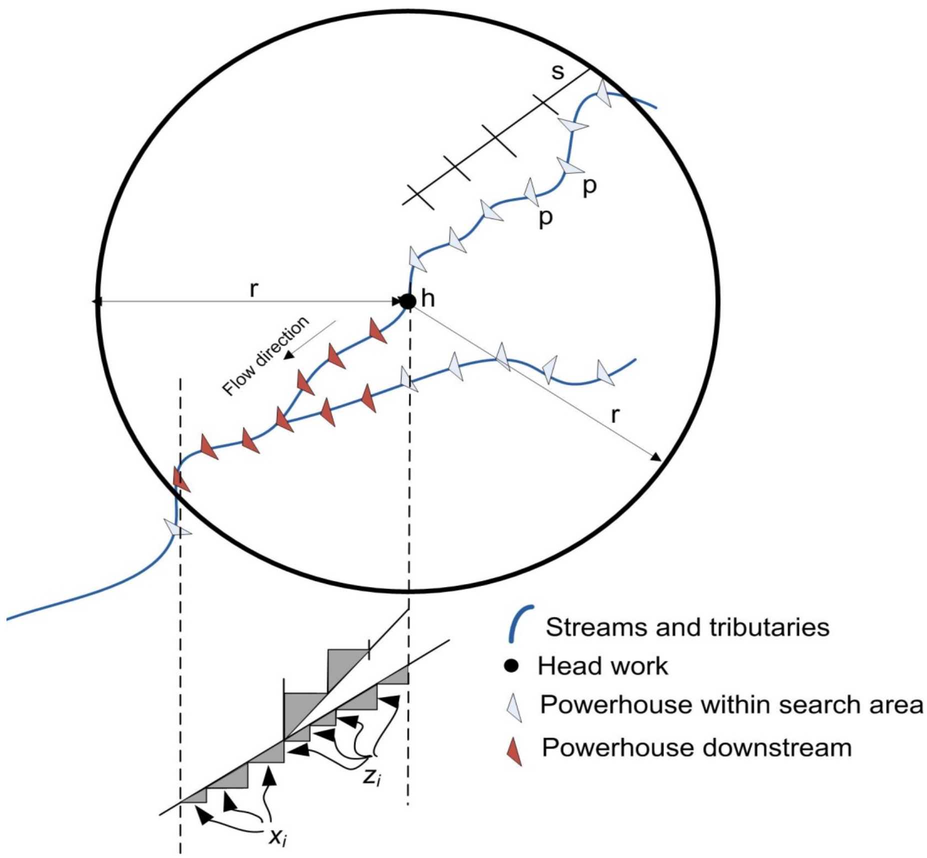


Figure 8-3: Locations of Powerhouses and headwork within search radius

8.2.7 Calculation of head

Elevation information from DEM data is clipped with stream network to generate topographic profile of streams and tributaries. The vertical distance between headwork and powerhouses are defined a hydraulic head, which is computed at the downstream for each powerhouse from available elevation in streams and tributaries. The local head H refers to the elevation between headwork and powerhouses and cumulatively summed powerhouse at the downstream called cumulative heads CH. While these calculate from stream to tributaries, it became negatives in head value therefore, decrease in cumulative head. The location of powerhouse for particular headwork is calculated by it value of gradient considering the difference of head between headwork and each powerhouses within circular search area. In order to simplify the analysis of potential output is estimated by product of slope also called stream gradient index followed by Eq.1.

8.2.8 Stream gradient index

The Stream Gradient Index (product of slope) is use to detect high potential site along river stretch. This value is approximated by local gradient of stream and total head at calculate form headwork to selected powerhouse, represents as follows:

Product of Slope (PS):

$$PS_i = S_i * CH_i$$

Eq.1

The value of slope in each interval defined as local slope S,

$$S_i = \frac{z_i}{x_i} \qquad \text{Eq.2}$$

Cumulative head CH calculated as:

$$CH_i = \sum_i^1 H_i \qquad \text{Eq.3}$$

Where, the elevation z difference between headwork power house define as local head H of each locations, x is the slope distance along the river between powerhouse and headwork, CH is cumulative of local head H, i is number of headwork within the watershed.

$$H_i = z_i - z_{i-1} \qquad \text{Eq.4}$$

The arc length L of stream to be considered as headrace length that runs along the river and horizontal distance HL is minimum headrace length (Euclidean distance), which also allows the representation of cut-off between headwork and powerhouse. The location of powerhouses within selected circular area is displayed complying with the criteria of the location selection for one headwork shown in Figure 8-3.

The possible location of powerhouses and their route line within selected radius of headwork by selecting maximum value of three products of slope and the computation formulate as:

$$PS_j = PS_{max,i} \qquad \text{Eq.4}$$

Where, PSmax,i is maximum value of three (PSj) production of slope (i. e, three power houses), j is number of search or headworks. The idea of setting a maximum PSmax is to determine potential location in stream with in circular area. The locations of powerhouse site corresponding to maximum PSmax value is shown in Figure 8-4.

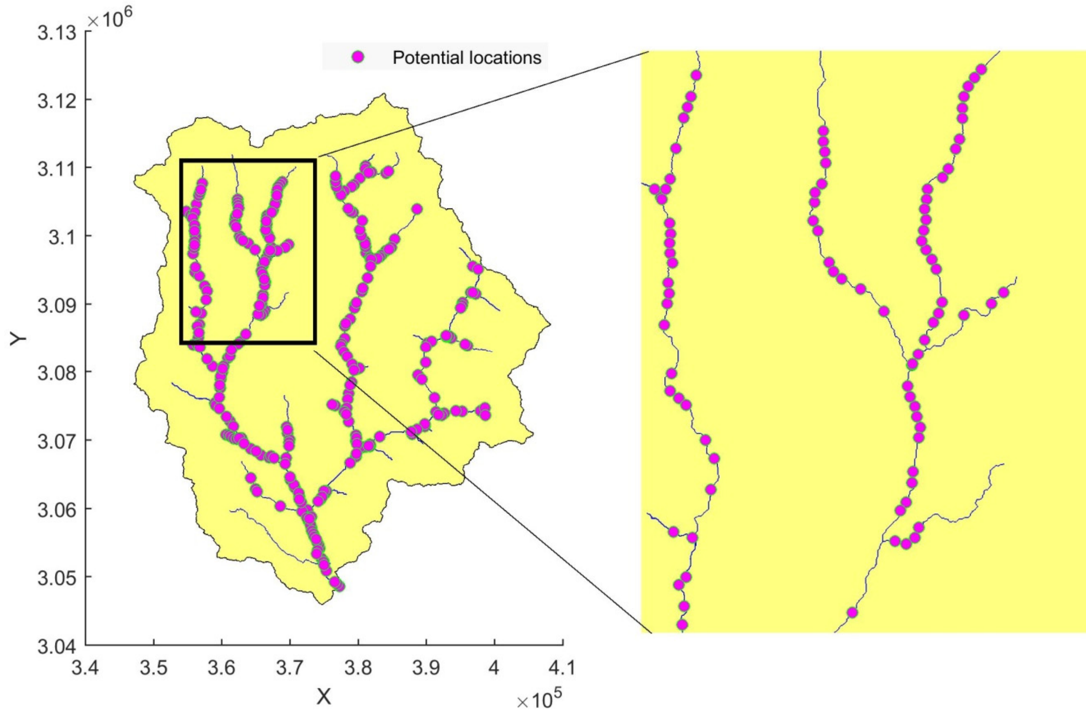


Figure 8-4: Location of Potential Sites along the streams found in this study

8.3 Economical Screening

The economical screening involves three major steps: cost estimation, Benefit assessment and economical/ financial analysis which are explained as follows:

8.3.1 Cost estimation

Hydropower projects are site specific. The project features depend upon requirement of the site so cost of different components vary from projects to projects. The components used for the cost estimation are: Weir, desander, waterway (pipe/ tunnel), Powerhouse, and Electro-mechanical equipments. The costs of these components were derived based on the relations derived in Chapter 6.

8.3.2 Assessment of project benefits:

Project benefits are calculated as revenue from energy sales. The energy sales rate provided by utility company (NEA) was used to estimate the benefits. The details are described in Chapter 6.

8.3.3 Economic analysis:

Finanacial analysis is carried out from the assessed project cost and benefits from the project. Net Present Value (NPV), Internal Rate of Return (IRR) and Benefit Cost Ratio (BC Ratio) are the financial indicators used for the assessment of the projects. A project is deemed financially feasible is NPV >0, IRR>interest rate and BC Ratio >1. The details of the financial analysis are presented in Chapter 6.

8.4 Technical Screening

Technical screening will be carried out by multi-criteria decision making tools. Kucukali (2014) lists the potential risks to the hydropower plants associated with: geology, land use and permits, environment issues, Grid connections, social acceptance, macroeconomic, natural hazards, regulatory uncertainties, access road and revenue. Although risks associated with social acceptance, land use and permits and environmental issues are identified as the most dominant ones, they require detail study for the assessment-which is not feasible to carry out at large scale study. Detail social and environment study needs to be carried while performing feasibility study of promising individual projects. The environmental sensitivness in the protected areas and their buffer zones will be however addressed.

The risks associated with macro economy and regulations is not associated with project in particular. They are associated with the political and economic landscape of the country. Since the techno-economical potential is assessed at 40% reliable flow, the risk in revenue due to hydrological variation is expected to have minor impact in this study.

Hence factors associated with geology, natural hazard, access roads are assumed to major factors governing the technical feasibility of the project. Long-term risks associated with the climate, population growth, hydropower development strategy etc is not incorporated in this study. The weightage of these parameters will be determined by the sensitivity analysis.

8.4.1 Geology

Geology has an important role in hydropower projects. It has an important implications in the project cost because the cost of foundation treatment of civil structures and most importantly the tunnel excavation is governed is governed by the geology. Himalayan geology is fragile and rocks are faulted and folded caused by compressing tectonic activities. So the geological map of Nepal prepared by Department of mines was used to extract the rock formation (Shown in Figure 8-5 and Figure 8-6). Similarly the location of major faults by Nakata (1998) was also used to determine their distance from the projects (shown in Figure 8-6). The weights provided are presented in Table 8-1.

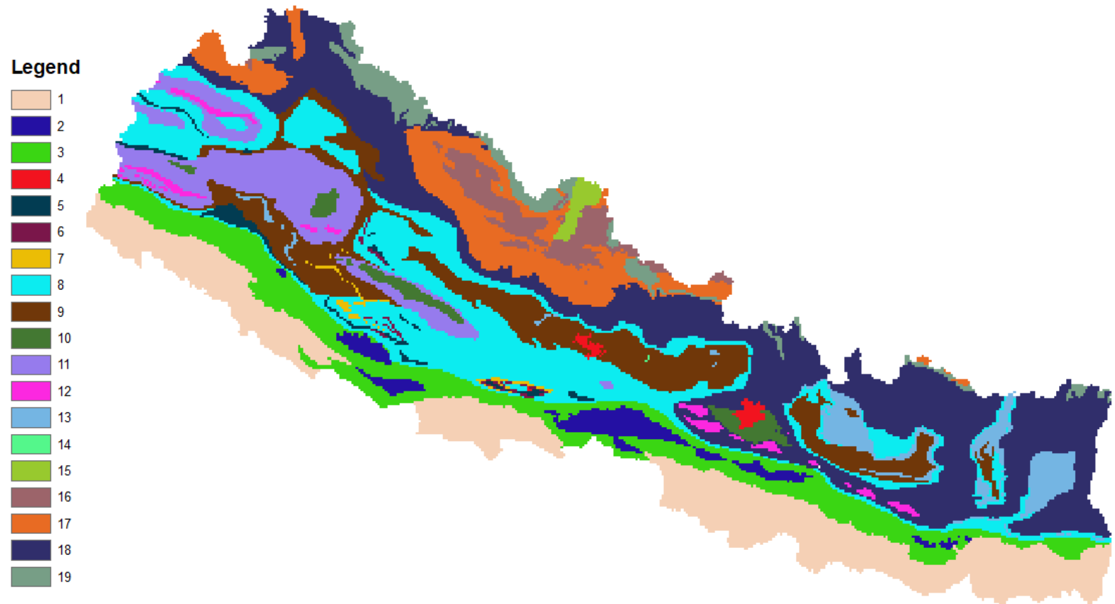


Figure 8-5: Regional geological map of Nepal

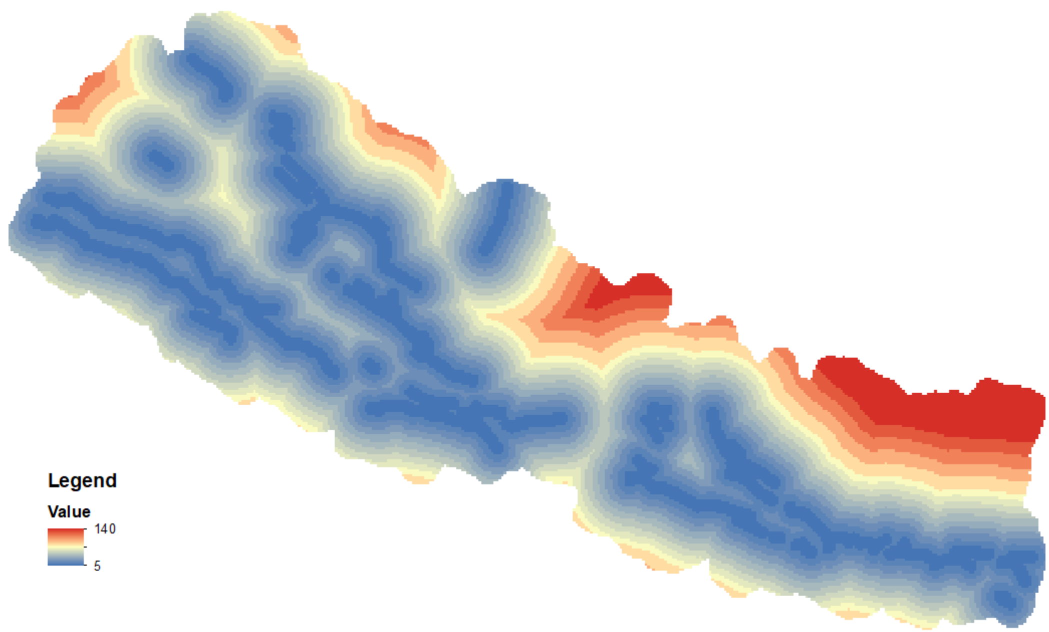


Figure 8-6: Map showing the distances from the major faults

Table 8-1: Weights and scores used for geology

Sub - criteria	Weightage	Unit	Score		
			100	50	25
Type of rock	0.5	[-]			
Distance from the major faults	0.5	km			

8.4.2 Access roads:

The impact of access roads on the projects is analysed with the following sub criteria:

i) Vicinity to the nearest road head (km/ MW)

The distance of project site from the nearest road head determines the length of the additional road that needs to be constructed to access the project site. The ability of the project to develop its own access road depends on the installed capacity of the project. In general, the project with higher installed capacity has potential to bear a longer road compared to the project with lower installed capacity. So, the distance of project from the nearest road head will be normalized by the installed capacity to remove the bias of the installed capacity. The project with short and long normalized distance will be scored high and low respectively. GIS based road network map developed by SNRTP project was used for the analysis. The buffer maps was created from the road network map (Figure 8-7) and the scores were provided as detailed in Table 8-2.

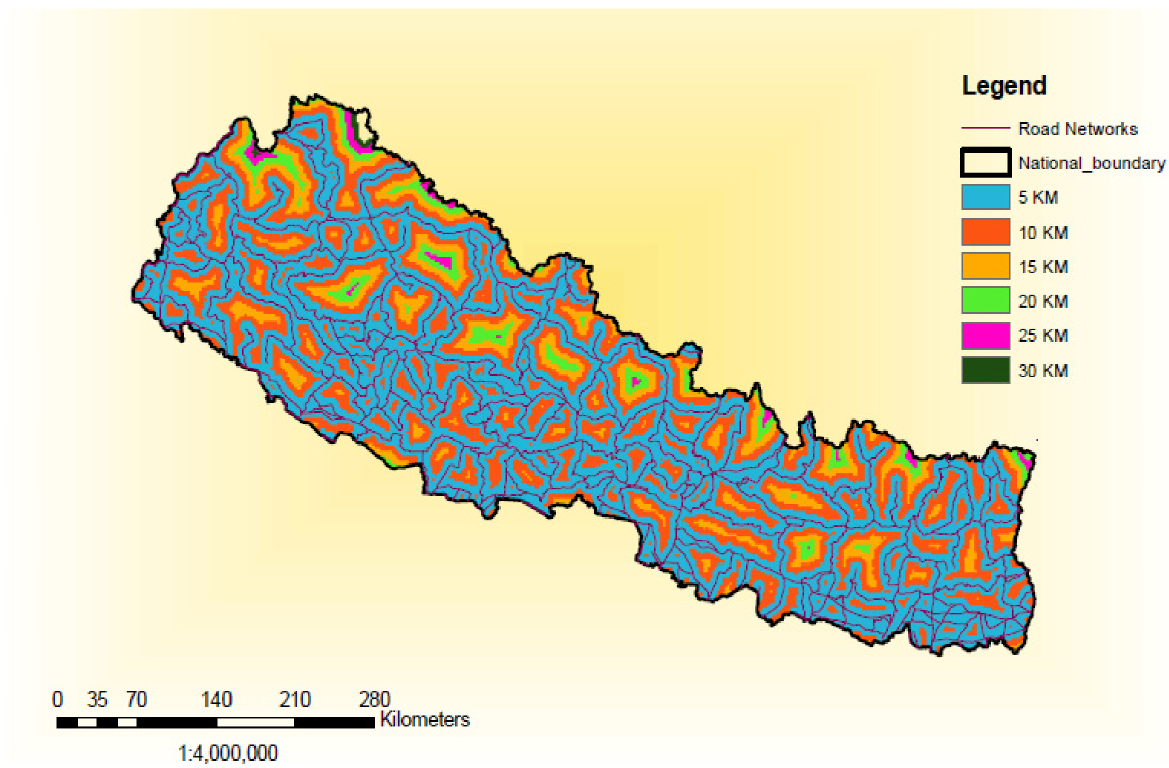


Figure 8-7: Road head map derived from road network map of SNRTP project

Table 8-2: Weights and scores used for access roads

Sub - criteria	Weightage	Unit	Score		
			100	50	25
Vicinity of the nearest road head	0.5	km/ MW			
Vicinity of the nearest Regional market	0.5	km/ MW			

ii) Vicinity of the market:

Price of construction material depends on how far the project site is located from the nearest market. This will determine the cost of haulage of materials to the project site. The project cost is determined according to the average rate of materials at the major cities of Nepal. Instead of analysing the additional cost of haulage, its impact will be assessed on the basis of scoring. The size of the project is expected to have little influence in this criteria. Projects located near and further from the principle market are scored as high and low respectively. The metropolitan and sub metropolitan cities of Nepal are referred as the principle markets. A buffer map is created to evaluate the project distance from the nearest principle markets is shown in Figure 8-8.

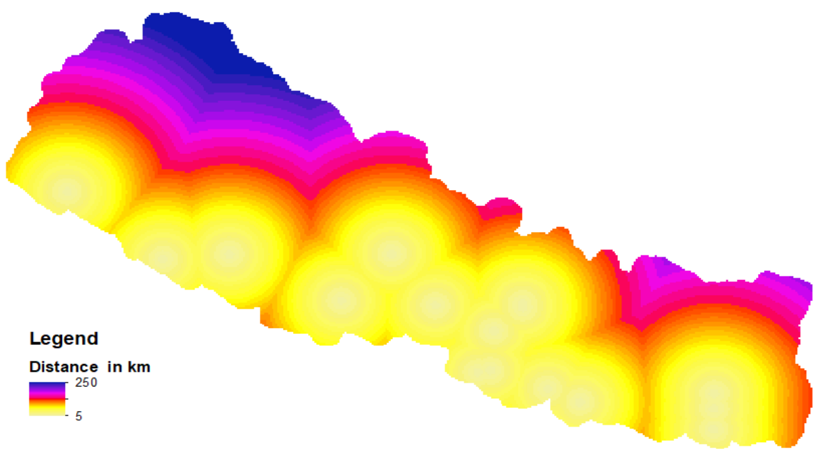


Figure 8-8: Map showing the distances from the principle markets

8.4.3 Transmission line

Major parts of the existing transmission line facilities is saturated with the haulage of existing power. It cannot be operated to haul techno-economical potential of the country, hence the identified projects will not be technically feasible due to the transmission limits. However, GON has plans to install transmission line with higher capacity which is expected to be realized in near future to meet its electricity development strategy. So, all planned and existing transmission line infrastructure are incorporated in this study. The impact of transmission line on the projects is analysed based on the vicinity to the substation. A buffer map of the transmission line distance with respect to the planned and existing substation was produced which is shown in Figure 8-9.

The project is assumed to develop its own transmission line to the nearest substation to evacuate its generated power. The ability of the project to construct its own transmission line depends upon the installed capacity of the project. A project with higher installed capacity can bear the cost of the longer transmission line whereas the project with lower installed capacity can only bear short transmission line. So, the length of the transmission line is normalized by the installed capacity to remove the installed capacity bias.

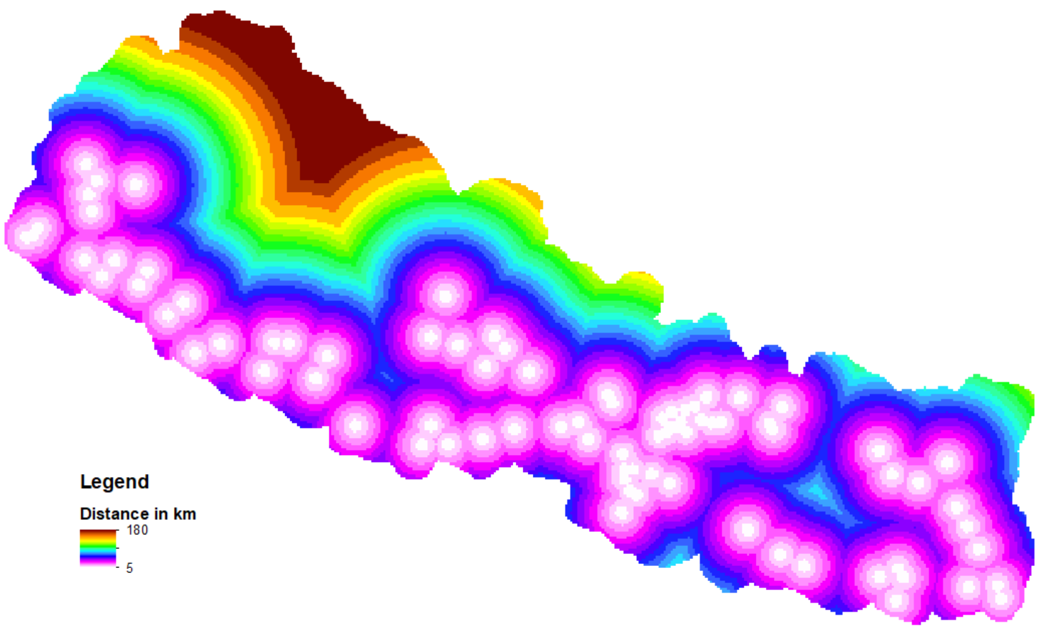


Figure 8-9: Map showing the distances from the existing and planned substations

The cost of transmission line depends upon its capacity, which is measured in kilo volts (kV). The required capacity of the transmission line is determined by the installed capacity of the project. Since, the capacity of the transmission line significantly determine its cost, the capacity biasness still exists in the normalized length. So, length of transmission lines with all other capacities are converted to equivalent length of 132 kV capacity prior to normalization. The weight assigned according to the length of the transmission line is presented in **Error! Not a valid bookmark self-reference.**

Table 8-3: Weights and scores used for transmission line

Sub - criteria	Weightage	Unit	Score		
			100	50	25
Length of transmission line (equivalent to 132 kV)/ MW	1	km/ MW	0		

8.4.4 Natural hazards

Following natural hazards will be considered as sub criteria:

i) GLOF hazard

ii) The basins which incorporate glaciers have potential GLOF hazard due to changing climate. GLOF hazard depends on the number of glacial lakes in the basin and the distance of project from those lakes. Glacier and glacial lake inventory prepared by ICIMOD is used for the analysis. The weights and scores provided in the analysis is presented in Table 8-4.

Table 8-4: Weights and scores used for GLOF and Seismic analysis

Sub - criteria	Weightage	Unit	Score		
			100	50	25
Percentage of area of glacier and glacial lakes in the catchment	0.5	[-]	0		
Earthquake hazard	0.5	PGA value			

iii) Earthquake hazard

Nepal lies along the active Main Himalayan Thrust Arc – where Indian and Eurasian plate interact – which makes it prone to earthquake hazards. Major earthquakes occurring in 700, 1100 (Lavé, 2012), 1255, 1408, 1681, 1803, 1810, 1833, 1866 and 1934 (Pandey et al., 1995) have been reported to have occurred within and close to Nepal. Recent Projects with combined installed capacity of 175 MW out of 787 MW, total installed capacity, were severely or partially damaged by the Gorkha earthquake and its aftershocks in 2015. Apart from the direct impact to the hydropower infrastructure, about 456 km of roads were affected by earthquake and earthquake induced landslides (ICIMOD 2015). The peak ground acceleration map for 63% probability of exceedance by Thapa and Wang (2011) was used in the analysis (shown in Figure 8-10). The weights and score used are presented in Table 8-4.

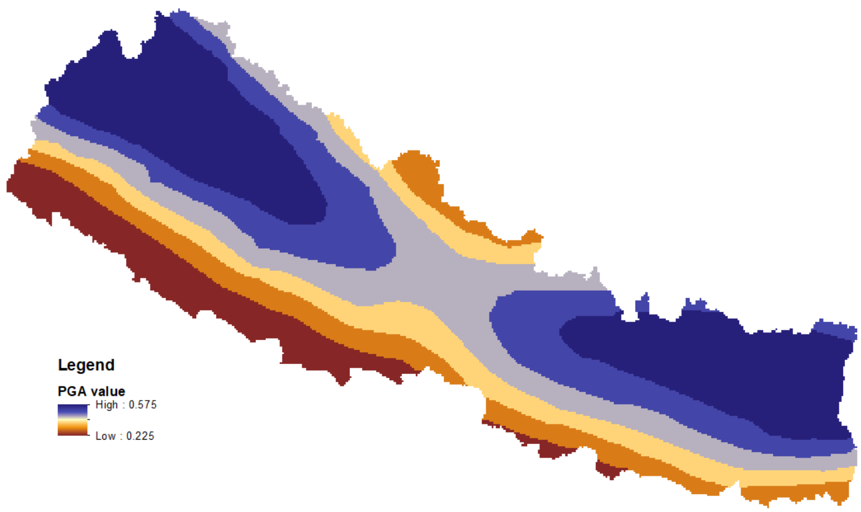


Figure 8-10: Map showing PGA at bedrock level at 63% probability of exceedence

8.5 Results and discussion

The criteria for search for the spotting tools were set as the distance between headwork and powerhouses is 500 m of intervals along all streams and tributaries, and radius is 10 km. All together 163,656 were identified in river basins of Nepal (Shown in Table 8-5). However, only 11,418 projects were observed to be economically feasible. The projects were then screened using the technical criteria, explained in Section 8.4, to obtain the technical feasible projects. A score higher than 50 was considered as techno-economically feasible projects. Only 1310 projects were observed to be techno-economically feasible. These economic feasible projects contain mutually inclusive ones. So, a basin wise optimization was carried out to select the mutually exclusive techno-economical RoR projects from the basin. After the projects are screened technical criteria's, the installed capacity of all feasible projects were added to determine the ROR Techno-Economical Hydropower Potential of Nepal. ROR Techno-Economical Hydropower Potential of Nepal was estimated as 32,680 MW.

Table 8-5: Details of the identified projects and economically feasible projects in basins

Basin	Identified projects	Economically feasible	Techno-economical feasible
Karnali	58263	3496	402
Gandaki	23568	2828	508
Koshi	21756	1653	314
Babai	4893	587	8
Bagmati	6843	753	17
East Rapti	3723	149	3
Kamala	3750	150	2
Kankai	1857	111	8

Mahakali	23226	232	26
Tinau	9213	737	4
West Rapti	6564	722	18
Total	163656	11418	1310

As an example, the spotting process, identified headworks and powerhouse locations in Bhotekoshi basin are shown in Figure 8-11, Figure 8-12 and Figure 8-13 respectively. For validation existing project locations sites for the Bhotekoshi catchment are tested in this study. These are done by plotting of there spatial geo-location into catchment map that is overlapping into calculated map of catchment. The validated plot is shown is Figure 8-14, where it can see the seven specific existing hydropower project's locations (currently running and under-construct projects). In this Figure, the red triangles indicate the high potential site calculates by stream gradient index from each search point and blue solid circular points is existing projects.

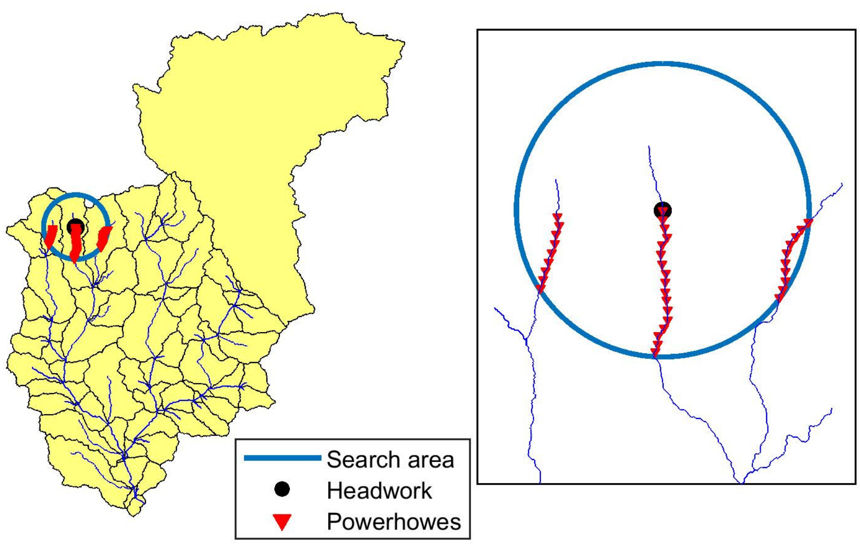


Figure 8-11: Location of study area in Nepal (left) and Bhotekoshi (right)

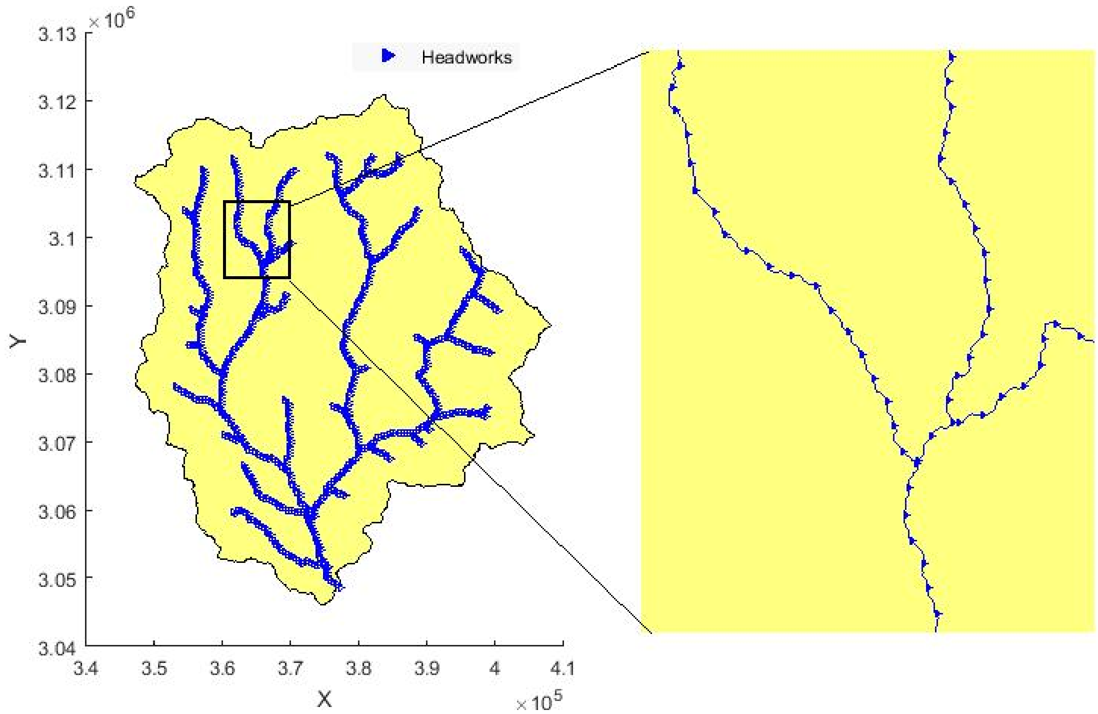


Figure 8-12: Location of Headwork along the stream networks

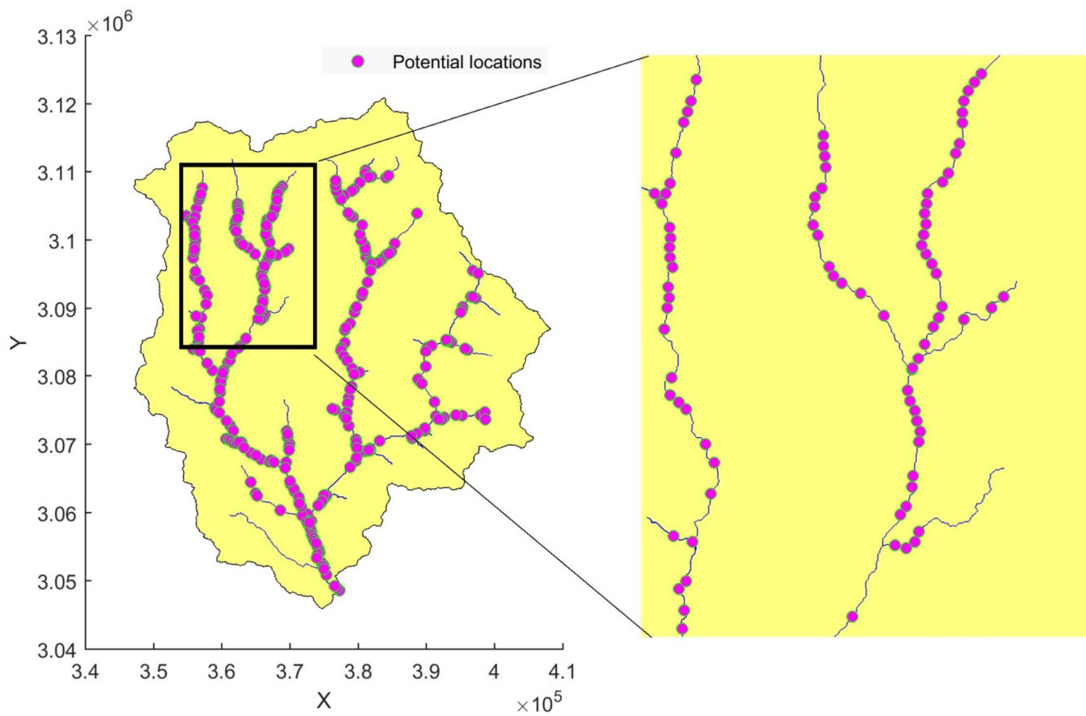


Figure 8-13: Location of Potential sites along the streams found in this study

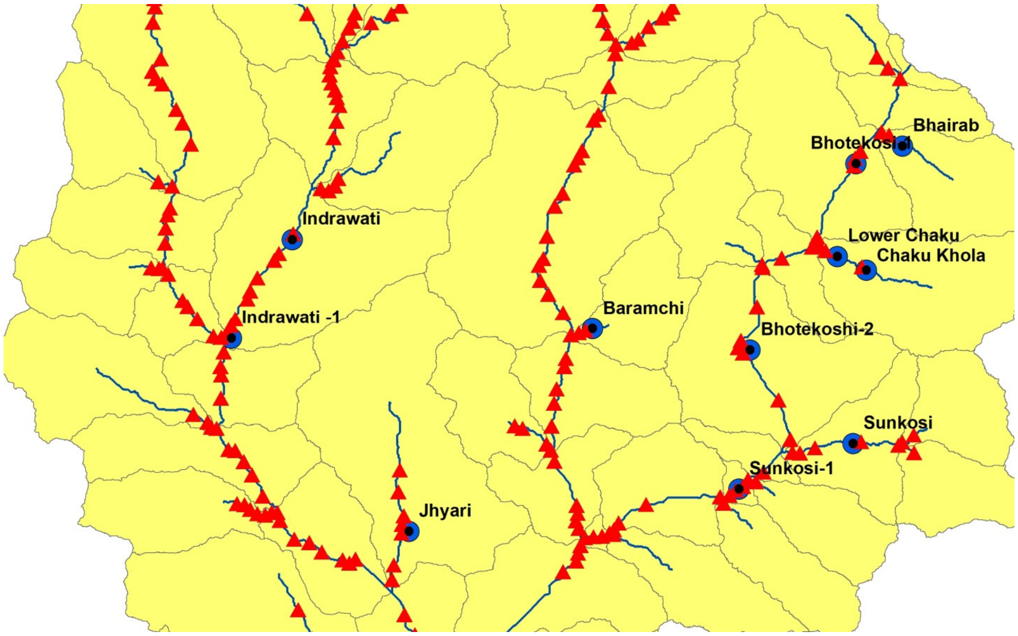


Figure 8-14: Comparison of the location of Potential sites with existing project locations

9. Run-of-the River Projects

Hydropower is power derived from the energy of water moving from higher to lower elevation. Run-off-River (ROR) hydropower schemes use the water available in the stream, without storage, to generate the power. So, the power generation from ROR plant varies according to the water availability during different seasons. Since, it is not economically feasible to harness energy from all available water in the river, the installed capacity of the plant has to be determined as tradeoff between the energy and cost of project components (which depend on design discharge). For the purpose of this study, the installed capacity is determined at 40% flow exceedance.

This chapter presents the methods adopted to identify ROR projects with installed capacity greater than 300 MW.

9.1 Methodology

The gross hydropower potential assessment showed that only limited river reaches in the Koshi, Gandaki and Karnali River had potential greater than 300 MW. So these projects were individually studied and their economic feasibility was determined.

The gross hydropower potential was computed in a river reach defined between two adjacent confluences. However, these reaches did not provide realistic project features. So, the river reaches with gross hydropower potential higher than 100 MW were first screened. This allowed combining two or more river reaches to generate 300 MW power. For example a river reach in a bend may be long and contain many confluence but is feasible for hydropower development.

The power of the selected reaches were recalculated deducting the environmental releases, incorporating head loss and electromechanical efficiencies. The river reaches (including combined ones) with power potential higher than 300 MW were then selected for the further analysis.

The sizing of project components of selected reaches were designed based on the evaluated design discharge and flood flow. The length and type of the water way is determined based on the topographic features and the cost was evaluated based on the relations derived in Chapter 6. The energy production was evaluated based on the computed monthly flow at the reach. Finally the economic analysis was carried out using the cost and revenue generated by the project.

9.2 Results

Altogether 49 projects with installed capacity greater than 300 MW were identified as economically feasible in the Koshi, Gandaki and Karnali River. The key project features of identified projects are presented in Table 9-1. The layout and other detailed features of the individual projects are presented in Appendix E.

The project features are identified using the topographic information and other available information at the basin scale. The detail features of the project will vary according to the local site conditions and the geology. A field inception of selected projects was carried out in the months of December and January to confirm the suitability of the site conditions. A summary is presented in and the details are presented in Appendix G. However, feasibility studies are required to confirm their technical and economic feasibility.

Table 9-1: Features of the identified RoR Projects with Installed capacity > 300 MW

S.N	Project Name	Installed Capacity (MW)	Design Discharge (m3/s)	Design Head (m)	Annual Energy (GWh)	Total Project Cost M NRs.)	Annual Revenue (MNRs.)	NPV (MNRs.)	IRR (%)	B/ C Ratio	RoE (%)
1	Arun 002	1069	372	335.00	5,800	180,227	34,223	79,331	14.68	1.44	31.48
2	Arun 003	512	192	156.00	2,822	95,530	16,726	28,458	13.18	1.30	26.03
3	Arun 004	623	194	188.00	3,433	125,426	20,342	22,911	11.96	1.18	21.75
4	Arun 100	545	221	159.00	3,056	108,068	18,197	17,666	11.78	1.16	19.72
5	Arun 103	362	224	103.50	2,024	66,666	12,047	22,259	13.57	1.33	27.13
6	Arun 104	513	614	89.40	2,626	207,120	13,826	(146,827)	1.68	0.29	(12.12)
7	Arun 105	412	425	74.50	2,195	107,117	11,685	(34,723)	6.40	0.68	2.29
8	Arun 200	812	168	261.00	4,400	122,981	23,318	52,826	14.58	1.43	30.88
9	Bheri 000	333	140	283.75	1,811	35,922	10,577	49,038	24.45	2.37	65.72
10	Bheri 101	336	81	493.41	1,815	35,802	9,813	41,970	22.44	2.17	58.29
11	Bheri 102	553	132	500.67	3,040	60,815	17,793	83,590	24.49	2.37	66.51
12	Bheri 103	429	179	286.34	2,344	55,055	12,693	43,443	18.38	1.79	44.15
13	Bheri 105	471	408	137.75	2,594	88,719	14,076	11,937	11.45	1.13	19.62
14	Budhi Gandaki 000	324	134	287.50	1,704	39,939	9,085	29,669	17.92	1.74	42.09
15	Budhi Gandaki 100	347	115	358.00	1,640	37,562	8,638	28,503	18.11	1.76	42.49
16	Dudh Koshi 100	323	62	623	1,635	41,477	8,666	23,689	16.11	1.57	35.58
17	Dudh Koshi 101	390	55	825	1,938	41,477	10,233	38,255	19.81	1.92	48.83
18	Dudh Koshi 102	342	45	876	1,702	31,490	9,023	40,202	23.56	2.28	61.99
19	Kali Gandaki 000	531	104	608	2,913	53,893	17,338	88,508	27.30	2.64	76.60
20	Kali Gandaki 100	563	101	663	3,082	60,264	18,334	89,391	25.63	2.48	70.64
21	Kali Gandaki 103	414	119	416	2,250	45,198	13,364	62,844	24.68	2.39	66.91
22	Kali Gandaki 104	433	288	180	2,122	65,677	11,211	15,402	12.53	1.23	23.14
23	Karnali Main 100	325	242	160	1,906	67,474	11,552	16,645	12.65	1.25	23.87
24	Karnali Main 102	1186	448	316	6,559	126,341	39,635	201,240	26.73	2.59	75.15
25	Karnali Main 103	512	697	88	2,943	117,542	17,926	10,139	10.93	1.09	18.00
26	Karnali Main 104	584	740	94	3,345	115,887	20,364	35,098	13.23	1.30	26.22
27	Karnali Main 105	440	1071	49	2,590	94,279	15,673	19,803	12.25	1.21	22.64
28	Marshyangdi 000	318	95	400	1,696	35,154	9,071	35,882	20.85	2.02	52.50
29	Marshyangdi 101	352	33	1266	1,880	32,811	10,056	48,157	25.55	2.47	69.35
30	Marshyangdi 103	328	102	384	1,743	44,645	9,320	25,668	16.14	1.57	35.85
31	Mugu Karnali 100	323	70	552	1,792	36,220	10,795	50,746	24.81	2.40	67.15
32	Mugu Karnali 101	340	51	791	1,901	38,834	11,477	53,679	24.61	2.38	66.52
33	Narayani 100	525	932	67	2,472	125,310	14,106	(36,268)	6.80	0.71	3.62
34	Sun Koshi 001	325	436	52	1,670	97,345	8,833	(48,464)	4.34	0.50	(4.34)
35	Sun Koshi 100	390	439	62	2,004	117,134	10,599	(58,131)	4.37	0.50	(4.21)
36	Sun Koshi 102	346	706	58	1,780	114,468	9,416	(65,552)	3.43	0.43	(7.14)
37	Sun Koshi 104	336	491	82	1,736	98,297	9,173	(46,485)	4.65	0.53	(3.41)

S.N	Project Name	Installed Capacity (MW)	Design Discharge (m3/s)	Design Head (m)	Annual Energy (GWh)	Total Project Cost M NRs.)	Annual Revenue (MNRs.)	NPV (MNRs.)	IRR (%)	B/ C Ratio	RoE (%)
38	Sun Koshi 105	319	397	96	1,380	88,965	7,168	(53,060)	3.09	0.40	(8.22)
39	Tama Koshi 100	328	90	435	1,568	37,728	8,773	29,632	18.38	1.79	43.59
40	Tama Koshi 101	375	131	342	1,796	87,196	9,304	(30,801)	6.05	0.65	1.03
41	Tama Koshi 200	410	52	932	1,927	34,838	9,942	44,215	23.48	2.27	61.62
42	Tamor 000	342	30	970	1,691	28,472	8,783	41,911	25.63	2.47	69.14
43	Tamor 101	349	32	1135	1,664	29,900	8,622	38,457	23.68	2.29	62.14
44	Tamor 102	328	93	312	1,638	48,377	8,520	13,186	12.94	1.27	24.38
45	Tamor 103	353	284	123	1,833	69,744	9,601	(4,884)	9.23	0.93	11.70
46	Trishuli 100	371	147	301	2,022	45,781	10,812	38,114	18.85	1.83	45.65
47	Trishuli 105	395	154	306	2,119	57,861	11,309	26,785	14.95	1.46	31.80
48	Trishuli 107	328	638	61	1,547	97,055	8,841	(48,020)	4.38	0.51	(4.23)
49	West Seti 100	486	35	1652	1,393	38,855	7,266	14,156	13.92	1.36	27.74

Table 9-2: Summary of field inception of RoR Projects with Installed capacity > 300 MW							
S. No.	**Project Name**	**Topography**		**Geology**		**DEM head (m)**	**Head observed in field (m)**
		Intake	**Powerhouse**	**Intake**	**Powerhouse**		
1	Bheri 105 RoR Project	The proposed intake site lies at Taranga, near Baraha Tal, Surkhet. The river flows in straight path with smooth flow. Sufficient space for surface structures is available at the left bank.	The proposed powerhouse site lies at left bank of Bheri River immediate u/s of its confluence with Karnali River. The flow of the river is smooth with curved path.	At the intake area, Upper Siwalik Formation of sandstone bed rock with conglomerate are exposed along the vertical scarp. The vertical scarp of about 100 m height shows unstable slope and there is a landslide just above the proposed headwork.	Powerhouse site is located on alluvial terrace of sand and gravel, sufficiently large to house powerhouse.	137	95
2	Narayani 100 RoR Project	The proposed intake site lies 500 m d/s from confluence of Seti and Trishuli River. The river flow is straight and smooth. No space is available for construction of surface structures.	Proposed powerhouse is located at Devghat area u/s of confluence of Narayani River with Kaligandaki River. Space is avaialbe for the construction of powerhouse on the right bank of the river in Devghat area of Tanahu district, but due consideration should be given to the religious	The area lies in Benighat Formation of the Lesser Himalaya Zone consisting of hard, strong quartzite with thinly foliated greenish, phyllite and slate. The joints are continuous, rough to planar and tight. The rock mass is fresh to slightly weathered. Right bank is covered with thin colluvium of steep slope	Proposed powerhouse lies on flat terrace of alluvial deposit consisting gravel and sand at Devghat area. At the right bank of Narayani River bed rock of the Siwalik rocks of sandstone and mudstone are exposed.	67	29

Table 9-2: Summary of field inception of RoR Projects with Installed capacity > 300 MW

S. No.	Project Name	Topography		Geology		DEM head (m)	Head observed in field (m)
		Intake	**Powerhouse**	**Intake**	**Powerhouse**		
			importance of the area. The river flows is smooth.	rock mass.			
3	Trishuli 107 RoR Project	The proposed intake site lies about 5 km downstream from Phisling, about 750 m downstream from the confluence of the Jawan Khola and the Trishuli. There is a suspension bridge over the Trishuli River at the site. The valley shows narrow gorge under the existing suspension bridge. No space is available for surface structures.	Proposed powerhouse site is located at Manakamana Cable Car Gate Station area along Prithivi Highway Area required for the construction of powerhouse is not available on surface on proposed left bank alignment, so underground structure is suggested.	The area lies in the Dhading Dolomite Formation, Lower Nawakot Group, the Lesser Himalaya Zone with bedrock of dolomite exposed at the both banks. The rocks are fresh to slightly weathered. Both banks are stable with precipitous peak of dolomite bed rock.	The bed rocks of quartzite, phyllite and slate are exposed in the area. An old landslide which can be active during construction period is located along Prithvi Highway. So it is recommended to shift the site to more stable area which is about 1 km upstream near the Ramilo Dada. Thin colluvium cover the bedrock in the area.	61	54
4	Tamor 103 RoR Project	The proposed intake site lies about 2 km u/s of the bridge at Mulghat on Dharan-Dhankuta Highway along the river. The intake lies between two bends of the river. There is some space	The proposed powerhouse site lies immediate u/s of confluence of Tamor River with Sunkoshi River on the left bank. The river flows in a straight path with	The area lies at Mulghat Formation, Ponsagawa Group of the Lesser Himalaya consisting schists and quartzite. Rock mass is slightly weathered to fresh. At the	The area lies at Major Quartzite, Ponsagawa Group of the Lesser Himalaya consisting fine grained white quartzite. At left and right bank of suspension bridge over	123	142

Table 9-2: Summary of field inception of RoR Projects with Installed capacity > 300 MW

S. No.	Project Name	Topography		Geology		DEM head (m)	Head observed in field (m)
		Intake	Powerhouse	Intake	Powerhouse		
		available on the left bank of the river (flood plain).	somewhat steep gradient in the area. No space for surface powerhouse is available at the proposed site.	left bank colluvial deposit covered with bedrock is present.	Tamor River, massive quartzite beds are present. The geology downstream of the suspension bridge is unstable with number of active landslides visible.		
5	Tamakoshi 101 RoR Project	The proposed intake site lies about 3.5 km u/s of the bridge at Nayapul, Dolakha on Manthanli-Charikot Highway along the river. The Tamakoshi River flows in a straight reach with generally smooth flow with few occurrences of rapid flow at the intake site. There is no space available for the construction of surface structures.	The proposed powerhouse lies d/s of the confluence of Khimti Khola with Tamakoshi River at Ambas, Ramechhap. The river flows in curved reach with high gradient and numerous rapids and falls. There is a flood plain and alluvial terrace on the right bank of the river but underground powerhouse seems more suitable from geological point of view.	The area lies at Proterozoic rocks of Lesser Himalayan Sequence. The area is located at gorge formed by steep slope of hard, very strong banded fine to medium grained gneiss.	The area lies in Proterozoic rocks consisting phyllite, quartzite, amphibolites and schist of Lesser Himalayan Sequence. Two level of alluvium terrace landform, consisting boulder, gravel and sand, along the both river banks are seen.	342	299

10. Storage Projects

10.1 Introduction

Hydropower is power derived from the energy of water moving from higher to lower elevation. On the basis of the quantity of the water available hydropower plants can be classified as run-off river plants without pondage, run-off river plants with pondage and reservoir plants. Run-off river plants without pondage do not storage water behind the dam and use water as it is available in the river. Run-off river plants with pondage allow storage of daily flow, available during the lean period of the year, behind the dam. The volume of storage is usually small and only sufficient to generate electricity during the peak periods of the day. So it is also referred as peaking run-off river plants. A reservoir type of plants allows sufficient storage behind the dam to carry over storage from the wet season to the next dry season for electricity generation.

With an average annual rainfall of about 1530 mm over the country, Nepal is generously endowed by nature in water resources. However due to high seasonal variability in rainfall, the water resources availability also has high variability. 60-90% of the total annual precipitation during monsoon (June-September) period. About 55 – 80% of the total annual run-off (225 billion cubic meters) occurs during the monsoon period, while the rest is conserved as snow and ground water which drains into the rivers during the dry season.

Nepal heavily relies on hydroelectricity with more than 90% of electricity generation comes from hydropower. Kulekhani hydropower plant, with an installed capacity of 60 MW, is the only reservoir type in the country. The remaining 673 MW of hydropower production comes from the run-off and peaking run-off plants. Due to high seasonal variability in river flow and lack of reservoir type of plants, the hydropower production drops to about 1/3rd of its total installed capacity during the dry flow season. Thus it becomes evident that reservoir type hydropower plants are required to regulate the seasonal variability in the hydropower production in Nepal.

10.1.1 Objective and Scope

The main objective of this section is to identify techno-economically feasible reservoir projects with capacity greater than 100 MW in Nepal. The scope includes:

- Identification of reservoir type projects greater than 100 MW
- Preparation of separate river-basin and physiographic maps showing the potential storage type hydropower projects

10.2 Methodology

A reservoir type of hydropower plant allows impoundment of water to enable flow regulation, on a daily basis or monthly basis, throughout a year or even on a multi-annual basis for a very large reservoir plants. The multi-annual type of reservoir type of projects require in depth analysis and detail data and is beyond the scope of this study. So this study focuses on the study of reservoir type projects enabling flow regulation in a monthly basis. The study will be carried out in two phases. The first phase will include identification of the potential reservoir projects and their rapid technical screening. More detailed technical and economic analysis of the screened projects is carried out at the second stage of the study.

The following methodology (Figure 10-1) was applied during the first stage of the study:

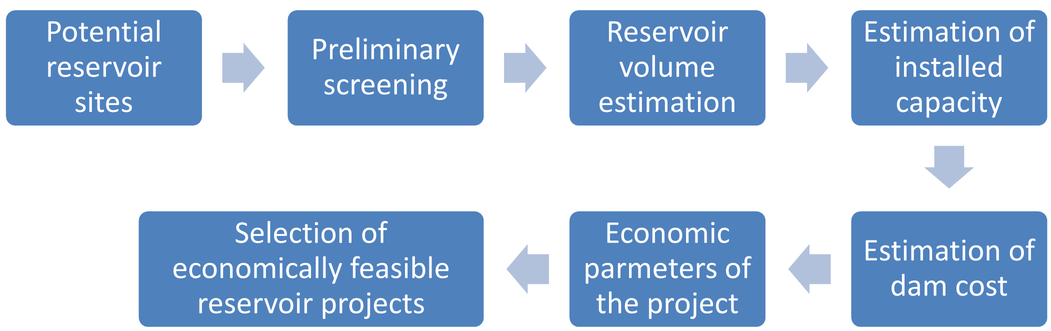


Figure 10-1: General methodology adopted for the identification of the reservoir projects

The following assumptions were further made to simplify the study:

- Powerhouse is located at the toe of the dam.
- Maximum height of the dam is assumed to be 200 m.
- 10% of the reservoir volume is assumed to be dead storage so only 90% of the water volume in the reservoir is available for the power computation.
- Water intake is located above the dead storage (10% of the height) of the reservoir.
- To accommodate the change in gross-head due to seasonal variation in reservoir volume, a constant gross-head calculated as the half of the live storage is used to compute power throughout the year.
- Evaporation and other losses from the reservoir are not taken in to account.

10.2.1 Identification of potential reservoir sites

Confluences of river and streams were considered as the preliminary reservoir sites. Confluences were extracted from the stream networks derived from the GIS. Each confluence serves as an outlet of a river/ stream reach and was treated as a unique outlet. On doing so, thousands of outlets were identified in each basin. The potential reservoir project sites considered in Gandaki basin are shown in Figure 10-2 as an example.

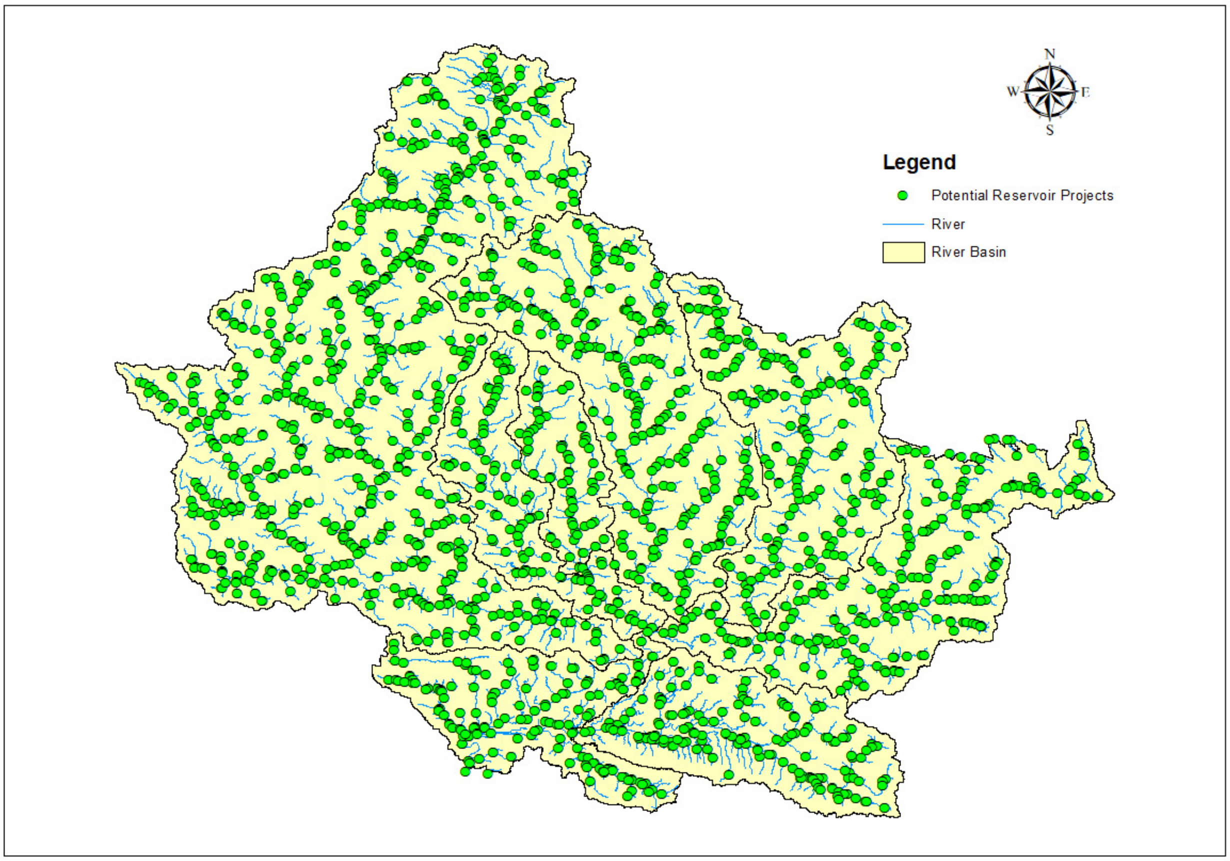


Figure 10-2: Potential Reservoir sites considered in the Gandaki River Basin

10.2.2 Preliminary screening potential reservoir sites

A storage projects requires an inundation area which can sufficiently store water. Most of the identified potential reservoir sites cannot meet such criteria. The reservoir volume estimation is computationally intensive so the identified sites have to be screened with preliminary criteria. The following criteria were used for the preliminary screening:

a) stream slope upstream of the outlet < 5%

b) elevation difference of the river reach < 200 m (smaller than the assumed maximum dam height)

c) Equivalent power using energy computed using the entire available flow is 100 MW or more on daily basis for six hours throughout the year

The reservoir projects obtained in Gandaki River basin after the preliminary screening is shown in Figure 10-3 as an example.

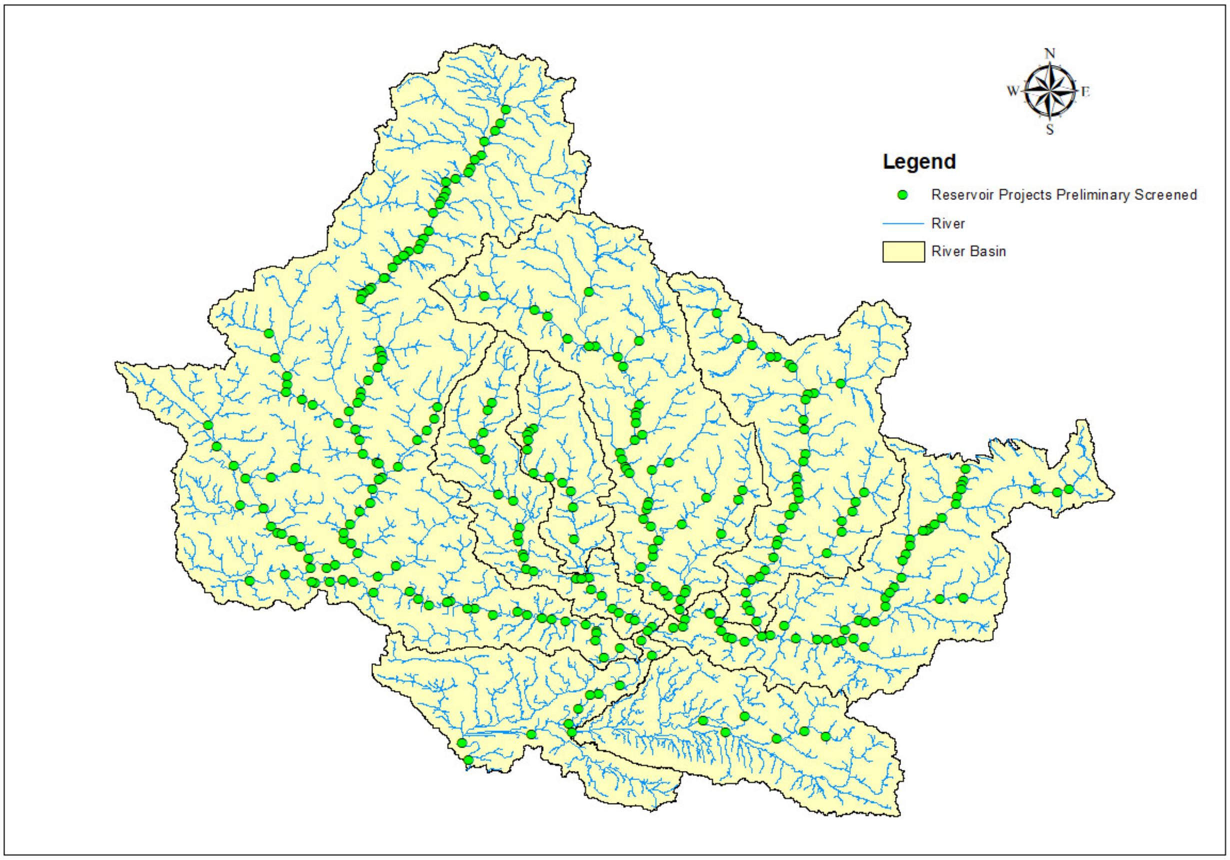


Figure 10-3: Potential Reservoir sites considered in the Gandaki River Basin after preliminary screening

10.2.3 Estimation of reservoir volume

Storage capacity were calculated from GIS Modelling with the use of Storage Capacity Tool from Spatial Analyst Supplemental Toolbox. The tool analyses the terrain and computes the volume enclosed between the terrain and the horizontal plane representing the dam height. The tool was modified to obtain the reservoir volume at different dam height. A framework applied to compute dam height vs reservoir volume curve is shown in Figure 10-4.

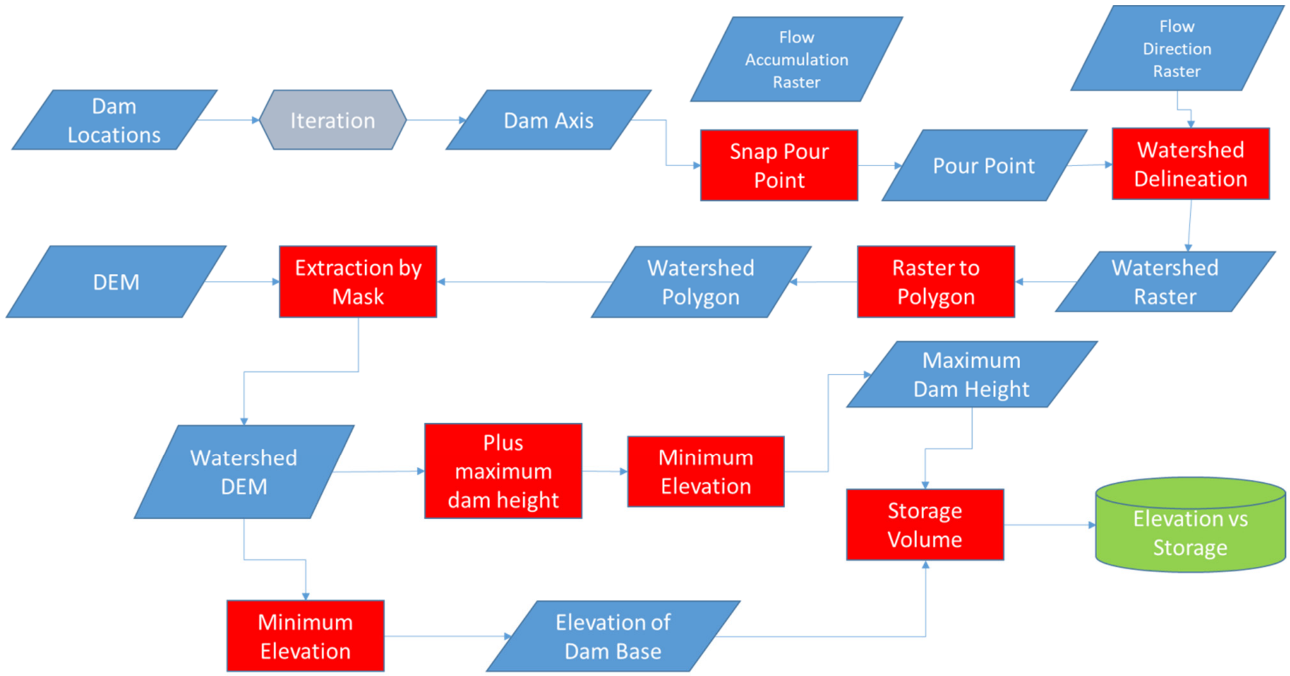


Figure 10-4: Framework adopted to compute elevation Vs reservoir volume

10.2.4 Estimation of dam material and cost

Economics of the dam, construction process and seismic performance were mainly considered in determining the type of the dam. Concrete Faced rockfill Dam (CFRD) was considered for the scope of the present study, considering its preference in a high seismic areas. A CFRD consist essentially of a zoned rockfill embankment sealed on the upstream side by a thin concrete slab which provides water impermeability to the dam. Owing to the steep upstream and downstream slopes, Concrete Faced Rockfill Dam (CFRD), are most often the cheapest type of dam. In addition to this, due to the advancement in the technology of compaction of materials, they are favorable from all technical point of view. As, all of the zoned rockfill is downstream from the water barrier, the sliding factor of safety often exceeds 7. Since all of the rockfill is dry, earthquake shaking cannot cause internal pore water pressure. The conditions of high shear strength, no pore pressure, and small settlement under seismic loading make this type of zoned rockfill inherently resistant to seismic loading.(ICOLD, 2010).

A schematic section of the CFRD consisting of sound compacted rockfill founded on a sound rock foundation is shown below. Outer slopes can be as steep as 1.3H: 1V. For a weaker rockfill and foundation, upstream and downstream slopes, zoning, drainage and construction are adapted to accommodate the weak rock. For a potentially erodible foundation, additional sealing and filter provisions are constructed downstream of the plinth. The zone designations of 1, 2, and 3 have become the standard:

• Zones 1A, 1B – concrete face protection (upstream) zones, in increasing order of maximum particle size,

• Zones 2A, 2B – concrete face supporting (downstream) zones, in increasing order of maximum particle size, these are processed granular materials, and

• Zones 3A, 3B, etc. – rockfill zones, in increasing order of maximum particle size.

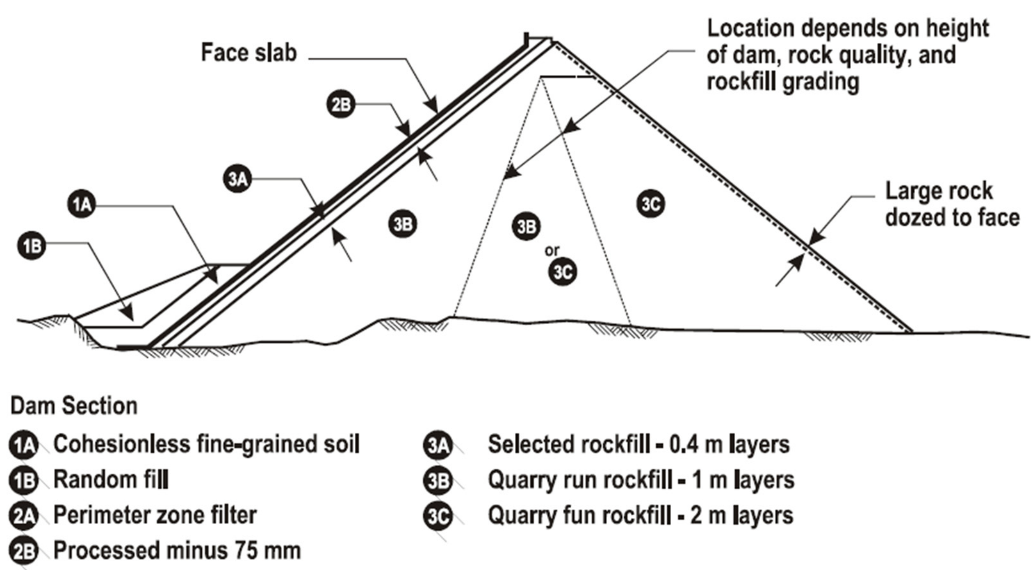


Figure 10-5: A typical section of CFRD adopted for the study (ICOLD, 2010)

The cross sectional area of each zone of materials of CFRD corresponding to each 0.5 m increase in height from the base of the abutment to the top of the crest were calculated according to the guidelines specified in the ICOLD bulletin 141, these cross sectional area were used in conjunction with the cross sectional data of the river valley at each outlet location to work out the overall dam material volume at those outlets. By treating the point with lowest elevation of each river valley as origin for that river valley, chainages at interval of 5 m left and right of the origin and their corresponding elevation values were extracted. Now, for each 20 m increase in storage height from 20 m to 200 meters, the height of dam for each chainage worked out earlier were calculated. The crest of the dam is placed 6.5 m above the FSL of the reservoir. As it is general practice in CFRDs to keep the joint between the face slab and parapet wall above the FSL, the above provision is provided accordingly. Similarly, the provision also takes into consideration the accommodation of abutment at flanks of the river valley. The average of two consecutive heights thus calculated were taken. These average heights were now compared with the heights for which the corresponding cross sectional area of different zones of material volume are known. By multiplying the cross sectional areas of different zones of dam material corresponding to the average dam height with the distance between two chainages whose heights were used to find out the average height, the volume of different zones of materials for each section were calculated. Finally the volume corresponding to same zone were added to give the total volume of different zones of a dam for different height for each outlet. The entire work of interpretation of cross section data of river valleys, comparison of dam heights with the heights corresponding to known cross sectional area of different zones of material and multiplication of cross sectional data with distances were carried out with program written in MATLAB.

10.2.5 Reservoir routing

Installed capacity of the storage project depends on the water balance in a reservoir which is governed by the interaction between the available in-flow, reservoir volume, outflow and the losses (Refer Figure 10-6). The outflowing discharge from the reservoir depends on the installed hydropower capacity of the plant. Hence the hydropower capacity of a reservoir plant has to be determined by an iterative procedure.

A simulation method was used to estimate the installed capacity of the reservoir which is described as follows:

$$V_{t+1} = V_t + Q_{in} - Q_{out} - E_t - L_t$$

V_{t+1} = Storage at the beginning of t+1th period

V_t = Storage at the beginning of tth time period

Q_t = Inflow volume during the tth time period

Q_{out} = Release volume at the t^{th} time period.

E_t = Net evaporation loss from reservoir during t^{th} period

L_t = Other losses during t^{th} period

For the simplicity, the losses from the reservoir are neglected in the computation.

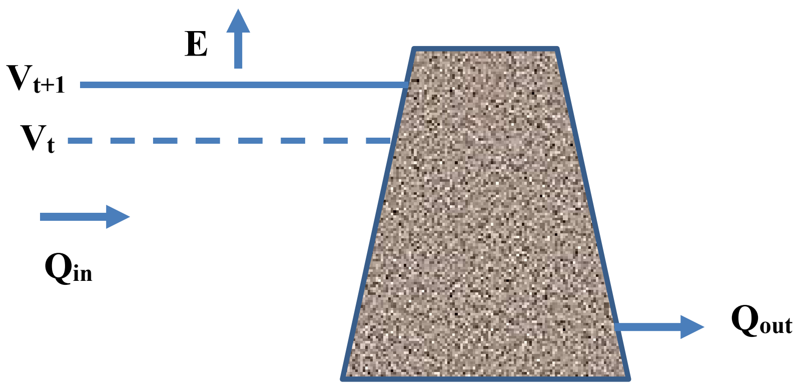


Figure 10-6: Variables determining the water balance in a reservoir

In this method, a hydrological year starts at the end of the wet season. So in case of Nepal October, which is typically the end of the monsoon season, is considered as the start of the hydrological year. Reservoir is assumed to be full at the beginning of a hydrological year. Inflowing monthly discharge is converted into inflowing monthly volume. The maximum possible monthly discharge that can be sustained for daily 6 hours peak duration throughout the year is estimated. A simulation method iterates the outlet discharge such that the reservoir volume is emptied at the end of the dry season and filled back during the wet season (as shown in Figure 10-7). Ten percentage of storage volume was considered as dead storage and only remaining volume of the reservoir was used for power generation. Mainly three criteria (consideration) were met during the calculation of maximum discharge. First, the volume of water above the maximum reservoir capacity was not taken into consideration, secondly the reservoir capacity would not deplete below the minimum active storage capacity for any month and lastly; reservoir capacity would replete to the maximum reservoir capacity before the onset of dry season. Installed Capacity of the project was then computed assuming no head loss in penstock between intake and powerhouse, while the average of active storage height added to the dead storage height was used as the head for the calculation of yearly energy generation assuming no head loss. The combined efficiency of turbine, generator and transformer was taken as 85 % for both calculation. The installed capacity and energy generation from the project was determined at all dam heights (varied between 20 m and 200 m at an interval of 20 m).

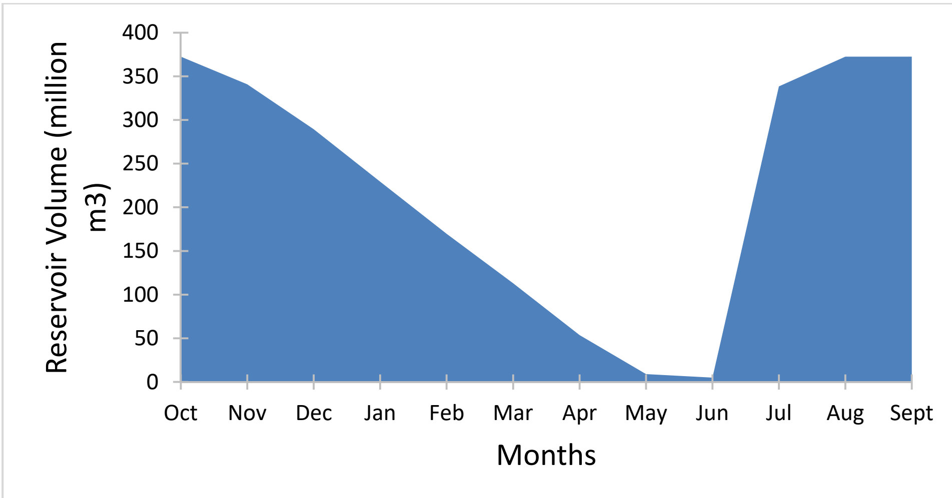


Figure 10-7: Variation of reservoir volume during a hydrological year

10.2.6 Economics and screening

Cost of materials of each zone of dam were calculated with the help of volume of materials calculated as explained above and rates of materials. Given the fact that most of the outlets are located in remote places far from city areas, higher cost of cement and reinforcement bars are considered while the labor cost and construction materials which could be found locally are considered to be slightly cheaper. The rate of materials used in the study are shown in Table 10-1.

Table 10-1: Unit rate of items used in the cost analysis

Item	Unit	Rate (NPR)	Remarks
Concrete	m^3	23260	Face slab, plinth slab, parapet wall
Sand	m^3	1000	Zone 1A
Random fill	m^3	1000	Zone 1 B
Filter material	m^3	1250/ 1300	Zone 2A, Zone 2B
Rock fill	m^3	1000	Zone 3A, Zone3B, Core, Zone 3C, D/s protection

Similarly revenues from the generated energy were calculated. For this purpose, the cost of each unit (KWh) of electricity is taken as NRs 10. Both the cost aspect and benefit aspect of all projects were expressed in Net Present Value. For this the interest rate (discount rate) was taken as 10 % and life of projects life to be 30 years. The operation and maintenance cost was taken as 10 % of yearly electricity revenue. Now the B/C ratio of every projects was calculated. No scrap value was considered in the calculation of B/C ratio.

Final screening of the projects are done on the basis of B/C ratio and Installed capacity. For the economic viability of the projects, only those projects with installed B/C ratio greater than 1.5 are taken. Similarly as the threshold of installed capacity is set at 100 MW for storage projects for the purpose of this study, only those projects with installed capacity greater than 100 MW are taken. At last the height of the dam corresponding to the best B/C ratio which is greater than 1.5 having installed capacity greater than 100 MW for each outlet is selected as the representative project for that outlet.

10.2.7 Validation

The reservoir projects identified in this study were compared with the location and capacity of the reservoir projects by Department of Electricity Development. The comparison is shown in Figure 10-8 and Table 10-2. Ten reservoir projects identified in this project lie significantly close to the ones identified in the previous studies. The installed capacity however varies which may be due to difference in the dam heights.

Table 10-2: Comparison of Reservoir project features identified in this study closer to the ones identified in the previous study

DOED Study			Current Study			
Project Code	Project Name	Installed Capacity (MW)	Reference Project Code	Project Name	Installed Capacity (MW)	Remarks
BR-3B	Bheri BR-3B	1192	KR-103241	Bheri-1	224	Newly identified project is about 2 km d/s of DOED project.
BR-5	Bheri BR-5	1269	KR-103518	Bheri-2	1754	Newly idenfified project is about 1.65 km u/s of DOED project.
KAN-CHI	Karnali Chisapani	10800	KR-103750	Karnali-1	6397	Newly identified project is about 1.5 km u/s of DOED project.
KG1-U	Kali Gandaki-1	1600	G-102611	Kali Gandaki-2	2550	Newly identified project is about 19.65 km d/s of DOED project with Ridi Khola.
KG2-U	Kali Gandaki-2	870	G-103487	Kali Gandaki-1	3889	Newly identified project is about 1.7 km d/s of DOED project.
SPG-U	Sapta Gandaki	700	G-103162	Narayani	4851	Newly identified project is about 7.2 km u/s of DOED project without Kaligandaki river.
SPK-MP-J*	Sapta Kosi Multipurpose (Indian Study)	3897	K-101351	Sapta Koshi	8181	Newly identified project is about 3.3 km d/s of DOED project with Kokaha Khola.
SR6	Seti SR-6	966	KR-102335	West Seti-1	418	Newly identified projece is about 1.7 km d/s of DOED project.
SUN2-J	Sunkosi-2 Storage (1985 Study)	1110	K-101132	Sun Koshi-1	3041	Newly idientified project is about 0.6 km d/s of DOED project.
TMR1-MP-J	Tamor-1 Storage	696	K-100664	Tamor	1706	Newly identified project is about 11 km u/s of DOED project.

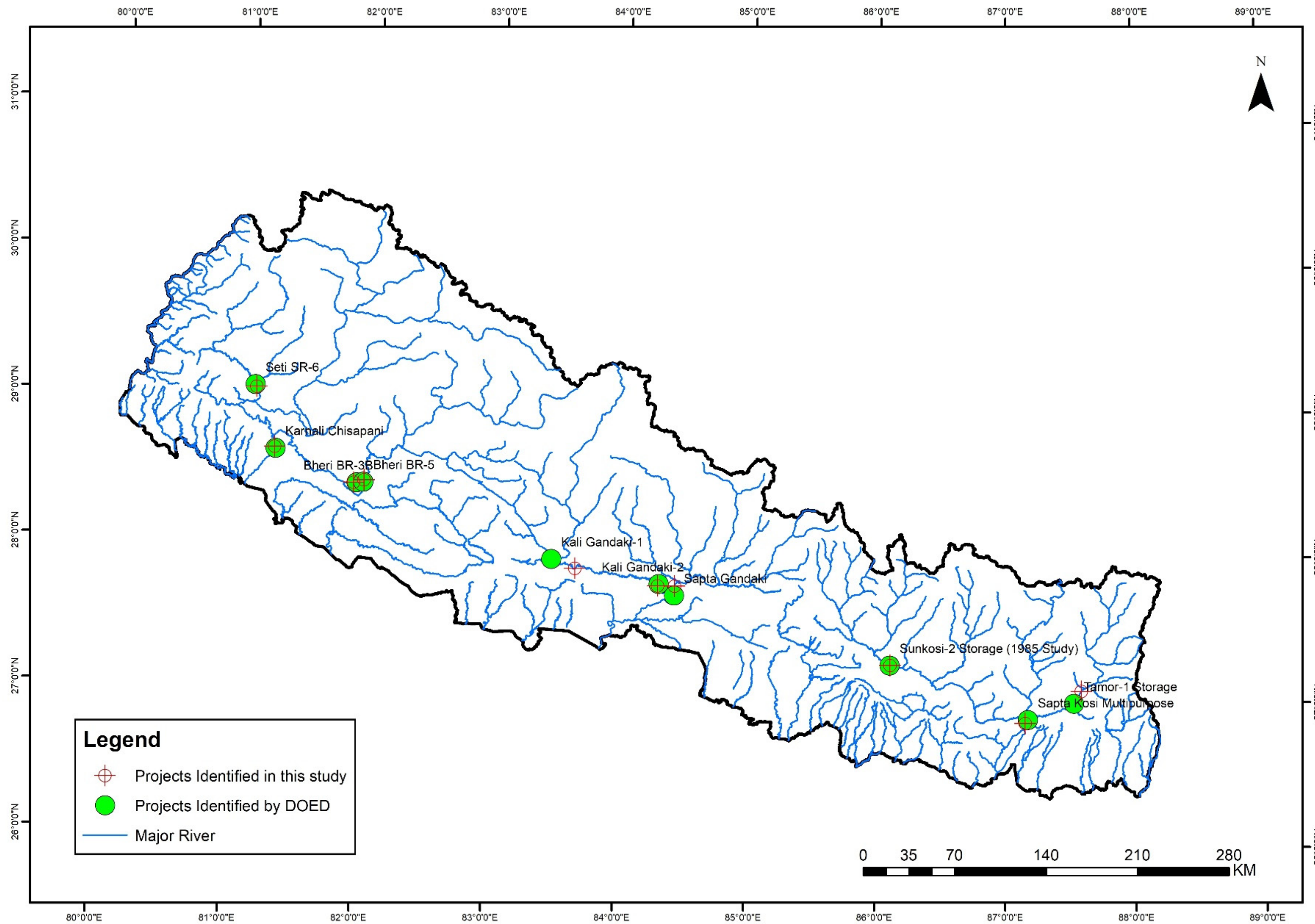


Figure 10-8: Map of reservoir projects identified closer to the ones identified in the previous studies

10.3 Results

A total number of 9, 8 and 18 reservoir projects were identified in the Koshi, Gandaki and Karnali River basins respectively. The spatial location of the identified projects are shown in Figure 10-9. The total installed capacity of the identified reservoir projects are 48,145 MW. The features of the projects in the Koshi, Gandaki and Karnali Basin are presented in Table 10-3, Table 10-4 and

Table 10-5 respectively. The details of individual projects are presented in Appendix F. A field visit was carried out in the month of December and January to carryout inception study of some of the identified storage project schemes. The summary of the field visit of the storage projects is provided in Table 10-6 and the details are provided in Appendix G.

Table 10-3: Features of the reservoir projects in the Koshi Basin

Project ID	Dam Height	Reservoir Area	Storage Volume	Installed Capacity	Energy	BC Ratio	Province	District	River Name
[-]	[m]	[km^2]	[mil m^3]	[MW]	[GWh]	[-]	[-]	[-]	[-]
Arun-1	46.5	1.1	17.63	134	161.4	1.92	Province 1	Sankhuwasabha, Bhojpur	Arun River
Arun-2	66.5	0.8	24.35	197	237.2	1.91	Province 1	Sankhuwasabha	Arun River
Arun-3	126.5	3.4	150.75	467	562.9	1.97	Province 1	Sankhuwasabha	Arun River
Arun-4	66.5	0.8	19.44	173	208.2	1.82	Province 1	Sankhuwasabha	Arun River
Arun-5	146.5	7.5	744.23	737	887.8	2.29	Province 1	Sankhuwasabha	Arun River
Sapta Koshi	206.5	166.1	11502.70	8181	9854.3	3.69	Province 1	Sunkoshi, Udayapur, Dhankuta, Khotang, Bhojpur, Sankhuwasabha, Tehrathum	SunKoshi River
Sun Koshi-1	186.5	90.4	6963.00	3041	3662.4	2.36	Province 3	Ramechhap, Sindhuli, Kavrepalanchowk, Dolakha	SunKoshi River
Sun Koshi-2	86.5	4.4	171.93	144	173.1	1.57	Province 3	Sindhupalchowk, Kavrepalanchowk	SunKoshi River
Tamor	206.5	36.2	2976.84	1706	2054.5	2.13	Province 1	Panchthar, Terhathum, Taplejung	Tamor River

Table 10-4: Features of the reservoir projects identifed in the Gandaki Basin

Project ID	Dam Height	Reservoir Area	Storage Volume	Installed Capacity	Energy	BC_Ratio	Province	District	River Name
[-]	[m]	[km^2]	[mil m^3]	[MW]	[GWh]	[-]	[-]	[-]	[-]
Budhi Gandaki-1	126.5	5.8	336.04	269	323.9	1.56	Province 3, 4	Dhading, Gorkha	Budhi Gandaki River
Budhi Gandaki-2	106.5	6.9	547.60	243	292.5	1.87	Province 4	Gorkha	Budhi Gandaki River
Kali Gandaki-1	206.5	166.3	10917.62	3889	4684.1	3.13	Province 4, 5	Nawalparasi-West, Tanahu,Syangja, Palpa	Kali Gandaki River
Kali Gandaki-2	206.5	63.3	5057.36	2550	3071.2	2.76	Province 4, 5	Syangja, Palpa, Gulmi	Kali Gandaki River
Kali Gandaki-3	206.5	44.3	3529.34	1655	1993.5	2.32	Pvovince 4	Parbat, Baglung, Myagdi	Kali Gandaki River
Marsyangdi	166.5	50.5	2569.10	960	1156.2	1.60	Province 4	Gorkha, Tanahu, Lamjung	Marsyandi River

Project ID	Dam Height	Reservoir Area	Storage Volume	Installed Capacity	Energy	BC_Ratio	Province	District	River Name
[-]	[m]	[km^2]	[mil m^3]	[MW]	[GWh]	[-]	[-]	[-]	[-]
Narayani	206.5	170.7	9373.45	4851	5843.3	3.38	Province 3, 4	Chitwan, Tanahu, Kaski, Lamjung, Gorkha, Dhading	Narayani River
Trishuli	166.5	74.1	4614.84	1494	1799.2	2.13	Province 3	Dhading, Nuwakot	Trishuli River

Table 10-5: Features of the reservoir projects identied in the Karnali Basin

Project ID	Dam Height	Reservoir Area	Storage Volume	Installed Capacity	Energy	BC_Ratio	Province	District	River Name
[-]	[m]	[km^2]	[mil m^3]	[MW]	[GWh]	[-]	[-]	[-]	[-]
Bheri-1	46.5	2.2	36.82	224	269.4	2.05	Province 6	Surkhet, Salyan	Bheri River
Bheri-2	166.5	51.7	3271.78	1754	2113.1	2.58	Province 6	Surkhet, Salyan, Jajarkot, Rukum-West	Bheri River
Bheri-3	66.5	2.7	57.66	173	208.2	1.85	Province 6	Jajarkot, Rukum-West	Bheri River
Bheri-4	66.5	1.1	37.02	149	179.0	1.56	Province 6	Jajarkot, Rukum-West	Bheri River
Bheri-5	66.5	1.0	22.72	146	175.5	1.71	Province 6	Jajarkot, Rukum-West	Bheri River
Bheri-6	66.5	0.8	26.23	139	166.9	1.64	Province 6	Jajarkot, Rukum-West	Bheri River
Humla Karnali	106.5	9.1	646.81	309	372.3	1.89	Province 6	Humla	Humla Karnali River
Karnali-1	186.5	277.4	19361.02	6397	7704.8	3.67	Province 6, 7	Kailali, Surkhet, Doti, Achham,Bardiya	Karnali River
Karnali-2	126.5	10.1	544.77	926	1114.9	2.53	Province 6, 7	Surkhet, Achham	Karnali River
Karnali-3	206.5	70.7	5181.57	2906	3499.9	2.80	Province 6	Dailekh, Achham, Kalikot	Karnali River
Karnali-4	46.5	1.1	38.48	144	173.1	1.76	Province 6, 7	Kalikot	Karnali River
Karnali-5	126.5	7.0	362.39	595	716.4	2.11	Province 6, 7	Kalikot, Bajura	Karnali River
Karnali-6	206.5	28.9	2447.41	1655	1993.5	2.36	Province 6, 7	Bajura, Mugu, Humla	Karnali River
Mugu Karnai	66.5	44.2	2375.43	140	168.6	1.84	Province 6	Mugu	Mugu Karnali River
Thuli Bheri-1	66.5	1.0	31.59	101	122.2	1.68	Province 6	Dolpa, Rukum-West	Thuli Bheri River
Thuli Bheri-2	86.5	1.4	52.62	135	162.9	1.56	Province 6	Dolpa	Thuli Bheri River
West Seti-1	106.5	11.3	383.18	418	503.3	1.73	Province 7	Achham, Doti	West Seti River
West Seti-2	186.5	34.6	2586.92	1147	1381.6	1.66	Province 7	Doti, Baitadi, Dadeldhura	West Seti River

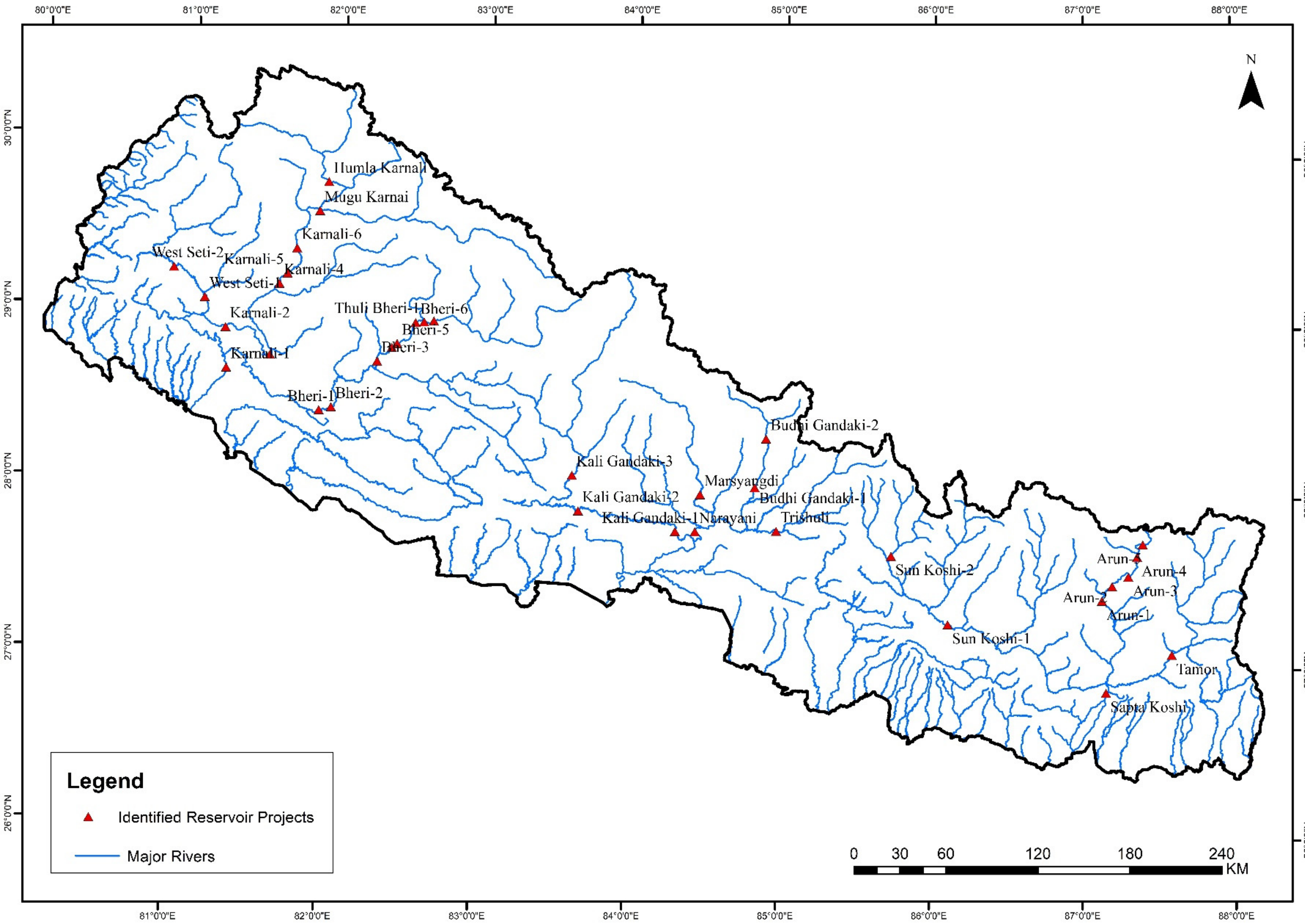


Figure 10-9: Spatial location of reservoir projects identified in this study

Table 10-6: Summary of field observations of the storage projects

S. No.	Project Name	Topography	Geology	DEM bed elevation (m)	Water surface elevation in field (m)
1	Karnali-1 Reservoir Project	The proposed dam axis lies about 3 km u/s of Karnali Chisapani Bridge along earthen Kuine Road. The river flows in a straight narrow gorge. The flow of the river is very smooth with no rapid formation.	The area lies in Middle Siwalik Formation of Siwalik Zone. Both Banks consists of bedrocks of sandstone with mudstone. The rocks are fresh to slightly weathered. The slopes are stable with no groundwater influences.	202	198
2	Bheri-2 Reservoir Project	The proposed dam axis is located at Baluwa Sangrahi, along Chinchu-Jajorkot Highway. The river flows in a curved path. The flow of the river is smooth with occasional rapids.	The area lies in Pink Quartzite Unit of Kubhinde Complex of Lesser Himalayan Zone. Both banks consists of bedrocks of Quartzite. The rocks are fresh to slightly weathered. The left bank shows unstable geology with vertical scarp.	529	505
3	Narayani Reservoir Project	The proposed dam axis lies about 3 km u/s of Dashdhunga Bridge along Narayangarh-Mugling Highway. The river flows in a straight path with smooth flow and no rapid formation.	The area lies in Dhading Dolomite Formation of Lesser Himalayan Zone. Both bank have exposed dolomite bedrocks. At a stream u/s of proposed site, Nourpul formation of phyllite and quartzite overlained by Dhading formation representing an inactive thrust can be seen. The slopes are stable with no groundwater influences.	197	192
4	Trishuli	The proposed dam axis lies about 5 km d/s of	The area lies in Tawa Khola Formation.	412	386

S. No.	Project Name	Topography	Geology	DEM bed elevation (m)	Water surface elevation in field (m)
	Reservoir Project	Galchi along Prithvi Highway. The dam axis lies between two bends of river with smooth flow. The river valley is wide at the proposed site.	Both banks consists of bedrocks of schist and quartzite covered by alluvial terrace. The slopes are stable with no ground water influences.		
5	Saptakoshi Reservoir Project	The proposed dam axis lies about 1 km d/s of Barahakhsetra at the confluence of Kosopa Khola with Saptakoshi river from right side. The river valley is wide and river flow is smooth. The stream coming from right side has high sediment yield capacity.	The Siwalik Zone bed rocks with gray colored coarse grained sandstone and variegated mudstone are present in the area. The rocks are fractured joints are weak. Numerous landslides are present on both banks from the proposed dam axis upto 1 km u/s of Barahakshetra.	120	105
6	Sunkoshi-1 Reservoir Project	The proposed dam site lies at the confluence of Bitijor Khola with Sunkoshi River about 20 km along Khurkot-Ghurmi Road from Khurkot. The river makes sharp right side bend immediately after the confluence and then flows in a straight path with occasional rapids.	The area lies in Proterozoic Undifferentiated Higher Himalayan Crystalline Zone of schist, quartzite, gneiss, migmatite. At the right bank, there is a steep dry slope hills with colluvium and alluvium mix deposit at the foot. The slopes are stable with no ground water influences.	435	428

11. Conclusion and Discussion

11.1 Conclusion

The gross hydropower potential of Nepal is estimated as 72,544 MW. Similarly the Techno-economical Hydropower potential is estimated as 32,680 MW. The discharge estimated by hydrological modelling was used to compute the power potential in Koshi, Gandaki, Karnali, Bagmati, Babai, Kankai, Tinau, West Rapti and Kanaki basins. In the case of Mechi, Bakaiya and Mhakali basins, which are ungauged, the discharge estimated by empirical method was used to compute the power potential.

Forty Nine Run-off-River projects with installed capacity greater than 300 MW were identified in the Koshi, Gandaki and the Karnali River basins. The total installed capacity of these identified projects is 21,651 MW.

Similarly 25 reservoir projects with installed capacity greater than 100 MW were identified by this study. The Koshi, Gandaki and Karnali basins incorporate 9, 8 and 18 of these projects respectively. The total installed capacity of reservoir projects is 48,145 MW.

11.2 Discussion

The Gross Hydropower Potential of different river basins determined by this study was compared with those reported in the literature. The comparison is shown in Table 11-1. The Gross Hydropower potential reported by *Jha* in Koshi, Karnali and other basins are lower than those estimated in this study. However, *Jha* reports higher power potential of Gandaki basin. Power potential of all river basins estimated by Bajracharya are higher than those computed in this study. Similarly *Prajapati* reports a higher power potential of the Karnali River basin than the current study. Compared to results of this study, Shrestha reports higher power potential in the Karnali, Gandaki and other smaller basins but lower power potential in the Koshi River basin.

Table 11-1: Comparison between the Gross Hydropower Potential in different basins of Nepal reported in the literature and current study

Basins	This study[4]	Shrestha [1966][5]	Jha [2010][4]	Prajapati [2015][4]	Bajracharya [2015][5]
Koshi	27,805	22,350	21,260		35,166
Gandaki	19,803	20,650	22,250		32,086

[4] Computed at 40% dependable flow
[5] Computed at mean annual discharge

Karnali	21,306	32,010	19,576	23,109	25,755
Other basins[6]	4,551	8,171	4,209		10,334

It should be noted that the figures reported in the literature are computed under different assumptions than this study. *Shrestha [1966]* and *Bajracharya [2015]* estimated the power potential at mean annual flow whereas *Jha [2010]* and *Prajapati [2015]* used 40% dependable flow (similar to this study). Mean annual flow is higher than the 40% dependable flow. *Jha* and *Prajapati* estimated the power potential considering the electromechanical efficiency. So the figures presented in column 4 and 5 of Table 11-1 are converted to 100% efficiency in order to compare with the results of this study. Electro-mechanical efficiency used in Shrestha's study is conflicting in the literature. *Bajracharya [2015]* reports the use of 80% efficiency whereas Jha *[2010]* reports the use of 100% efficiency in Shrestha's study. Although Shrestha's 1966 work could not be accessed for the verification, Shrestha states in his recent article that "… take in to account overall power/ energy of all the water flowing in the Nepal territory…" (Shrestha, 2016) which indicates that 100% efficiency might have been used. So this study assumes that *Shrestha's* [1966] estimation was based on 100% efficiency.

The study is carried out using the ASTER-GDEM terrain data at a spatial resolution of 30 m. Although the validation of gross-heads showed acceptable results, the estimation can be improved using more accurate and refined commercial DEM data.

The hydrological modelling in this study could not be carried out in refined details, due to the time limitations. A fine scale modelling of individual basins will require months. So, refining the hydrological models can improve the accuracy of discharge estimations and thus improve the accuracy of the power potential estimations as well.

The ROR projects and reservoir projects are identified based on the topographic information only. The location of the project components depend on the topographic condition and geological condition of the site. Although field visit was carried out to verify the layout of some of the projects, projects identified in this projects should be further studied in detail to determine their techno-economical feasibility.

[6] The Gandaki River is excluded from the calculation

References

Alterach, J., Peviani, M., Davitti, A., Vergata, M., 2009. EVALUATION OF THE RESIDUAL POTENTIAL HYDROPOWER PRODUCTION IN ITALY. Hydropower Dams 5.

Alvarado-Ancieta, C.A., 2009. Estimating the costs of E & M equipment. Int. Water Power Dam Constr.

Andaroodi, M., 2006. Standardization of civil engineering works of small high-head hydro- power plants and development of an optimization tool. Ecole Polytechnique Fédérale de Lausanne.

Arefiev, N., Badenko, N., Ivanov, T., Kotlyar, S., Nikonova, O., Oleshko, V., 2015a. Hydropower Potential Estimations and Small Hydropower Plants Siting: Analysis of World Experience. Appl. Mech. Mater. 725–726, 285–292. doi:10.4028/www.scientific.net/AMM.725-726.285

Arefiev, N., Nikonova, O., Badenko, N., Ivanov, T., Oleshko, V., 2015b. Development of Automated Approaches for HydropowerPotential Estimations and Prospective Hydropower Plants Siting 2, 41–50. doi:10.17770/etr2015vol2.260

Bajracharya, I., 2015. Assessment of Run-Of-River Hydropower Potential and Power Supply Planning in Nepal using Hydro Resources. Institut für Energietechnik und Thermodynamik, eingereicht an der Technischen Universität Wien.

Bajracharya, R.B., 1994. Preliminary seismic risk evaluation of Nepal. Individ. Stud. by Particip. to Int. Inst. Seismol. Earthq. Eng. 30, 113–127.

Ballance, A., Stephenson, D., Chapman, R., Muller, J., 2000. A geographic information systems analysis of hydro power potential in South Africa. J. Hydroinformatics 2, 247–254.

Bharati, L., Gurung, P., Maharjan, L., Bhattarai, U., 2016. Past and future variability in the hydrological regime of the Koshi Basin, Nepal. Hydrol. Sci. J. 61, 79–93. doi:10.1080/02626667.2014.952639

DMG, D. of M. and G., 1994. Geological map of Nepal.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Eickemeier, P., Matschoss, P., Hansen, G., Kadner, S., Schlömer, S., Zwickel, T., Stechow, C. Von, 2011. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press. doi:10.5860/CHOICE.49-6309

Emerson, D., Vecchia, A., Dahi, A., 2005. Evaluation of Drainage-Area Ratio Method Used to Estimate Streamflow for the Red River of the North Basin , North Dakota and Minnesota Scientific Investigations Report 2005 – 5017 Evaluation of Drainage-Area Ratio Method Used to Estimate Streamflow for th, Scientific Investigations Report.

Feizizadeh, B., Haslauer, E.M., 2012. GIS-based procedures of hydropower potential for Tabriz basin, Iran, in: GI_Forum 2012: Geovizualisation, Society and Learning. pp. 495–502.

Gordon, J.L., 1983. Powerhouse concrete quantity estimates. Can. J. Civ. Eng. 10, 271–286.

Hall, D.G., Cherry, S.J., Reeves, K.S., Lee, R.D., Carroll, G.R., Sommers, G.L., Verdin, K.L., 2004. Water Energy Resources of the United States with Emphasis on Low Head/Low Power Resources.

Hannah, D.M., Kansakar, S.R., Gerrard, A.J., Rees, G., 2005. Flow regimes of Himalayan rivers of Nepal: Nature and spatial patterns. J. Hydrol. 308, 18–32. doi:10.1016/j.jhydrol.2004.10.018

ICIMOD, I.C. for I.M.D., 2011. Glacial lakes and glacial lake outbursts floods in Nepal. Kathmandu.

ICOLD, 2010. Concrete face rockfill dams: Concepts for design and construction. CIGB - Bull. 141 408.

IEA, 2015a. Energy and Climate Change. World Energy Outlook Spec. Rep. 1–200. doi:10.1038/479267b

IEA, 2015b. World Energy Outlook 2015 Factsheet, Global energy trends to 2040:The energy sector and climate change in the run-up to COP21. doi:10.1787/20725302

IHA, 2016a. A breif history of hydropower [WWW Document]. URL http://www.hydropower.org/a-brief-history-of-hydropower (accessed 6.28.16).

IHA, 2016b. Hydropower Status Report.

IRENA, 2012. Hydropower.

Jha, R., 2010. Total Run-of-River type Hydropower Potential of Nepal. Hydro Nepal J. Water, Energy Environ. 8–13. doi:10.3126/hn.v7i0.4226

Khatri, P., Khadka, S., Bhattarai, U., Prajapati, R., 2014. Standardization and Development of Civil Design Framework for Small Hydropower Project in Nepal, in: Rentech Symposium Compendium. pp. 66–71.

Kucukali, S., 2014. Risk Assessment in Hydroenergy Projects: Learning from Experts and Data, in: Leal Filho, W. (Ed.), Handbook of Renewable Energy. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–17. doi:10.1007/978-3-642-39487-4_5-1

Lavé, J., 2012. Evidence for a Great Medieval Earthquake (È 1100 A . D .) in the Central Himalayas , Nepal. Science (80-.). 1302, 1302–1305. doi:10.1126/science.1104804

Le Fort, P., 1975. Himalayas: the collided range. present knowledge of the continental arc. Am. J. Sci.

Mool, P.K., Maskey, P.R., Koirala, A., Joshi, S.P., Wu, L., Shrestha, A.B., Eriksson, M., Gurung, B., Pokharel, B., Khanal, N.R., Panthi, S., Adhikari, T., Kayastha, R.B., Ghimire, P., Thapa, R., Shrestha, B., Shrestha, S., Shrestha, R.B., 2011. Glacial Lakes and Glacial Lake Outburst Floods in Nepal, Icimod. doi:978 92 9115 193 6

Mukherjee, S., Joshi, P.K., Mukherjee, S., Ghosh, A., Garg, R.D., Mukhopadhyay, A., 2012. Evaluation of vertical accuracy of open source Digital Elevation Model (DEM). Int. J. Appl. Earth Obs. Geoinf. 21, 205–217. doi:10.1016/j.jag.2012.09.004

NEA, 2017. Annual Report of Nepal Electricity Authority, Nepal Electricity Authority. doi:10.1017/CBO9781107415324.004

Palomino Cuya, D.G., Brandimarte, L., Popescu, I., Alterach, J., Peviani, M., 2013. A GIS-based assessment of maximum potential hydropower production in La Plata basin under global changes. Renew. Energy 50, 103–114. doi:10.1016/j.renene.2012.06.019

Pandey, M.R., Tandukar, R.P., Avouac, J.P., Lavé, J., Massot, J.P., 1995. Interseismic strain accumulation on the Himalayan crustal ramp (Nepal). Geophys. Res. Lett. 22, 751–754. doi:10.1029/94GL02971

Pradhan, P.M.S., 2009. Hydropower Development, in: Dhungel, D.N., Pun, S.B. (Eds.), The Nepal--India Water Relationship: Challenges. Springer Netherlands, Dordrecht, pp. 125–151. doi:10.1007/978-1-4020-8403-4_5

Prajapati, R.N., 2015. Delineation of Run of River Hydropower Potential of Karnali Basin- Nepal Using GIS and HEC-HMS. Eur. J. Adv. Eng. Technol. 2(1), 50–54.

Punys, P., Dumbrauskas, A., Kvaraciejus, A., Vyciene, G., 2011. Tools for Small Hydropower Plant Resource Planning and Development: A Review of Technology and Applications. Energies 1258–1277. doi:10.3390/en4091258

REN21, 2016. Renewables 2016 - Global status report.

Setiawan, D., 2015. Potential Sites Screening for Mini Hydro Power Plant Development in Kapuas Hulu , West Kalimantan : a GIS approach. Energy Procedia 65, 76–82. doi:10.1016/j.egypro.2015.01.034

Shrestha, H.M., 2016. Exploitable Potential, Theoretical Potential, Technical Potential, Storage Potential and Impediments to Development of the Potential: The Nepalese Perspective. Hydro Nepal J. Water, Energy Environ. 1–5. doi:10.3126/hn.v19i0.15340

Shrestha, H.M., 1966. Cadastre of Potential Hydropower Resources in Nepal. Moscow Power Institute.

Singal, S.K., Saini, R.P., Raghuvanshi, C.S., 2010. Energy for Sustainable Development Analysis for cost estimation of low head run-of-river small hydropower schemes. ESD 14, 117–126. doi:10.1016/j.esd.2010.04.001

Singhal, M.K., Kumar, A., 2015. Optimum Design of Penstock for Hydro Projects. Int. J. Energy Power Eng. 4, 216. doi:10.11648/j.ijepe.20150404.14

Tachikawa, T., Kaku, M., Iwasaki, A., Gesch, D., Oimoen, M., Zhang, Z., Danielson, J., Krieger, T., Curtis, B., Haase, J., Abrams, M., Crippen, R., Carabajal, C., 2011. ASTER Global Digital Elevation Model Version 2 – Summary of Validation Results, NASA Land Processes Distributed Active Archive Center and the Joint Japan-US ASTER Science team. doi:10.1017/CBO9781107415324.004

Thapa, R.D., Wang, G., 2013. Probabilistic seismic hazard analysis in Nepal. Earthq. Eng. Eng. Vib. 12, 577–586. doi:10.1007/s11803-013-0191-z

Upreti, B.N., Kumahara, Y., Nakata, T., 2007. Paleoseismological study in the Nepal Himalaya—Present status 1–9.

Upreti, B.N., Le Fort, P., 1999. Lesser Himalayan crystalline nappes of Nepal: Problems of their origin, in: Special Paper 328: Himalaya and Tibet: Mountain Roots to Mountain Tops. Geological Society of America, pp. 225–238. doi:10.1130/0-8137-2328-0.225

USDA, 2004. Hydrology National Engineering Handbook Chapter 11.

Varis, O., Kummu, M., Härkönen, S., Huttunen, J.T., 2012. Greenhouse Gas Emissions from Reservoirs, in: Tortajada, C., Altinbilek, D., Biswas, K.A. (Eds.), Impacts of Large Dams: A Global Assessment. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 69–94. doi:10.1007/978-3-642-23571-9_4

WECS, 2011. Water resources of Nepal in the context of climate change.

WECS, 2005. National Water Plan, Government of Nepal, Water and Energy Commission Secretariat (WECS), Kathmandu.