Dissertation

Assessment of Run-Of-River Hydropower Potential and Power Supply Planning in Nepal using Hydro Resources

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Abstract

The basic premise for the development of water resources in the country is the availability of accurate and reliable information about the resources. Nepal is rich in water resources but, lacks the reliable information about the hydro potential. The first estimation of the theoretical hydro potential was done about 5 decades ago with limited data and analysis tools. Since then very few studies have been done in this field. Therefore, the first part of this study estimates the theoretical run-of-river hydropower potential of Nepal. A GIS-based spatial tool and SWAT (Soil and Water Assessment Tool) hydrological model have been used to estimate hydro potential. The estimated total theoretical run-of-river hydro potential of Nepal is 119,185 MW at 30% flow exceedance and 103,341 MW at annual mean flow. Although large numbers of hydropower plants are currently under-construction, it is unlikely that the growing electricity demand in the country can be met from these power plants at the current rate of development. Therefore, the second part of this study deals with the power generation and expansion planning of Nepal for the period 2015-2030. The modeling tool, LEAP (Long-range Energy Alternative Planning), has been used for this purpose. The major problems associated with the development of transmission lines in Nepal are discussed.

The critical issue to be addressed by the government and politicians to end the power crisis in the country is the development of transmission lines besides developing the new power plants. Therefore, the first priority has to be given towards the completion of under-construction transmission lines in the major power corridors where hydro projects are being developed and new hydro projects are being planned to build. This will not only connect the hydro projects currently under-construction in the national grid of the country, but also, attracts new investment in the hydro power sector which will help develop power capacity to meet the future electricity demand.

The reduction of transmission and distribution losses plays a significant role in the supply side management. The required power plant capacity decreases significantly when the system loss is reduced. The study shows that electricity mix has to be used in the power supply planning to meet the future electricity demand. The current trend of run-of-river based hydropower development has to be changed and the priority has to be given in the development of storage type hydropower. Other renewable energy sources such as solar and wind, have to be used in the power generation. Furthermore, the result shows that the current rate of power capacity development will not be enough even to meet the base case electricity demand. The timely development of transmission lines, construction of new power plants with a suitable electricity mix and reduction of power losses in the system are the key points to meet the future electricity demand and end the power crisis in the country.

Kurzfassung

Die Grundvoraussetzung für die Erschließung von Wasserressourcen eines Landes ist die Verfügbarkeit von genauen und zuverlässigen Informationen über die Ressourcen. Nepal ist reich an Wasserressourcen, jedoch fehlt es an zuverlässigen Informationen über das Wasserkraftpotential. Die erste Schätzung des theoretischen Wasserkraftpotentials wurde vor ca. 5 Jahrzehnten mit begrenzten Daten und Analysehilfsmittel erstellt. Da seitdem nur sehr wenige Studien in diesem Bereich durchgeführt wurden, behandelt der erste Teil dieser Studie die Abschätzung des theoretischen Laufwasserkraftwerkpotentials in Nepal. Ein GIS-basiertes Raumgerät und ein hydrologisches Soil and Water Assessment Tool (SWAT) Modell wurden verwendet um das Wasserkraftpotential abzuschätzen. Einer Abschätzung zur Folge beträgt das totale theoretische Laufwasserkraftpotential in Nepal 119.185 MW bei 30% sicherem Zufluss und 103.341 MW bei Jahresmittelfluss. Obwohl derzeit einige Wasserkraftwerke gebaut werden, ist es unwahrscheinlich, dass der steigende Strombedarf im Land durch die Kraftwerksparkerweiterung abdeckt werden kann. Darum wird im zweiten Teil der Studie auf die Stromerzeugung und die Ausbauplanung in Nepal im Zeitraum von 2015 bis 2030 eingegangen. Hierfür wurde die Modellierungssoftware Long-range Energy Alternative Planning (LEAP) eingesetzt. In weiterer Folge wird das damit verbundene Problem des Ausbaus des Übertragungsnetzes erörtert.

Der kritische Punkt der von der Regierung zeitnah angegangen werden muss um die Elektrizitätskrise im Land zu beenden, ist der Ausbau des Übertragungsnetzes neben der Entwicklung neuer Kraftwerke. Erste Priorität hat der rasche Ausbau des Übertragungsnetzes im Bereich der sich im Bau befindlichen Wasserkraftwerke und dort wo weitere Projekte geplant sind. Dadurch werden nicht nur die sich im Bau befindlichen Kraftwerke ans Netz angeschlossen, sondern ebenfalls neue Projekte attraktiver, was in weiterer Folge dazu beiträgt, die installierte Leistung zu erhöhen um den Strombedarf abdecken zu können.

Im Versorgungsmanagement spielt die Reduktion der Übertragungs- und Verteilungsverluste eine bedeutende Rolle, da die erforderliche installierte Leistung signifikant reduziert werden kann, falls die Systemverluste abnehmen. Die Studie zeigt, dass ein Elektrizitätsmix im Versorgungssystem eingesetzt werden muss um den Bedarf abdecken zu können. Der aktuelle Trend hin zu Laufwasserkraftwerken muss zu Gunsten des Ausbaus von Speicherkraftwerken und anderen erneuerbaren Energieträger wie Wind und Photovoltaik geändert werden. Des Weiteren zeigen die Ergebnisse, dass die momentane Entwicklungsrate der installierten Leistung auch nicht ausreicht um den Basisfall-Strombedarf abzudecken. Der zeitgerechte Ausbau des Übertragungsnetzes, die Errichtung zusätzlicher Kraftwerke im Rahmen eines passenden Energiemix und die Reduktion der Systemverluste sind die Schlüsselstellen um den künftigen Elektrizitätsbedarf abdecken zu können und die Stromkrise zu beenden.

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Abbreviations

ADB	Asian Development Bank
ASTER GDEM	Advanced Space borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DOED	Department of Electricity Development
E & M	Electrical and Mechanical
EFOM	Energy Flow Optimization
EIA	Environmental Impact Assessment
EMS	Electricity Mix Scenario
ENEP	Energy and Power Evaluation Program
FDC	Flow Duration Curve
FDI	Foreign Direct Investment
GDP	Gross Domestic Product
GeoSFM	Geospatial Stream Flow Model
GHG	Green House Emission
GIS	Geographical Information System
GoN	Government of Nepal
GWh	Giga Watt-hour
H_2O	Water
HEC-HMS	Hydrologic Engineering Center-The Hydrologic Modeling System
HEP	Hydroelectric Project
HRU	Hydrologic Response Unit
IEE	Initial Environmental Evaluation
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
LDC	Load Duration Curve
LEAP	The Long -range Energy Alternatives Planning System
MAED	The Model for Analysis of Energy Demand
MARKAL	MARKet Allocation
masl	Meters above sea level
MESAP	The Modular Energy System Planning
MESSAGE	The Model for Energy Supply Systems and Their General Environmental Impact
MOWR	Ministry of Water Resources
MSE	Mean Square Error

MW	Mega Watt
MWSWAT	MapWindow Soil and Water Assessment Tool
NEA	Nepal Electricity Authority
NEMS	National Energy Modeling System
O&M	Operation and Maintenance
PBIAS	Percent Bias
POLES	The Prospective Outlook on Long-term Energy System
PPA	Power Purchase Agreement
PRISM	Parameter-elevation Regression on Independent Slope Model
PRM	Planning Reserve Margin
PROR	Peaking Run-of-River
PS	Planning Scenario
PV	Photovoltaic
Q40	Discharge at 40% dependable flow
Q60	Discharge at 60% dependable flow
ROR	Run of River
RORQ40	Run-of-River Hydro Plant designed at 40% dependable flow
RORQ65	Run-of-River Hydro Plant designed at 65% dependable flow
RS	Remote Sensing
RSME	Root Mean Square Error
SCS-CN	Soil Conservation Service-Curve Numbers
SHN	Synthetic Hydro Network
SRTM	Shuttle Reconnaissance Topography Mission
SWAT	Soil and Water Assessment Tool
TauDEM	Terrain Analysis Using Digital Elevation Models
TDLRS1	Transmission and Distribution Loss Reduction Scenario 1
TDLRS2	Transmission and Distribution Loss Reduction Scenario 2
TED	Technology and Environment Database
USDA	United States Department of Agriculture
USSR	Union of Soviet Socialist Republics
UTM	Universal Transverse Mercator Coordinate System
WaSiM	Water Flow and Balance Simulation Model
WGS	World Geodetic System

Nomenclature

A	Total upstream drainage area (km^3)
A_1, A_2,	Basin area of basin number 1, 2,...n (km^2)
a_{11}, a_{21}.	Area of the part of basin number 1, 2 included in the height zone1,2,...
Ax	Drainage area at gauged location (km^2)
A_y	Drainage area at ungauged location (km^2)
c_0	Regression constant
c_1,c_2,c_3	Regression coefficients
e	Base of natural logarithm
E	Mean basin elevation (m)
Ea	Amount of evapotranspiration on day *i* (mm H_2O)
E_{NS}	Nash-Sutcliffe efficiency
f_{11} , f_{12},	Fraction of the catchment area for basin number *1* included in the height zone 1, 2.....n
f_{21} , f_{22}	Fraction of the catchment area for basin number *2* included in height zone 1, 2.....n
g	Acceleration due to gravity (m/s^2)
H	Gross head (m)
ΔH	Error in head drop (m)
H_{error}	Relative error in head drop(%)
M	The ranked position on the list (dimensionless)
M_1, M_2.	Mean specific discharge of basin number 1, 2, ...n
m_1, m_2.	Zonal specific discharge for zone 1, 2 ($m^3/s/km^2$)
n	Number of sub-basins
□	Turbine Efficiency
n_e	The number of events for a period of record (dimensionless)
$\tilde{O}_{i,j}$	Estimated discharge for month i and year j at ungauged location (m^3/s)
P	Power generation (W)
ΔP	Error in power estimation (W)
P_{error}	Relative error in power estimation
P_{rb}	The probability that a given flow will be equaled or exceeded (% of time)
Q	River discharge (m^3/s)
ΔQ	Error in discharge estimation (m^3/s)
Q_1, Q_2,	Observed discharge for a basin number 1,2,...n
Q_{av}	Mean of observed discharge (m^3/s)

Q_{error}	Relative error in discharge
Q_{gw}	Amount of return flow on day i (mm H_2O)
Q_i	i^{th} observed discharge (m^3/s)
$Q_{i,j}$	Discharge for month i and year j at gauged location
Q_m	Mean annual discharge (m^3/s)
Q_{surf}	Amount of surface runoff on day i (mm H_2O)
Q_u	Discharge at upstream end of stream (m^3/s)
R	Mean annual precipitation
R^2	Coefficient of determination
R_{day}	Amount of precipitation on day i (mm H_2O)
RSI	Relative sensitivity index
S	Maximum soil moisture retention
S_{av}	Mean of simulated discharge (m^3/s)
S_i	i^{th} simulated discharge (m^3/s)
S_l	Mean basin slope
SW_0	Initial soil water content on day i (mm H_2O)
SW_t	Final soil water content (mm H_2O)
t	Time (days)
W_{seep}	Amount of water entering the vadose zone from soil profile on day i
(mm	H_2O)
ρ	Density of water

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CHAPTER 1

Introduction

This chapter presents the introductory part of the thesis regarding the research background and the problem to be studied & analyzed. Section 1.1 describes the research background and section 1.2 enunciates the problem statement of the study. Section 1.3 and 1.4 explain the objectives and the scope and limitations of the research. Finally, section 1.5 describes the structure of the thesis.

1.1. Research Background

Energy is considered one of the most important ingredients of economic development. Studies have shown that a strong correlation exists between the energy consumption and the economic development in a country [1,2,3,4,5,6]. Therefore, a continuous availability of clean energy at affordable cost is a must for sustainable economic development. Among the different types of energy resources available in the world, fossil fuel based resources are predominant for primary energy supply and would continue to supply almost 80% of the world energy use through 2040 [7]. However, fossil fuel use is the primary source of the global Green House Gas (GHG) emission. As regards the global GHG emission, the share of the carbon dioxide gas (CO_2) emitted from the fossil fuel use is 56.6% [8] and the link between the increased GHG emission and the global warming [9] has been recognized. Different strategies have been proposed to reduce the GHG emission and mitigate the effect of climate change. Studies have shown that the life cycle GHG emissions from the technologies that use renewable energy resources are less compared with those technologies based on fossil fuel [10,11]. Therefore, the renewable energy plays a vital role in the mitigation of the climate change. There are different sources of renewable energy. One of them is the hydropower, which is currently the most common and the important source of the renewable energy for power generation and offers a significant role in the reduction of GHG [12].

The electricity demand is burgeoning in many developing countries and increasing in the developed world. It has been projected that the world electricity demand will double between 2000 and 2030, increasing at an annual rate of 2.4% [13]. To meet such growing electricity demand while complying with an environmental regulation is a difficult task. Among the various forms of renewable energy sources that can be harnessed to meet the electricity demand, the hydropower is the most matured, cost-effective and reliable technology and is the largest renewable energy source for power generation in the world [14]. It supplies about 16% of the global electricity needs and over the four-fifth of the global renewable electricity [15]. The hydropower has the best energy conversion efficiency of all known energy sources and has good energy return on investment (EROI) compared to other sources of energy [16]. It is therefore very important to assess the hydropower potential and well document all the potential sites in a country. Many countries rich in water resources have up-to-date information about the hydro potential of their countries. The reliable information about the magnitude and extent of resources in a country helps in future energy planning and selection of potential sites for hydropower development.

Geographically, Nepal is situated in between two giant countries, India and China. Nepal is endowed with huge water resources. There are more than six thousand rivers and rivulets in Nepal [17]. The big river basins like the Saptakoshi, Narayani, Karnali and Mahakali are fed by rivers originated from high Himalayas. Besides these, there are seasonal flow rivers like the Bagmati, Rapti, Babai, Kankai etc. originated from the Mahabharat hill range. Within a span of 90 to 230 km, the altitude rises from less than 100 m at South to 8848 m at North from sea level in Nepal [18]. This unique topography has endowed with immense water power potential in Nepal and it is utmost important to assess this potential. The theoretical run-of-river(ROR) hydropower potential of Nepal has been recognized as 83,000 MW, of which about 45,000 MW is considered technically feasible and 42,000 MW is considered economically feasible [19].

In spite of the abundant hydro resources in the country, only a tiny fraction of it has been harnessed and utilized so far. As of now, the total installed hydropower capacity is 728.941 MW, which is 93% of country's installed power capacity [20]. Out of this, the capacity of storage hydro plant is only 92 MW and the rest is ROR hydro plants. On an average, power demand and number of consumers are increasing each year at a rate of 9.34 % and 10.87 % respectively since 2000 [21]. However, the rate of capacity addition is almost stagnant compared to the growth of electricity demand in the country. The government proposed an ambitious plan for developing 10,000 MW of hydropower in 10 years (between 2010 and 2020) and 25,000 MW in 20 years (2010-2030) [22, 23]. However, so far only about 200 MW has been realized. As a result, power crisis which surfaced in the country in 2006 brought a multitude of economic and social problems. As Nepal does not have the proven reserves of fossil fuel, the only option is to harness the hydro resources available in the country to produce electricity.

Therefore, this study takes a step forward and assesses the hydro potential of the rivers in Nepal, analyzes the current power crisis in the country and proposes power generation and expansion plan to utilize hydro resources and other sources of renewable energy available in the country.

1.2. Problem Statement

Any country should have up-to-date and accurate information about the natural resources. Such information is required for the management and the better utilization of the resources. Out of the various natural resources available in Nepal, water resource is the most important one. The available water resources in Nepal have abundant hydro potential which can be harnessed for the development of the country, but there is a lack of reliable and accurate information about the hydro potential in Nepal. The fundamental information regarding the magnitude and distribution of the potential in the country helps in planning, formulating policies and strategies for the development of hydropower.

The first assessment of the theoretical hydropower potential of Nepal was done by Shrestha during his PhD research work in the former USSR about 50 years ago with limited data and analysis tools. Shrestha [24] assessed 83,280 MW as the theoretical hydro-potential of Nepal. The estimate was made at a time when very little river discharge and precipitation data were available. The estimation was made by using the average discharge. Lots of changes have happened since then as regards the hydrological data and computation technology. Now 154 hydrometric stations and 337 precipitation stations have been established in different parts of the country and provide more accurate hydrological data for more than 30 years [25]. There have been advances in information technology such as remote sensing, computational tools such as geographic information system (GIS) and various hydrological modeling tools which can process and analyze the data more accurately and provide better results. Using these latest technologies, the potential can be estimated more accurately than before. However, very few studies have been done in this field after the first assessment. Albeit Nepal Electricity Authority (NEA) studied the power potential of the several rivers in the past [26, 27, 28] with the assistance of foreign experts, all of these studies are rather project oriented and do not cover the entire part of the country. Moreover, these study reports are not accessible to the public. It has, therefore, necessitated reassessing the theoretical ROR hydro potential of the rivers in Nepal by using the latest computational and analysis tools to come up with the accurate and better results.

Electricity plays a vital role in the socio-economic development of a country. However, Nepal has been facing an acute electricity crisis since 2006 and has become a perennial problem since then. Extended hours of power cut up to sixteen hours/day have been witnessed in January, 2009 [29]. Power crisis, even during the wet season when all hydropower plants operate at full capacity, has been experienced since 2008 due to the capacity deficits in the system. Looking at this grave problem, government of Nepal declared the National Electricity Crisis in 2008 and announced 38 points measures to address the problem [30]. However, due to the lack of concrete plans, the government failed to address the problem. Albeit the large numbers of hydropower plants are under-construction and many are in different stages of development, it is unlikely that the demand for electricity can be met from only the domestic electricity generation at least for a foreseeable future.

Therefore, this research has been carried to study the supply side management of Nepalese power sector, mainly focusing on power generation and expansion plan using country's hydro resources.

1.3. Objectives and Research Questions

The primary objectives of this dissertation are to assess the theoretical ROR hydropower potential of the rivers in Nepal and power supply modeling to develop power generation and expansion plan for the period 2015 to 2030.The specific objectives of the research are:

a) To estimate the theoretical ROR hydropower potential of the rivers in Nepal and its distribution according to the river basin.
b) To study the characteristics of demand and supply of power in Nepal.
c) To develop the power supply model with various supply alternatives to meet the electricity demand for the period 2015 to 2030.

To achieve the aforementioned objectives, this dissertation analyzes the following research questions:

a) What is the actual state of theoretical ROR hydro potential in Nepal and how are they distributed in the country?
b) What are the major issues related to the current power crisis in the country from the demand and the supply side perspective?
c) How can the ongoing power crisis be solved using hydro resources available in the country?
d) How much ROR and storage hydro plants have to be constructed by the year 2030 to satisfy the domestic power demand and how much investment is required to build these hydropower plants?
e) What should be the proper electricity mix plan to meet the future power demand in the country?

The first question requires the estimation of potential head and discharge of the river basins in the country. A GIS based spatial analysis tool will be used for this purpose. The second question involves the analysis of the nature of demand and supply of power and identification of the major issues related to the problem. The third, fourth and the fifth questions require the power supply modeling of Nepalese power sector.

1.4. Scope and Limitation

This dissertation estimates the ROR hydro potential of the rivers in Nepal and analyzes the characteristics of demand and supply of power in the country. The power supply model is built to develop power generation and expansion plan for the period 2015 to 2030 and country's hydro resources are utilized in the plan. Hydrological models are developed for three major river basins to estimate the stream flow to be used in the assessment of the hydro potential. The required weather data for the hydrological model are collected from different sources for the period 2000 to 2009. The precipitation and temperature data are collected from the Department of Hydrology and Meteorology, Nepal and the rest of data like humidity, wind speed and solar radiation are taken from the global weather data. In the absence of local data, other required data such as soil and land use data are used from different sources. Only the theoretical ROR hydro potential is assessed in this study. The estimation of storage and pumped storage hydro potential is left for further study. Also the technical and economical potential are not covered in this study.

The technology and cost data used in the model are obtained from various domestic sources and in the absence of the domestic data, international sources are used. The results of the model are helpful for policy makers to plan and formulate the policies and strategies in advance of power generation and expansion, so that the future electricity demand can be met. It is also useful for the investors as well and provides the information about the opportunity to invest on the new hydropower plants.

1.5. Structure of the Thesis

This dissertation has been structured into seven chapters. Chapter 1 describes the research background of the thesis. The motivation along with the problem statement is presented. This chapter also presents the research questions and scope and limitations of the study. Chapter 2 explains the literature reviewed during the research work. The first part of this chapter explains the literature related to various methodologies of hydro potential estimation, while the second part relates to various energy planning models. The last part is about the review of previous work in Nepal. Chapter 3 explains the methodological approach adopted in this study. Chapter 4 explains the watershed modeling to estimate the discharge and its use in hydropower potential estimation. This chapter begins with the description of the major river basins in Nepal. Then the different types of data used in the model and their sources are explained. Finally, the result of the estimated ROR hydropower potential is provided for each river basin. Chapter 5 explains the role of power sector planning to develop hydropower in the country. Likewise, the various stages of hydropower project planning and development in Nepal are briefly discussed in this chapter. Chapter 6 is related to the power supply modeling and development of power generation and expansion plan to meet the future electricity demand. This chapter begins with the analysis of the characteristics of demand and supply of power in the country. Then the present status of hydropower development (existing, under-construction, generation license granted) is briefly discussed. The present status of transmission line development and the associated problems in transmission line construction are discussed briefly. Finally, the power supply model is developed and the result is presented. Chapter 7 presents the main findings of the research and recommendations for further research.

CHAPTER 2

Literature Review of The Hydro Potential Estimation

In this chapter, the literature reviewed in study is presented. The chapter begins with the literature related to various methodologies of hydropower potential estimation. Then the review of previous work in Nepal is presented. The literature related to various energy planning models is provided. Lastly, a brief description of LEAP (The Long-range Energy Alternatives Planning System) model is given.

2.1. Hydropower Potential Calculation

Hydropower potential is a function of head drop and discharge at certain flow exceedance. The theoretical ROR hydropower potential is calculated by using equation (1).

$$P = \rho \times g \times Q \times H \qquad (1)$$

Where,

P = Power generated in Watt (W)
ρ = Mass density of water (kg/m^3)
g = Acceleration due to gravity (m/s^2)
Q = Discharge (m^3/s)
H = Gross head drop (m)

If there are numbers of sub-basins in a given basin, the total power of the basin can be calculated by summing the potential of all sub-basins.

$$P = \sum_{i=1}^{n} \rho \times g \times Q \times H \qquad (2)$$

Where,

i = *Sub*-basin number = *i............n*
n = *Number* of sub-basins

The mass density of water is taken as 1000 kg/m^3 and acceleration due to gravity as 9.81 m/s^2. The gross head is the elevation difference between headrace and tailrace. By estimating the head drop, H and discharge, Q of any basin, the theoretical hydro potential can be calculated.

2.2. Review of Methodologies for Hydropower Potential Estimation

As described in Section 2.1, the estimation of hydropower potential requires the estimation of head drop H and river discharge Q. Different methodologies have been developed to estimate the head drop and discharge. Head drop can be calculated manually from the topographic map or automatically along the river system from Digital Elevation Model (DEM) using GIS software.

Estimation of discharge is a little more difficult because the river flow depends upon the number of processes taking place in the catchment. The main processes are surface runoff from precipitation, ground water flow, snow and glacial melt and evapotranspiration. Generally, discharge observations are done only at a few locations in the river catchment and therefore, the observed discharge data are not available at the location of interest. Therefore, the discharge estimation is required upstream and downstream of the observed point as the river flow changes with every new tributary. Discharge estimation is also required for an ungauged river basin. Some of the methodologies used to estimate the river discharge are: linear regression method, drainage area ratio method and hydrological simulation.

Regression equations have been used to estimate the discharge at gauged and ungauged sites in many countries. In this method, several parameters such as drainage area, land use, climate variables, geomorphology etc. are used as the independent variables to develop the regression equation of stream flow for the given catchment [31]. The equation (3) shows the typical regression equation developed to estimate the stream flows and power potential for Alaska and Hawaii [32].

$$ln(Q_m) = ln(c_0) + c_1.\ln(A) + c_2.ln(R) + c_3.ln(E) + \cdots \quad (3)$$

Where,

Q_m = Mean annual discharge (m^3/s)
A = Total upstream drainage area (km^2)
R = Mean annual precipitation (mm)
E = Mean basin elevation (m)
c_0 = Regression Constant
c_1, c_2, c_3 = Regression Coefficients

The U.S. Geological Survey developed a multiple regression equation to estimate the monthly stream flow characteristics at the selected sites in the upper Missouri river basin. The data from 47 gauge stations were used to develop the regression equations. Basin area, mean annual precipitation, mean basin elevation, main-channel length and slope, forest area in the basin, precipitation intensity were used as independent variables [33].

Drainage area ratio method is a widely used technique in many cases where limited stream flow recorded data are available. This method is easy to use, requires little data, does not require any development, and many times, is the only method available because regional statistics or precipitation-runoff models have not been developed [34]. However, this method is valid where the watersheds are of similar size, land use, soil type and rainfall have similar pattern [35]. This method is the most appropriate for use when the ungauged site lies on the same stream as a gauging station and the accuracy depends on the closeness of two sites (gauged and ungauged), similarities in drainage area, and other physical and climatic characteristics of the basin [36]. Discharge is estimated by drainage area weighting using equation (4)

$$\bar{Q}_{i,j} = \frac{A_y}{A_x} Q_{i,j} \qquad (4)$$

Where,

$\bar{Q}_{i,j}$ = Estimated discharge for month *i* and year *j* at ungauged location

$Q_{i,j}$ = Flow for month *i* and year *j* at gauged location

A_y = Drainage area at ungauged location

A_x = Drainage area at gauged location

Hydrological modeling is another method of estimating the river discharge. Hydrologic models are the simplified, conceptual representation of a part of the hydrologic cycle. They are used for hydrologic prediction and for understanding the hydrologic process. The type of modeling depends upon the objective of the study and may be chosen as lumped, semi-distributed, distributed models [37]. Hydrological modeling is used in conjunction with GIS. Kurse et al. [38] have used Soil and Water Assessment Tool (SWAT) hydrological model to estimate the river discharge and used the simulated discharge to assess the hydropower potential of Kopili River basin in Assam, India. Porarinsdottir used simulated discharge data from the hydrological model WaSIM, while assessing the hydropower potential in Iceland. Narula et al. [39] has used the SWAT hydrological model to estimate stream flow for small hydropower scheme in an ungauged mountainous watershed in the Western Ghat, India.

2.3. GIS in Hydropower Potential Estimation

Traditionally hydropower potential is estimated for a particular site by using historical data of discharge. Very limited tools were available to estimate the stream flow at ungauged locations. Due to the complexity involved in hydrological phenomena, the estimation of discharge at ungauged location based on the observed data of some specific sites using the traditional estimation method poses doubts regarding the accuracy and reliability of the assessment. Furthermore, the assessment based on the location specific recorded data does not cover the entire potential basin, thus leaving the more potential sites at other locations. The collection of observed data from a large number of gauging stations is costly as well.

With the advent of modern computation tools such as GIS, remote sensing (RS) and hydrological models, the aforementioned constraints have been addressed comprehensively. The realistic representation of: (i) terrain, (ii) complex hydrological phenomena and (iii) varying climate are now possible through the spatial tools and modeling techniques. GIS is a computerized data management system that is used to digitally represent, store, manipulate, analyze and manage all types of spatial or geographical data [40]. RS is the acquisition of information about an object or phenomenon without making physical contact with the object. Some of the applications of GIS are: assessment of natural resources, environmental management, disaster mitigation, land use management, groundwater studies etc. [41, 42, 43, 44, 45, 46, 47, 48].

GIS and RS are being extensively used with hydrological models to estimate hydropower potential in recent times. Kulkarni et al. [49] developed a stream flow simulation model using remote sensing data for snow and glacier fed small river in Himanchal Pradesh, India and used the model runoff to estimate the hydropower potential. Kerr Wood Leidal Associates Limited [50] evaluated the hydropower potential of the Piaxtla River basin in Mexico using GIS based Rapid Hydro Assessment Model and the hydrological modeling of the basin. Räsänen et al. [51] studied the existing and planned reservoirs for irrigation and its effect on hydropower production. The approach consisted of hydrological and hydropower modeling and irrigation operation of multipurpose reservoirs on a catchment scale. Fay et al. [52] assessed the hydropower potential of the rivers on the island, Saint Lucia by using globally available satellite and local rainfall data. The runoff processes were modeled applying a hydrological model taking into account the regional climate conditions. Ouarda et al. [53] used the indexed sequential hydrological modeling to estimate the project-dependable hydropower capacity for several federally owned/operated projects in the Colorado River Basin. Coskun et al. [54] used the remote sensing satellite data to derive the synthetic drainage network and developed regression based hydrologic model to estimate the hydropower potential in the Solaki watershed located in the Eastern Black Sea, Turkey.

GIS is also used to locate and select the potential hydropower sites. Cuya et al. [55] used the Arc-GIS based tool VAPIDRO-ASTE to assess the maximum hydropower potential in the La Plata basin. Ballance et al. [56] used the GIS to identify quickly the potential sites for micro and macro hydropower sites in South Africa. Rojanamon et al. [57] selected the potential sites for a small ROR hydropower project in Thailand using GIS, economic and environmental criteria. Similar studies can be found at [58, 59, 60, 61]. GIS and remote sensing technologies are integrated with the hydrological models in the recent developments and extensively used for many applications [62]. However, some of the limitations of GIS-based hydrological models are the requirement of the enormous amount of data, expensive GIS software and resolution of temporal data. The simulated results from the GIS-based hydrological model can be used for the water resource planning where the observed data are not available or insufficient.

Most of rivers in Nepal are ungauged or very poorly gauged and therefore, the observed discharge data are not sufficient for the assessment of hydro potential. Therefore, GIS-based hydrological model is developed to simulate the discharge and is used to estimate the hydro potential of the rivers in Nepal.

2.4. Selection of Hydrological Models

Hydrological models are classified as lumped models, semi-distributed models and distributed models. In lumped hydrologic models, hydrological parameters are assigned at basin level and are assumed constant throughout the basin. Data requirements are low in this model but their limited representation of the spatial variability of the natural system may restrict their applicability for integrated management purpose [63]. In semi-distributed models, the hydrologic parameters are partially allowed to vary at sub-basin level by dividing the basin into a number of smaller sub-basins, but the sub-basins with the same parameters are lumped together. This model is a compromise between lumped and distributed models in terms of their representation in spatial variability and data requirement. These models are more physically based than the lumped models and they require less input data than fully distributed models [64]. In distributed models, the parameters are fully allowed to vary by splitting the given basin into smaller cells. Apart from the detailed description of the hydrological processes, the model provides more realistic representation of the basin. However, the main constraint is the extensive data requirement and computational time and resources. These models tend to have good explanatory depth but low predictive power.

Some of the important factors to be considered while selecting the hydrologic models are: availability of data, study objectives, desired accuracy, cost of the software and cost related to the acquisition of the input data, processing speed of the computer at hand, user support etc. An extensive review and comparison of the different existing hydrological models have been given by Cunderlik [64]. Based on the accessibility of the models from the data requirement, cost of the tools, user friendliness and user support aspects, SWAT model was selected in this study.

2.4.1. SWAT Hydrological Model

SWAT model was developed to study the influence of land management practice on water, sediment and agricultural yields in a large watersheds with varying soils, land use and management conditions over long period of time and is a semi-distributed hydrological model. It can simulate surface runoff, percolation, sediment transport, nutrient loading, and ground water flow and reservoir storage. It can be applied to large un-gauged watersheds. SWAT model first divides a watershed into sub basins which is connected through a stream channel and then these sub basins are further divided into smaller homogenous units with an unique combination of soil, land use and vegetation types in a watershed known as Hydrologic Response Units (HRU). The runoff is predicted for each sub-basin and is routed to obtain the total runoff for the basin. This model has been used in various countries to estimate the hydro potential, impact of land management practices on water, sediment and agricultural chemical yields and run off simulation [65, 66, 67, 68, 69]. The advantages of this model is that it is freely available and some of its version can be integrated with open source GIS interfaces and requires less data compared with the distributed hydrological models. Figure 1 represents the hydrologic cycle that works in SWAT model. The details of the SWAT can be found in [70].

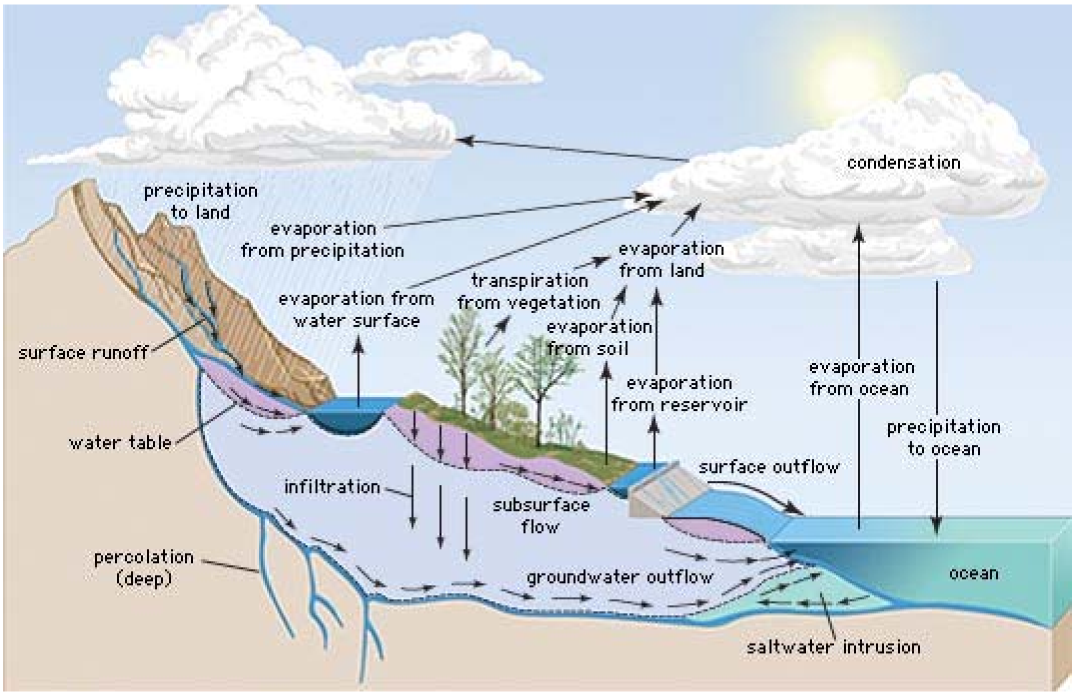

Figure 1: Schematic representation of hydrologic cycle [71]

SWAT uses water balance principle. The following water balance equation is used by SWAT [72]:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \tag{5}$$

Where,

SW_t = Final soil water content (mm H_2O)

SW_0 = Initial water content on day i (mm H_2O)

t = Time (days)

R_{day} = Amount of precipitation on day i (mm H_2O)

Q_{surf} = Amount of surface runoff on day i (mm H_2O)

E_a = Amount of evapotranspiration on day i (mm H_2O)

W_{seep} = Amount of water entering the vadose zone from soil profile on day i ($mm\ H_2O$)

Q_{gw} = Amount of return flow on day *i* ($mm\ H_2O$)

2.5. Review of Previous Study in Nepal

The history of the hydropower development started in Nepal with the construction of small hydropower plant at Pharping, near Kathmandu in 1911. The installed capacity of the plant was 500 kW. Since then, no new power plants were built till the year 1936. In 1936, the second hydropower plant (640 kW) was commissioned at Sundarijal. Morang Hydropower Company was established in 1939 and built 677 kW Sikarbas Hydropower plant at the Chisang Khola in 1942 [73]. However, the formal development of hydropower was institutionalized only after the commencement of the development planning process in 1956. The First Five-year Plan (1956-61) targeted to build 20 MW hydropower in Nepal and the institution "Electricity Department of HMG" was formed with the responsibility of generation, transmission and distribution of electricity [74]. Despite the attempt to develop the hydropower in Nepal, the very fundamental information like the magnitude and distribution of hydro resources in the country was not available at that time. The first attempt was made by Shrestha to assess the hydro potential of Nepal in his PhD study in the former USSR during 1963 to 1966.

Shrestha was constrained by data and analysis tools. The availability of hydrological and meteorological data was very limited. Only 44 hydrometric stations were there in Nepal during that time. Among these hydrometric stations, the long period (18 years or more) hydrometrical records were available only for seven stations for the rivers Saptakoshi, Tamur and Mahakali. For the rest of the stations, the available discharge data were only for 2-3 years. The analysis tool was limited only to the simple regression and some empirical relations. Figure 2 presents the methodology used by Shrestha in his study.

Firstly, the hydrographic and topographic characteristics of the basin were studied and the relationship between the rainfall and altitude of each river basin was established. The graph was plotted using the rainfall and elevation data for the known stations. Also, the river length and its altituditional variation were studied. Based upon the study of hydrographic and topographic characteristics of the basin, the given basin was divided into number of zones. Then the zonal specific discharge was estimated using the mean specific discharge of the basin for which the hydrometrical data was available. Following equation (6) was used to estimate the zonal specific discharges for different height zones situated above the hydrometrical stations:

$$M_1 = f_{11}m_1 + f_{12}m_2 + f_{13}m_3 \dots\dots\dots\dots + f_{1n}m_n$$
$$M_2 = f_{21}m_1 + f_{22}m_2 + f_{23}m_3 \dots\dots\dots\dots + f_{2n}m_n$$

....
.... *(6)*

$$M_n = f_{n1}m_1 + f_{n2}m_2 + f_{n3}m_3 \dots\dots\dots\dots + f_{nn}m_n$$

$$f_{11} = \frac{a_{11}}{A_1}, f_{12} = \frac{a_{12}}{A_1} \dots\dots, f_{21} = \frac{a_{21}}{A_2}, f_{22} = \frac{a_{22}}{A_2}, M_1 = \frac{Q_1}{A_1}, M_2 = \frac{Q_2}{A_2}$$

Where,

$M_1, M_2....M_n$ = Mean specific discharge of basin number *1,2,....., n* for which hydrometrical data is available (m^3/s.km^2)

$Q_1, Q_2 ....Q_n$ = Observed discharge for a basin number *1, 2*... (m^3/s)

$A_1, A_2, \quad A_n$ = Basin area for basin number *1, 2, ... n* (km^2)

$f_{11}, f_{12}, ...f_{1n}$ = Fraction of the catchment area for basin number *1* included in the height zone *1, 2.....n*

$f_{21}, f_{22}, \ f_{2n}$ = Fraction of the catchment area for basin number *2* included in height zone *1, 2.....n*

$a_{11}, a_{21}.....$ = Area of the part of basin number *1, 2* included in the height zone*1*

$m_1, m_2....$ = Zonal specific discharge for zone 1, 2

In equation (6), the area of the basin included in certain height zone ($a_{11}, a_{12},...a_{1n}$) was estimated by Hack's law which establishes the empirical relationship between the stream length and catchment area. This methodology was applied for all the big rivers and tributaries and zonal specific discharge was estimated. Average discharge was calculated using this zonal specific discharge. All the rivers with catchment area greater than 300 km^2 were considered in the estimation of potential. The rivers with catchment area > 1,000 km^2 were classified as major rivers and the rivers with catchment area in between 300-1,000 km^2 were classified as small rivers. The head was estimated from the contour map for each zone. Using the head and average zonal discharge, the power was calculated for both major rivers and small rivers using 80% system efficiency. Table 1 presents the estimated potential by Shrestha.

Looking at the methodology adopted by Shrestha, number of questions can be raised regarding the accuracy of the estimation. The equation (6) which was used to estimate the zonal specific discharge is questionable. The zonal specific discharge at certain altitude level *(m_1, m_2, m_3..)* were estimated by solving the system of linear equations for different basins. The physical and climatic characteristics of one basin may be different from other basins and therefore, the zonal specific discharge of one basin may be different from another basin although the selected location is at the same altitude. However, the assumption was made that the zonal specific discharge at same altitude will be same irrespective of the characteristics of basins. Although the basin catchment area was estimated from topographic map for major basins, the zonal area was estimated using the

Hack's law which does not provide the accurate area. Therefore, the accuracy of the estimation made by Shrestha is questionable.

Table 1: Estimated theoretical hydropower potential in Nepal [17]

Basin Name	Estimated Theoretical Hydro Potential (MW)		Total Potential (MW)
	Major Rivers (A >1,000 km^2)	Small Rivers (1,000 km^2 > A ≥300 km^2)	
Karnali Basin	28,840	3,170	32,010
Koshi Basin	18,750	3,600	22,350
Narayani Basin	17,950	2,700	20,650
Mahakali Basin	3,840	320	4,160
Southern Rivers	3,007	1,004	4,011
Gross Potential (MW)			83,181

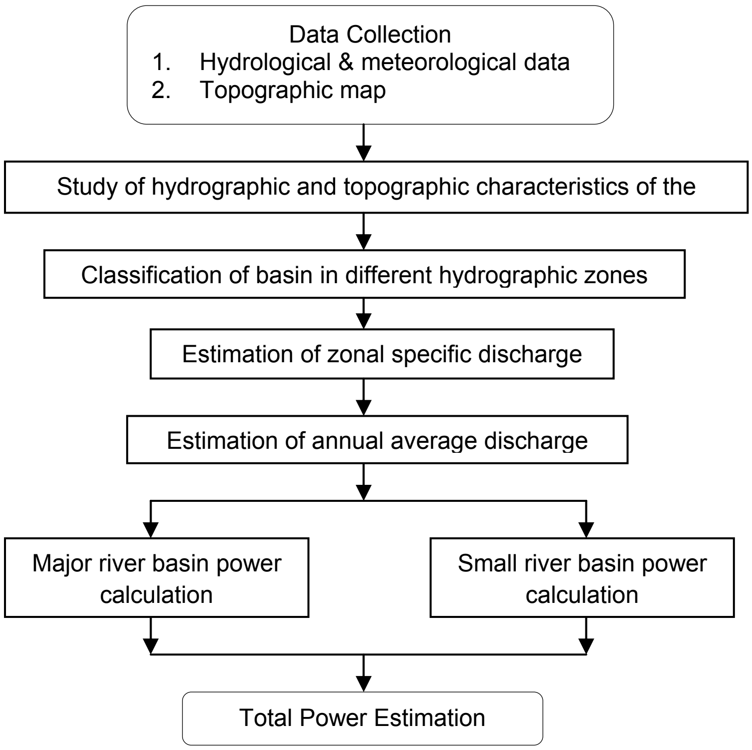

Figure 2: Flowchart of the methodology used by Shrestha (Source: Author)

2.6. Review of Energy Planning and Modeling Approach

Energy planning is the process of estimating future energy demand, choosing the suitable supply means to meet the demand and developing appropriate policies and strategies to implement the plans into actions in a national or international coverage. Energy modeling is the process carried out by computer based software to simulate the energy demand of a region or a nation and provide the suitable supply means. Energy models were first developed in 1970s after the advent of computer and has become an integral part of national energy planning after the first oil crisis [75, 76, 77]. Environmental consideration has evolved as an integral part of the energy planning after the Rio Earth in 1992 [78].

A comprehensive review of the evolution of different types of energy planning models focusing on macro or national level from 1977 to 2003 have been provided by Jebaraj et al. [79]. Energy models are simplified representations of the real energy systems. It includes only those aspects that the model developers think important at the time of modeling. Hundreds of energy models have been developed around the world at an institutional or national level in both developed and developing countries as per the specific needs and requirement of the country. These models vary considerably in their purpose, assumptions, structure, analytical approach, study methodology, mathematical approach, time horizon, sectoral coverage, geographical coverage and data requirement. Beeck [80] has provided a comprehensive review of different types of energy models and their classification. Figure 3 presents the classification of the energy models from different perspectives. A comparative study of different energy demand models can be found in [81].

2.6.1. Modeling Tools

There are different types of computer based energy modeling tools. Connolley et al. [82] made a review of different computer based energy modeling tools that can be used to analyze the integration of renewable energy. Altogether 37 computer tools have been considered. The detail information about various energy modeling tools can be found at [83, 84, 85]. Different types of existing energy models (computerized-models) today are:

a) Energy Demand Models: Energy demand models are built to forecast the future energy demand either in a region or in the entire country level. The widely used computer based tools include: The National Energy Modeling System (NEMS), The Model for Analysis of Energy Demand (MAED), Model d' Evaluation de la Demande En Energie (MEDEE), Energy and Power Evaluation Program (ENEP-BALANCE).
b) Modular Packages: These tools consist of different components such as macroeconomic components, energy demand and supply, environmental component in a single package and integrated together. The modeler can choose one or all components according to the need. Some of the widely used tools are: The Long-range Energy Alternative Planning (LEAP), The Energy and Power Evaluation Program (ENEP), The modular Energy System and Planning (MESAP), The Prospective Outlook on Long-term Energy Systems (POLES), The Modular Energy System Analysis and Planning Software (MESAP), Energy Tool Box (ETB) and ENERPLAN.
c) Energy Supply Models: These tools are used to find the least cost options to supply the energy for a given demand. These models generally use a simulation or optimization method. Some of widely used supply models include: Energy Flow Optimization Model (EFOM), The Model for Energy Supply Systems and Their General

Environmental Impact (MESSAGE), The Wien Automatic System Planning Package (WASP), MARKet ALlocation (MARKAL) and RETscreen.

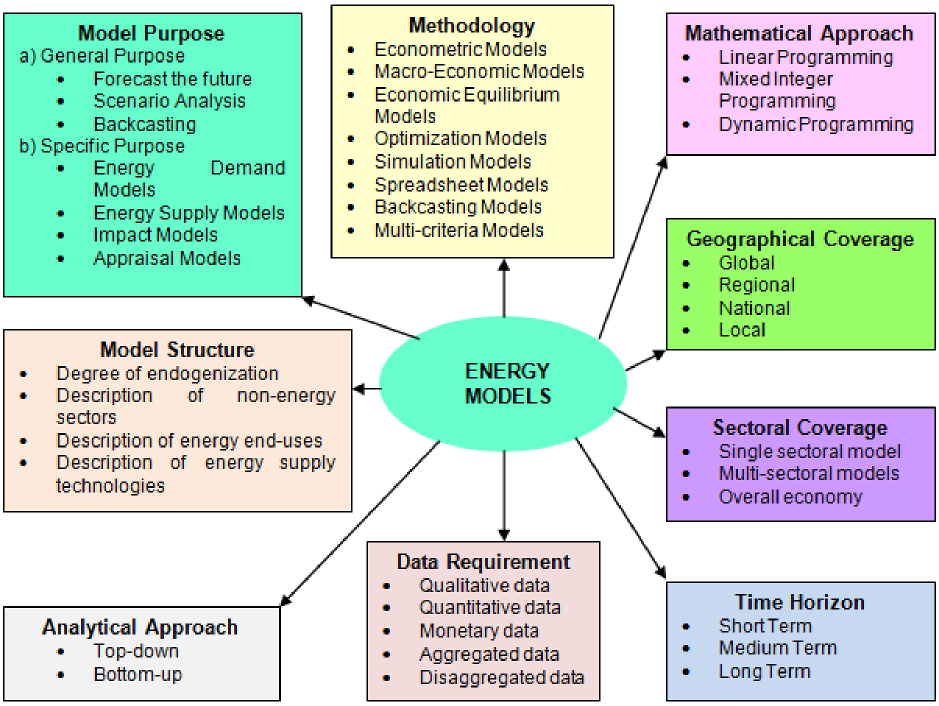

Figure 3: Classification of Energy Models [80]

2.6.2 The LEAP Model

LEAP, the Long range Energy Alternative Planning System, is a widely used integrated energy planning software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. LEAP is an integrated modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy and to analyze emissions of local and regional air pollutants [86]. LEAP has been successfully used throughout the world to estimate future energy demand and supply side management, environmental emission and for integrated energy planning [87, 88, 89, 90, 91,92, 93, 94, 95]. The model uses accounting framework to generate a consistent view of energy supply and demand based on the physical description of the energy system and different scenarios can be build to provide alternative pathways for energy supply and demand. LEAP can be used as a medium to long-term modeling tool. The main advantages of LEAP are the low initial data requirements for start up, flexibility and ease of use, which allow the decision makers to move quickly from policy ideas to policy analysis without having to resort to complex models [81]. Wide range of modeling approaches such as bottom-up, end-use and top-down macroeconomic techniques can be used to develop demand side energy modeling and on the supply side, simulation and accounting methodologies can be used for modeling electricity generation and capacity expansion planning.

Figure 4 shows the overall structure of the LEAP energy system model. Demographics and macroeconomic variables are treated as exogenous variables in LEAP and therefore, these variables are created outside the LEAP analysis framework as "Key Assumption". Modeling starts in LEAP with demand analysis. Transformation analysis is basically an energy supply simulation to meet the energy demand. It includes power generation, oil refining and gas production module. The conversion and transportation of energy are simulated from the point of extraction to the point of final energy consumption. In Resource Analysis, the data regarding the availability of resources, including both fossil and renewable resources, cost of indigenous production, imports and exports of both primary and secondary fuels are entered.

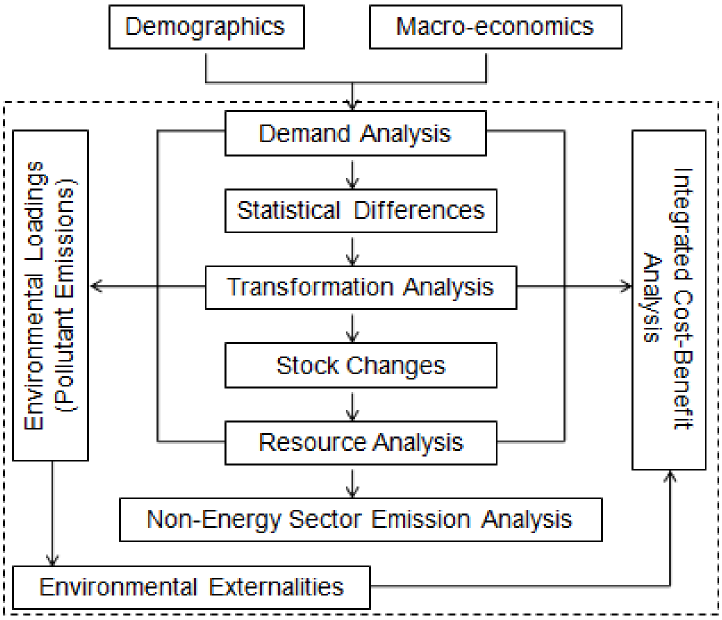

Figure 4: Overall structure of LEAP model [96]

CHAPTER 3

Methodology and Tools for Hydro Potential Estimation

This chapter explains the methodology employed and tools used in the estimation of hydropower potential of Nepal. Also, the methodology used in the power generation and expansion planning is presented.

3.1. Methodology Used in Hydropower Potential Estimation

The methodology used in the estimation of hydro potential consists of mainly two parts: i) estimation of discharge along the river system and ii) estimation of potential head drop. Section 3.1.1 describes the methodology used to estimate the river discharge by rainfall-runoff modeling and Section 3.1.2 explains the methodology applied to estimate the potential head drop along the river system. Figure 5 shows the flowchart used in this study to estimate the hydropower potential of the river. The details are discussed below:

3.1.1. Discharge Analysis

To estimate the discharge along the river lengths, hydrological model was built using SWAT tool. The use of SWAT tool requires some specific data to build the hydrologic model. The required data are: (i) Digital Elevation Model (DEM), (ii) stream network, (iii) land use map, (iv) soil map and (v) weather data (precipitation, temperature, solar radiation, wind velocity, relative humidity). These data have to be pre-processed before setting up SWAT model.

In this study, MWSWAT was used to build a hydrological model. MWSWAT is the version of SWAT which runs on MapWindow GIS [97]. MapWindow can be downloaded from http://www.mapwindow.org/. After the installation of MapWindow GIS, MWSWAT is installed as a plugin. The modeling work starts with a new project. Before starting the modeling work in SWAT, all the required GIS data have to be made ready. The following steps describe the SWAT model setup:

1. Process DEM (Watershed Delineation)

SWAT model setup starts with the DEM processing to delineate watershed. MWSWAT uses TauDEM (Terrain Analysis using Digital Elevation Model) automatic watershed delineation function. First of all, the DEM was extracted and then projected in the Universal Transverse Mercator (UTM) coordinate system. This projected and extracted DEM was used in watershed delineation. The stream polyline is also selected for burning the stream. Stream burning ensures that flow is forced into those cells that correspond to the true locations of streams. It involves raising the elevation of all cells in the DEM that do not fall along the stream network. Then stream network threshold value is provided to define the stream. The point network shape file is used to define the watershed outlets. This step divides the given watershed into a number of sub-basins as per the specified threshold value of catchment area.

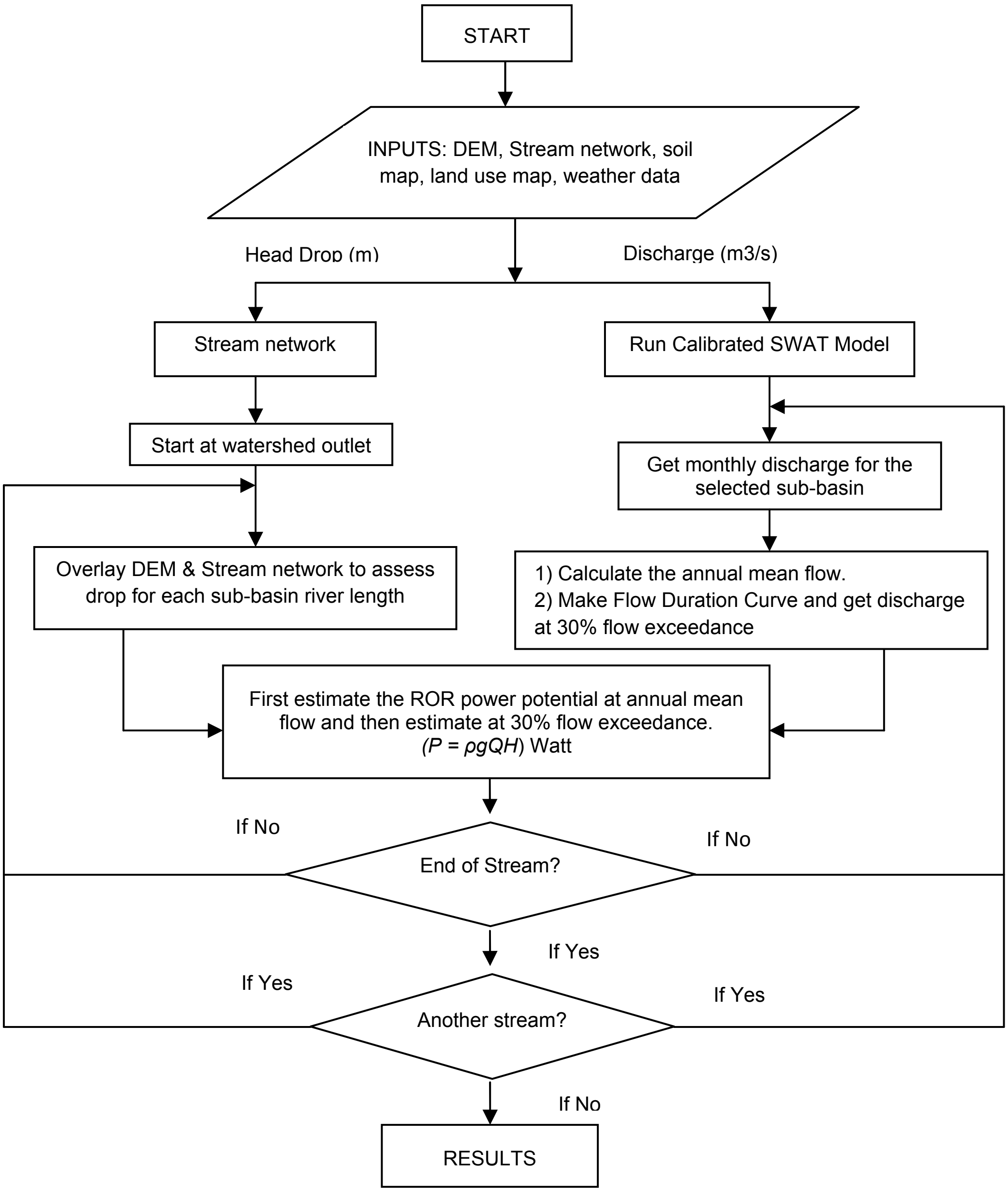

Figure 5: Flow chart for estimation of theoretical ROR hydropower potential Diagram extended from Kurse, 2010.

2. Create Hydrologic Response Units

After having delineated the watershed, the second step is the creation of Hydrologic Response Units (HRUs). HRUs are the areas within a watershed that are homogeneous in terms of soil type, land use and slope and respond hydrologically in a similar way. In this step, SWAT divides the basins into smaller pieces which have the particular soil, land use and slope range combination known as HRU. In this step, land use and soil map are required. The processed land and soil map is used in this step. Also, slope bands have to be provided.

3. SWAT setup and Run

This is the third step in the SWAT model setup. In this step SWAT input files are written and SWAT model is run. Before running the model, simulation period, rainfall-runoff/routing method, rainfall distribution and potential evapotranspiration method are selected in the "SWAT Setup and Run" screen.

4. Calibration and Validation

Once the model is built, it is calibrated by tuning the model parameters within recommended ranges to match the simulated output with the observed data. This involves the comparison of model results with the recorded runoff data at selected outlets. After the calibration of the model, the validation is done. After the calibration and validation of model, it is used to get the monthly discharge data for the selected basin.

3.1.1.1. Flow Duration Curve

The flow-duration curve (FDC) is a cumulative frequency curve that shows the percent of time that flow in a stream is likely to equal or exceed some specified value of interest [98, 99]. For example, it can be used to show the percentage of time the river flow can be expected to exceed a design flow of some specified value or to show the discharge of a stream that occurs or is exceeded some percent of the time (e.g. 70% of time). Applications of FDC are of interest for many hydrological problems related to hydropower generation, river and reservoir sedimentation, water quality assessment, water-use assessment etc. [100]. Hydropower design and hydro potential calculation require stream flow data which can be obtained from the flow duration curve.

FDC also helps to study the flow characteristics of streams and for comparing one basin to another. The shape of FDC is determined by the hydrologic and geologic characteristics of the watershed and the curve may be used to study the hydrologic response of a watershed to various types of inputs such as snowmelt, rainstorms etc.[101]. The shape of FDC is significant in evaluating the stream and basin characteristics. The slope of the curve at upper end shows the type of flood regime the basin is likely to have, whereas the slope of the lower end of the curve indicates the ability of basin to sustain low flows during dry seasons. Figure 6 shows a typical FDC for the Saptakoshi River in Nepal. This figure has steep slope from left to right end which indicates the yearly variation of the flow in the river. The upper end decreases rapidly which indicates the flood characteristics of the river and the lower end is relatively flat which shows the flow during dry season.

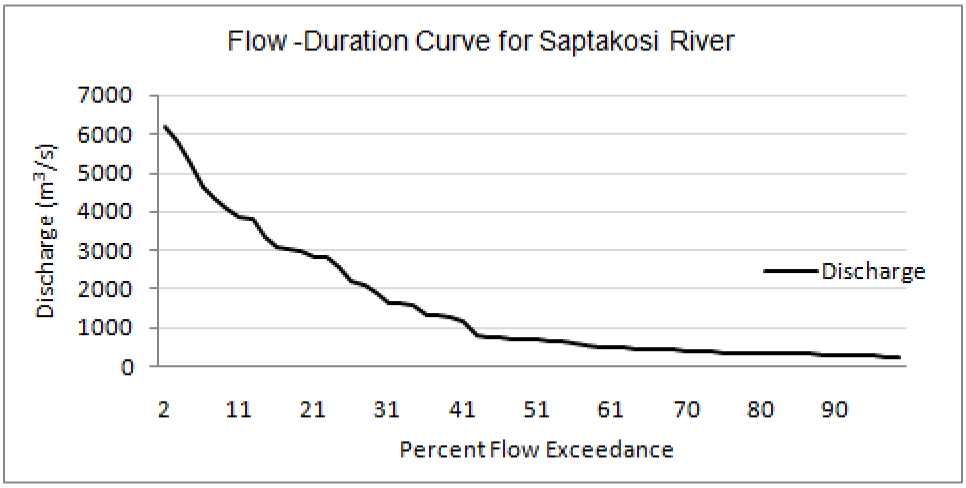

Figure 6: A typical flow duration curve of the Saptakoshi River in Nepal (Source: Author)

FDC can be prepared for the daily, weekly or monthly stream flow data. The following steps are followed to prepare the flow-duration curve [99].

1. Sort out or rank the average monthly (or daily) discharges for the period of record from the largest value to the smallest value involving a total 'n_e' number of values.
2. Assign each discharge value a rank M, starting with 1 for the largest monthly discharge value.
3. Calculate the exceedance probability as follows:

$$P_{rb} = 100 \times \left[\frac{M}{(n_e + 1)} \right] \tag{7}$$

Where,

P_{rb} = The probability that a given flow will be equaled or exceeded (% of time)

M = The ranked position on the list (dimensionless)

n_e = The number of events for a period of record (dimensionless)

MS-excel can be used to prepare flow-duration curve. The excel function "RANK" can be used to calculate the rank and the data can be arranged in descending order in Spreadsheet.

3.1.2. Potential Head Drop Estimation

The Hydropower potential assessment requires the drop in head along the river. For each sub-basin river, the potential head drop has to be computed. There are different methods of estimating the head drop along the river course. One of the simple methods is to overlay the DEM of the basin, sub-basin and river network shape file and obtain the raster value of upstream and downstream end point of each sub-basin river. The difference in raster value between the upstream and downstream end points of the river in a given sub-basin is the potential head drop of the river. The watershed delineation generates the river network, which also provides the information like stream link, stream order, stream length, slope and head drop information for each stream. Figure 7 shows the overlay of stream network over the sub-basins. When any stream passing over the sub-basin is selected, it will pop-up the detail information of the stream like drop in elevation, stream order, stream length, slope etc. as shown in Figure 8. In this figure, the drop in elevation for the selected stream inside the highlighted sub-basin from upstream point 1 to downstream point 2 is 680 m. The detail information of all the streams can be obtained from the attribute table in Arc GIS. All these actions are done in the GIS environment.

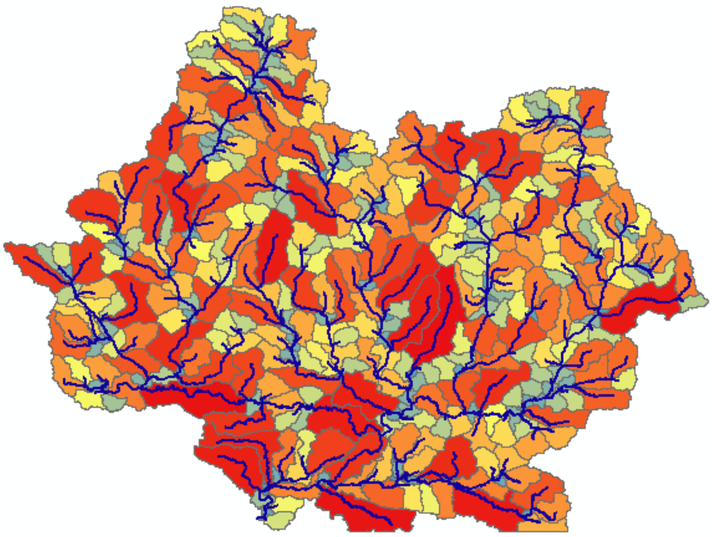

Figure 7: Overlay of stream network over the sub-basin (Source: Author)

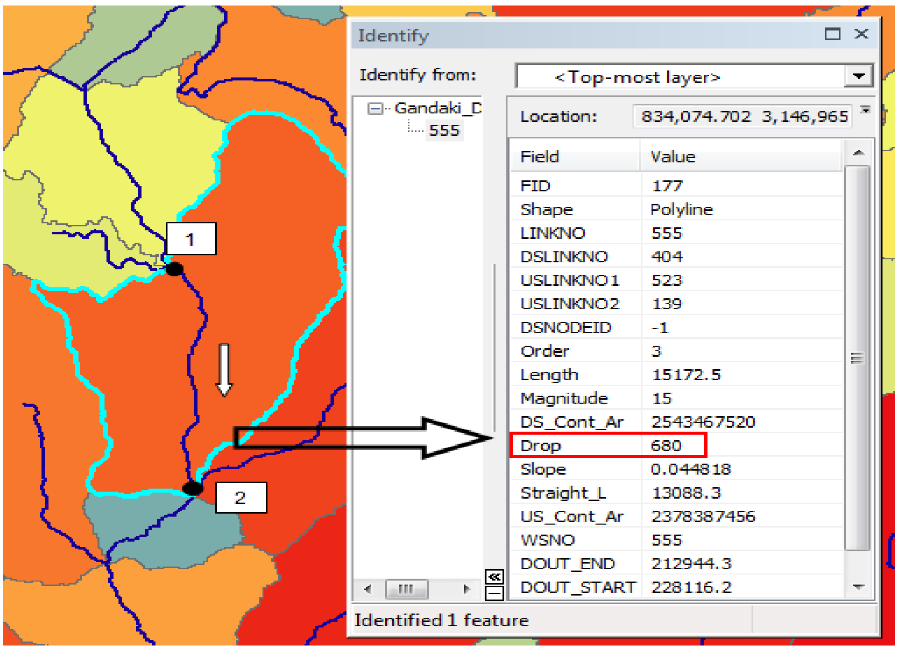

Figure 8: Elevation drop information of the stream from upstream point 1 to downstream point 2 (Source: Author)

3.1.3. Hydropower Potential Estimation

Once the potential head drop and flow exceedance or design discharge are estimated, the ROR hydro potential can be calculated using equation (1) from Section 2.1, Chapter 2. This process is repeated for all the sub-basins and total potential are arrived at by adding the potential of each sub-basin.

3.2. Methodology for Power Generation and Expansion Planning

In this study, the modeling tool, LEAP has been used for power generation and expansion planning. The future electricity demand is projected within LEAP, or estimated outside LEAP and entered in LEAP model. The electricity generation modeling starts with the introduction of transmission and distribution losses. Then the module output properties such as shortfall rule to meet the unmet demand, priority for domestic use or export etc. are set. Likewise, different factors related to power generation such, as system peak load shape, planning reserve margin, exogenous and endogenous capacity, dispatch rule, energy availability, plant life and capital cost information are entered into the model. Various power generation technology options are provided. Lastly, the possible various alternative scenarios are developed to supply the power for future electricity demand. Figure 9 shows the structure of LEAP for power supply modeling. The model answers the following three questions as the output:

a) How much capacities have to be installed to meet the future electricity demand?
b) When should the power plant be built?
c) What should be the proper electricity mix?

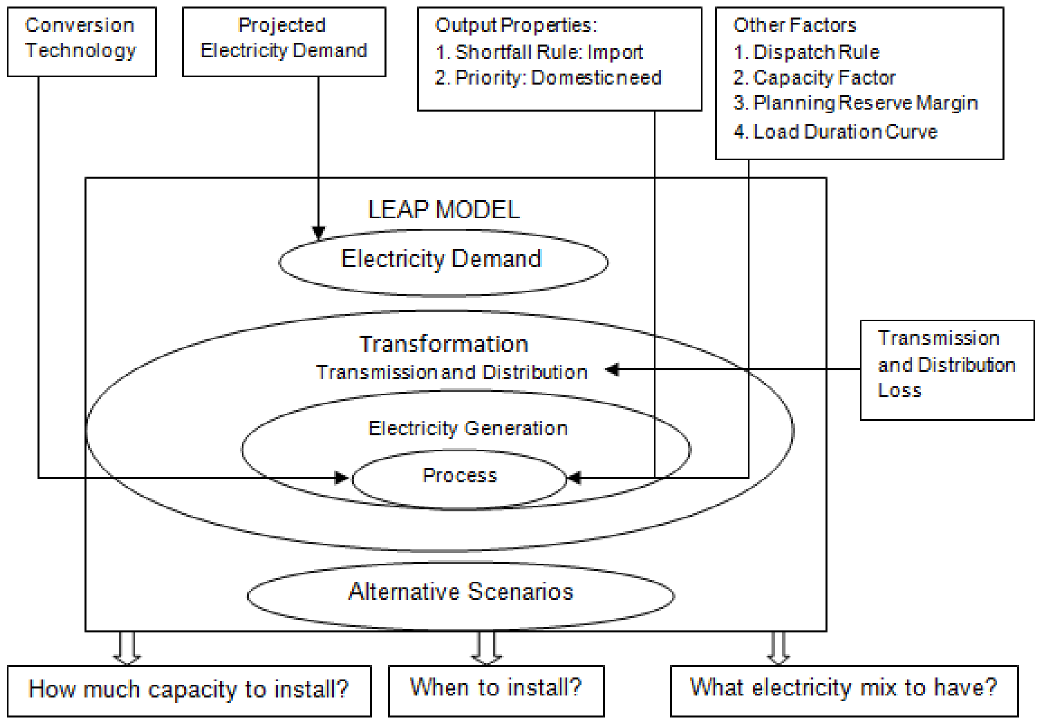

Figure 9: LEAP model for power generation and expansion planning (Source: Author)

CHAPTER 4

River Basin Modeling for Hydro Potential Estimation

This chapter explains the watershed modeling and its use for hydropower potential estimation. The chapter begins with the brief description of major river basins in Nepal. Then the different types of data used in the model and their sources are presented. The calibration, validation and evaluation of the model are described and finally the ROR hydro potential estimate of Nepal is provided.

4.1. Major River Basins in Nepal

Geographically, Nepal is situated in the central part of the Himalayan Arc between two giant countries, India and China in South Asia. Nepal lies within latitude 26°15' to 30°30 N' and longitude 80°00' to 88°15' E, stretches from over 800 km northwest to southwest with varying width between 90-240 km. The total area of Nepal is 147,181 km^2. Within an average width of about 150 km, the altitude changes from less than 100 masl to 8,848 masl [18].

There are large numbers of river and rivulet fed by rainwater, snow and glacier melt water and groundwater recharge in Nepal. Hydrologically, the rivers in Nepal can be classified into three categories:

a) Rivers originating from the Himalayas or Tibetan plateau
b) Rivers originating from Mahabharata mountain range and
c) Rivers originating from Siwalik mountain range.

The first category of rivers is glacier, snow plus rain-fed rivers and therefore, they are perennial in nature. The Sapta Koshi, Sapta Gandaki (Narayani), Karnali and Mahakali rivers belong to this category. These rivers are very important from the hydro potential point of view. The second category of rivers is fed by precipitation as well as ground water regeneration and therefore the flow is high during the rainy season but sustains the flow during the dry season. The Bagmati, Mechi, Kankai, Kamala, Tinau, West Rapti and Babai rivers belong to this category. These rivers are also important from the hydro potential point of view. The third category of rivers is also rain-fed but has very low groundwater regeneration and therefore, these rivers dry up during the dry season. These rivers are not important from the water resource utilization point of view. The rivers in Nepal are characterized by seasonal fluctuation of flow round the year and have a maximum flow from July to August during monsoon season and decline to their minimum from February to March during the dry season. About 80% of the total flow occurs during four months from June to September [102]. The major river basins are shown in Figure 10 and are described briefly in the following sections.

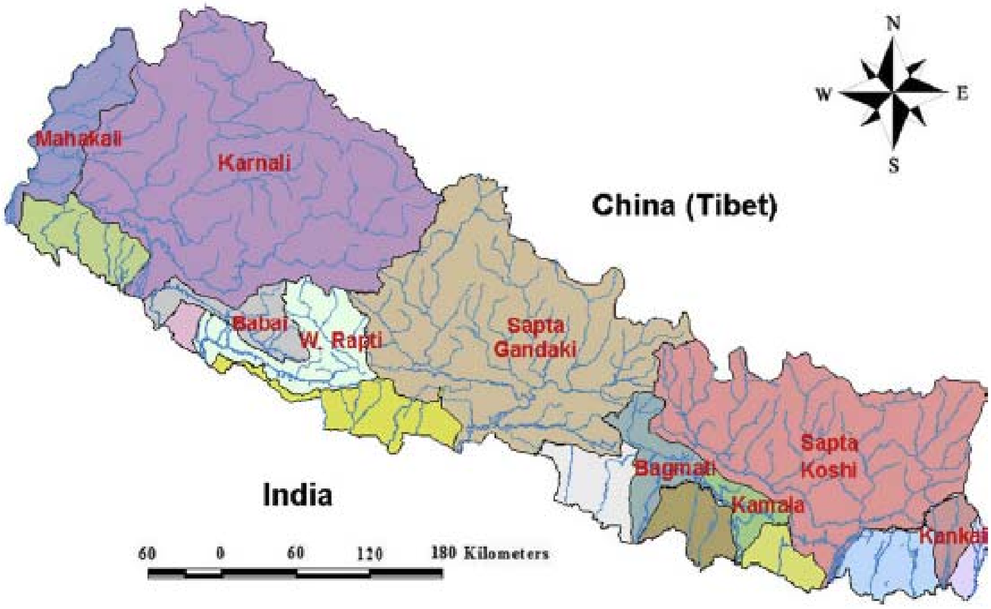

Figure 10: River Basins of Nepal [103]

4.1.1. The Sapta Koshi River Basin

The Sapta Koshi basin is the biggest river basin in Nepal and lies in between the latitude 26°52'0" to 29°6'41" N and longitude 85°44'51" to 89°14'53" E. The total catchment area of this basin is 54,100 km^2 at Chatara-Kohtu gauge station. More than half of this catchment, 29,400 km^2 lies in Tibet, China. This basin has 5,770 km^2 of glaciers, including Nepal and Tibet [104] and out of which about 1,409 km^2 lies in Nepal consisting of 779 number of glaciers with an estimated ice reserve of 152 km^3. The elevation of this basin varies from 140 masl to 8,848 masl. About 50% of basin area is above 4,000 masl [105]. This basin has three main tributaries:- Sunkoshi, Arun and Tamur and these tributaries meet at Tribeni confluence. After the Tribeni confluence, the river is called the Sapta Koshi.

The Sunkoshi River has its origin in Tibet, China and has four main tributaries: -Indrawati, Tamakosi, Dudhkoshi and Likhu Khola. The Sunkoshi in the upper part before entering into Nepal is called Poique in Tibet, China [106]. The Bhotekoshi also originates in Tibet, a few miles south of the watershed of the Arun River. Dudhkoshi and Tamakoshi originate from the edge of Mount Everest. The Indrawati originates from the eastern watershed of the Gosainkund and starts its journey from Lagntang National Park and is joined by Melamchi Khola at Dolalghat. The Tamakoshi River meets Khimti Khola at Barphu and the combined river joins Sunkoshi at Khurkot. The Tamakoshi starts from the Rolwaling and Gaurishankar area. The Dudhkosi originates in the southwestern part of the Mount Everest and meets the Bhotekoshi at Namche. The Dudhkoshi meets the Sunkoshi at Bhataude. The Sunkoshi River basin has 18,000 km^2 catchment area. Out of which 14,500 km^2 lies in Nepal and the rest lies in Tibet [104]. The Arun River originates in Tibet and enters into Nepal at Khimthanka. This basin has a large number of glaciers and lakes of different sizes. It has 34,000 km^2 catchment area, out of which only 5,240 km^2 lies in Nepal. The Tamur River starts from the western watershed of the Kanchanjunga and it meets the Yanma Khola, Ghunsa and Simbua Khola at different places in its course. Finally, it meets the Sunkoshi and Arun at Tribeni. The total length of the Tamur River is about 175 km from the source [106].

4.1.2. The Karnali River Basin

The Karnali river basin lies in the western part of Nepal and is the longest river system in Nepal. The total catchment area of this basin is 45,076 km^2 and out of this, about 41,550 km^2 lies in Nepal and the rest lies in Tibet, China. This basin consists of 1,361 numbers of glaciers with an area of 1,740 km^2 and an estimated ice reserve of 127 km^3. It has three major tributaries: Seti, Bheri and Karnali and originates from Tibet, north-west of Taklakot. This river is called Ghaghara in India.

The Karnali River is the main tributary of Karnali basin. It originates from the glacier, Mapchadhunga in Tibet at an altitude of 3,969 masl and enters Nepal at Khojarnath [106, 107]. It is named as the Humla Karnali in Nepal. The 202 km Seti River drains out from the western part of the catchment and joins the Karnali River in Doti district. Another major tributary, 264 km long Bheri River which originates in the western part of Dhaulagiri Himalaya joins the Karnali near Kuineghat in Surkhet [108]. It makes delta in the Terai plains of Nepal and again joins before entering India. The Seti River is another major tributary of Karnali basin. It starts its journey from the southeastern part of Rikhi Himal. It makes a very narrow, deep gorge between Chainpur and Shalimar valley. After passing through several gorges, it finally joins the Karnali river at Silgarhi Doti. The catchment area of the Seti River is about 7,500 km^2 and is 202 km long [106]. The Bheri River, the biggest tributary of the Karnali basin originates in the Kanjiroba Himalaya and is 264 km long. The catchment area of this river is about 12,400 km^2. It joins with the Thuli Bheri at Chiragaon and the combined river joins the Sani Bheri at Jajarkot. Finally, it meets the Karnali River near Kuineghat in Surkhet.

4.1.3. The Narayani River Basin

The Narayani also known as Gandaki, is the important basin in Nepal and lies to the central part of Nepal. It extends from latitude 27°21' to 29°20' N and longitude 82°55' to 85°50' E. The total catchment area of this basin is about 36,329 km^2 and about 32,140 km^2 lies in Nepal [106] and rest in Tibet, China. There are 1,025 numbers of glaciers in this basin covering an area of 2,030 km^2 and an ice reserve of 191 km^3. This basin also contains the three of the world's 14 mountains over 8,000 m, Dhaulagiri, Manaslu and Annapurna I [109]. The major tributaries of this basin are Kaligandaki, Seti, Marsyangdi, Burhi Gandaki and Trishuli River.

The Kaligandaki originates in the Nhubine Himal Glacier in the Mustang region of Nepal near border with Tibet at an altitude of 6,268 m. The river flows through a steep gorge known as the Kali Gandaki Gorge, the world's deepest gorge, between the mountains Dhaulagiri and Annapurna I. At Devighat, it meets the Trishuli River, then it is joined by the East Rapti River draining from the inner Terai valley, Chitwan. The length of this river is 332 km and has a catchment area of 11,850 km^2. The Seti River originates from the Annapurna Himalaya range and is joined by Mardi Khola at Puranchaur and Sardi Khola at Ghalegaon. Finally, it meets the Trishuli River at Gaighat. The total length of this river is about 125 km and has a catchment area of about 3,000 km^2.

The Marsyangdi River starts its journey from the west of the Thorung peak of Manang. It is joined by Nar Khola at Chame. It meets another stream known as Dudh Khola at Dharapani. It is joined by Chepe Khola at Chepe ghat and Dorondi stream at Siling and finally meet the Trishuli River at Mugling [106]. The length of this river is 153 km and has about 4,600 km^2 catchment area. The Burhi Gandaki originates from Larke Himal and joins with Shiaf Khola, draining out from Taple Himal at Ngyak. Finally, it meets the Trishuli River at Benighat. The total length of this river is 117 km and has 5,840 km^2 catchment area.

The Trishuli River is another major tributary of the Narayani basin. It starts in Tibet and joined by Lende Khola at Rasuwagarhi. It meets Chilime Khola and Langtang Khola draining out from Gosaikunda at various points. It joins with the Burhi Gandaki at Benighat and follows a westerly course up to Mugling and meets the Marsyangdi River. More than 60% of the total catchment area of this river lies in Tibet and 9% of this area is covered by snow and glaciers. About 85% of the catchment area lies above 3,000 m [110].

4.1.4. Climatic Characteristics of Nepal

Due to the physiographic and climatic characteristics of the country, the distribution of precipitation varies considerably in time and place, thereby causing the temporal and spatial variation of river flows in Nepal. Physiographically, Nepal can be divided into five regions: a) High Himalaya, b) High Mountains, c) Middle Mountains, d) Siwaliks and e) Terai [111]. The plain land, Terai which lies to the southern part of Nepal and Siwaliks have the tropical to subtropical climate. The valley bottoms of the Middle Mountains have also subtropical climate, but have warm temperate in the valley side and cool temperate climate on higher part of the mountain and experience occasional snowfall. The High Mountains and High Himalayas have alpine with the permafrost snowline (3,000-5,000 masl). The amount of rainfall and its distribution varies considerably from east to west due to the physiography of Nepal.

Strong spatial and temporal variations exist in rainfall distribution in Nepal ranging from less than 150 mm to more than 5,000 mm [112]. The amount of precipitation varies from south to north and east to west. The southeastern part of the country receives the higher annual total precipitation compared to the northwestern part and there is also altitudinal variation of monsoon precipitation. Maximum precipitation occurs around 1000 masl in the Narayani Basin and around 1,500 masl in the Saptakosi Basin. The annual precipitation is about 300-400 mm in the northern Himalayan region, 1,000-1,500 mm in the subtropical and tropical region and 1,500-2,500 mm in the temperate region [104]. Precipitation variation between 1,500 to 2,500 mm predominates over the most part of the country.

4.2. Data Collection and Processing

The basic data required for the rainfall-runoff hydrological modeling are: (i) Digital Elevation Model (DEM), (ii) Stream Network, (iii) Land use/Land cover data, (iv) Soil data and (v) Weather data (precipitation, temperature, solar radiation, wind velocity, relative humidity). These data were collected from various sources and are presented in Table 2. These data were preprocessed before using them as the input to the hydrological model.

Table 2: Type and Sources of Data Collection

S.N.	Data Types	Sources
1	ASTER-GDEM 30m	ASTER Global Digital Elevation Model [113]
2	Land use/Land cover raster map	Global Land Cover 2000 [114]
3	Soil Data	FAO Digital Soil Map [115]
4	Daily Precipitation Data	DHM, Nepal [116]
5	Monthly Discharge Data	DHM, Nepal [116]
6	Daily Weather Data	Global Weather Data for SWAT [117]
7	Administrative Boundary Map	ICIMOD Mountain Geo Portal [118]

4.2.1. Digital Elevation Model

DEM is a digital cartographic/geographic dataset of elevations in xyz coordinates [119]. DEM is widely used in many applications such as geomorphology and landscape studies, archeology, forestry and wildlife management, geological and hydrological modeling, GIS, climate impact studies and educational programs [120]. There are two publicly available DEM dataset: SRTM (Shuttle Radar Topography Mission) and ASTER GDEM (Advanced Space borne Thermal Emission and Reflection Radiometer Global-DEM). ASTER GDEM has 30 m resolution compared to 90 m resolution in SRTM DEM [121] and is better for mountainous terrain than SRTM [122]. Therefore, ASTER GDEM was selected in the present study. The DEM dataset of the Nepal region (1°× 1° resolution) was downloaded from ASTER GDEM website in the form of tiles. These tiles were merged by using Data management tool available in Arc GIS toolbox. Merged DEM was clipped using the administrative boundary map of Nepal. Since Nepal lies in the projected coordinate system in WGS 1984/ UTM zone 44N and 45N, the clipped DEM was projected at Northern Hemisphere, WGS 1984/UTM zone 44N coordinates system. Figure 11 shows the projected DEM map of Nepal.

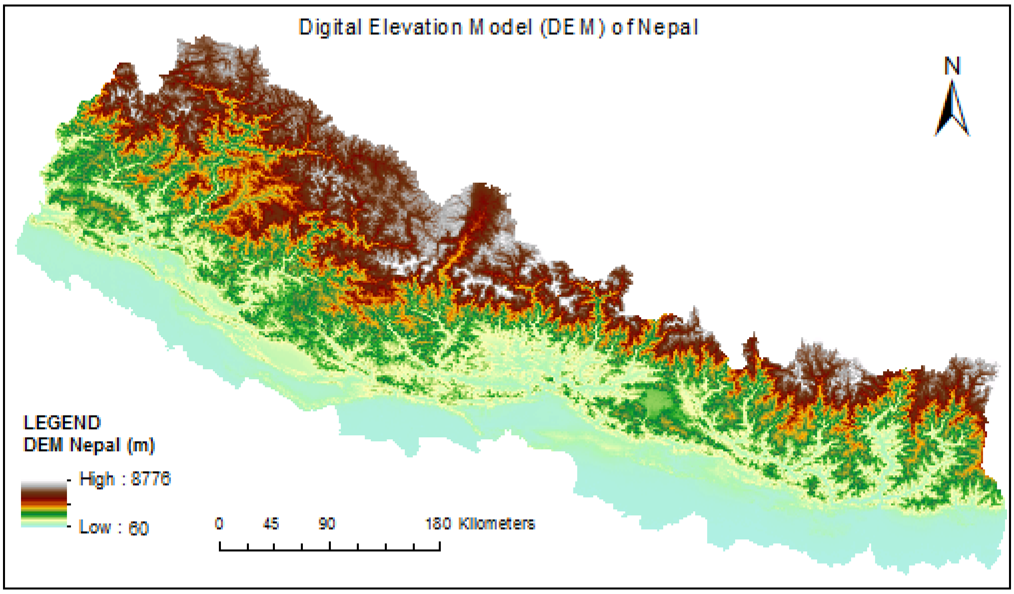

Figure 11: Projected Digital Elevation Model of Nepal (Source: Author)

4.2.2. Watershed Delineation

The first step in any kind of hydrological modeling is the delineation of streams and watersheds and getting some basic watershed properties such as area, slope, flow length, stream network density etc. The process of delineating watersheds by using DEM is referred to as terrain pre-processing [123]. In this study, the watershed was delineated using the "Hydrology" tool within the Spatial Analyst tools in Arc Toolbox. Following steps are followed for the watershed delineation.

1. Fill Sink: It is very important to use a DEM with no depression or sinks because the flow direction cannot be assigned for the sinks. Water is trapped in the sink and hence cannot flow out. Sinks in elevation data are mostly due to errors in the data and are often caused by sampling effects and the rounding of elevations to integer numbers. As the cell size increases, the number of sinks in a dataset also increases. Therefore, to create an accurate representation of flow direction and accumulated flow, it is necessary to use DEM devoid of sinks. Sinks were filled in the DEM using "Fill" within the Hydrology tool in Spatial Analyst tools. Fill tool modifies the elevation values to remove sinks.
2. Flow Direction: Flow direction must be known for each cell because it determines the ultimate destination of water flowing from every cell in the raster. This is done with "Flow direction" tool. This tool outputs a raster showing the direction of flow out of each

cell. There are eight output directions related to the eight adjacent cells into which flow could travel. This is referred to as an eight-direction (D8) flow.

3. Flow Accumulation: This tool computes the accumulated number of cells upstream of a cell flowing into each down slope cell in the output raster. If no weight raster is provided, a weight of 1 is applied to each cell and the value of cells in the output raster is the number of cells that flow into each cell. Cells with high flow accumulation are located in drainage channels rather than on hillsides or ridges.
4. Snap Pour Point: This tool is used to ensure the selection of points of high accumulated flow when delineating drainage basins using the Watershed tools. It snaps the pour point to the cells of highest flow accumulation within a specified distance. It converts the pour point into raster format needed later in the watershed delineation step.
5. Watershed: This tool calculates the contributing area above a set of cells in a raster. Flow direction grid and raster version of the pour point are given as input. Figure 12 presents the delineated watershed along with the stream network for the Narayani basin. The delineated watershed for the Kosi and Karnali are given in APPENDIX 1.
6. Stream Definition: Stream network can be defined from DEM using the output from Flow Accumulation function. Using the Raster Calculator tool in ArcGIS, the threshold value of upstream cells was defined to the results of Flow Accumulation using Map Algebra expression.
7. Stream to Feature: This tool converts a stream network in raster format into polyline feature. This stream polyline is used for stream burning during watershed delineation in SWAT model setup.
8. Raster to Polygon: This tool converts a raster dataset into polygon features. The delineated watershed was converted into watershed polygon which was used to extract the required portion of the DEM, land use and soil dataset to be used in SWAT model.

4.2.3. Point Network

The location of runoff stations is required for hydrological modeling and is given as input to the model. The longitude, latitude and elevation information of each station were inserted in Excel and then converted into shape file using ArcGIS. These files were projected in WGS 1984/UTM zone 44N coordinates system.

4.2.4. Land Use and Soil Map

The land use/land cover raster map was downloaded from Global Land Cover 2000 [114] for the Asia region. The required portion of map was extracted with the help of the Koshi, Narayani and Karnali basin watershed boundary polygon using the ArcGIS Spatial Analyst tool. The raster was then projected at WGS 1984/UTM zone 44N coordinate system. The land use map provides the spatial information regarding the uses of land for agriculture, human settlement, forest areas and water bodies. The soil raster map was downloaded from FAO Digital Soil Map site [115] for the Asia region and the required portion was extracted and then projected at WGS 1984/UTM zone 44 N coordinate system. The soil map provides the information about the soil type and soil properties.

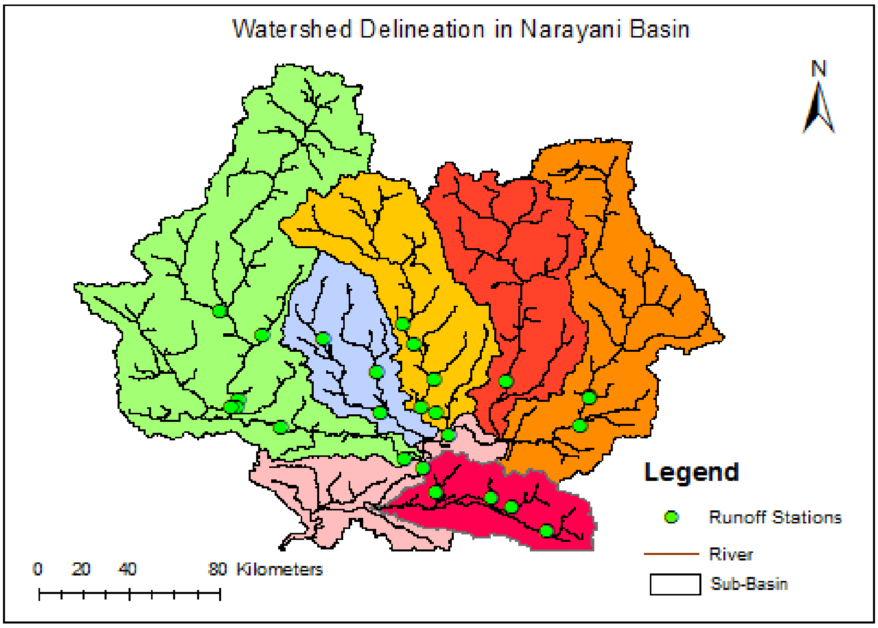

Figure 12: Delineated Watershed in the Narayani Basin (Source: Author)

4.2.5. Weather Data

For the Koshi basin, the daily precipitation data were collected from 28 numbers of rain gauge stations from Department of Hydrology and Meteorology (DHM), Nepal for the period 2000 to 2007. For the Narayani basin, precipitation data were collected from 26 numbers of rain gauge stations for the period 2000-2007. Likewise, for the Karnali basin, the daily precipitation data were collected from 26 numbers of rain gauge stations for the period 2000-2007. Since local data was not available for the part of the basin that lies in Tibet, global weather data [117] were used for precipitation. The data continuity is very important for any hydrological modeling. So the data continuity was checked to find the missing data. The missing data can be filled by interpolation. However, in here the missing data were filled with value -99. The value -99 indicates the missing data in SWAT model and this missing data are filled with weather generator file in SWAT tool. The daily minimum and maximum air temperature data were collected from fifteen stations from DHM, Nepal for each basin. The temperature data are required for the hydrological model to compute the snow melt, type of precipitation (snow or rain) and potential evapotranspiration. For the part of the basin that lies in Tibet, global weather data were used for daily minimum and maximum temperature. Since there are no climatology stations in Nepal above 3000 m elevation, the global weather data were used for temperature. SWAT tool requires the specific file format for precipitation and temperature data. So the collected precipitation and temperature data were arranged as per the required format.

The daily discharge data were collected from DHM, Nepal for the period 1995-2007. Table 3 shows the list of river gauge stations used in the Koshi basin for the purpose of calibration and validation. Table 4 presents the details of the river gauge stations in the Narayani basin. Table 5 presents the list of river gauge stations in the Karnali basin for the purpose of calibration and validation. The data from 2000 to 2002 were used for the warm up period, 2003 to 2005 were used for model calibration and the rest two years data were used for the model validation. The rest of the weather data, such as relative humidity, wind velocity and solar radiation were collected from global weather data.

Table 3: List of river gauge stations used in the Kosi basin (Source: DHM, Nepal)

S.N.	Station ID	River	Location	Latitude	Longitude
1	652	Sunkosi	Khurkot	27° 20' 11"	86° 00' 01"
2	600.1	Arun	Uwa Gaon	27° 35' 21"	87° 20' 22"
3	682	Tamur	Majhitar	27° 09' 30"	87° 42' 45"
4	695	Saptakosi	Chatara-Kothu	26° 52' 00"	87° 09' 30"

Table 4: List of river gauge stations used in the Narayani basin (Source: DHM, Nepal)

S.N.	Station ID	River	Location	Lalitude	Longitude
1	420	Kali Gandaki	Kotagaon Shringe	27° 45' 00"	84° 20' 50"
2	450	Narayani	Narayan Ghat	27° 42' 30"	84° 25' 50"
3	449.91	Trishuli	Kali Khola	27° 50' 08"	84° 33' 12"

Table 5: List of river gauge stations used in the Karnali basin (Source: DHM, Nepal)

S.N.	Station ID	River	Location	Lalitude	Longitude
1	280	Karnali	Chisapani	28° 38' 40"	81° 17' 30"
2	240	Karnali	Asara Ghat	28° 57' 10"	81° 26' 30"
3	269.5	Bheri	Samaiji Ghat	28° 31' 00"	81° 40' 00"

4.3. Setup of the SWAT Model

The SWAT model was set up for each basin as per the methodology described in Section 3.1.1, Chapter 3. During the watershed delineation, the stream network threshold value was provided to define the stream. Likewise, three slope bands were provided due to the steep gradient of the basin during the creation of HRUs. Altogether 4,390 numbers of HRUs and 1,273 numbers of sub-basins were created for the Koshi basin. The total catchment area of the Koshi basin is 53,902 km^2 as per the SWAT report. Likewise, 1,545 numbers of HRUs and 390 numbers of sub-basins were created for the Narayani basin. The total catchment area of the Narayani basin is 36,329 km^2 as per the SWAT report. As per HRU report created by SWAT, 1,591 numbers of HRUs and 236 numbers of sub-basins were created for the Karnali basin. The total catchment area of the Karnali basin is 45,076 km^2 as per the SWAT report. The HRU reports created by SWAT are provided in the Appendix 2. The HRU report provides the information about the distribution of watershed for land use, soil and slope.

Before running the model, simulation period, rainfall distribution and potential evapotranspiration method were selected in the "SWAT Setup and Run" screen. For the potential evapotranspiration, Penman-Monteith method was selected. Skewed distribution was selected for rainfall distribution. Soil Conservation Service-Curve Numbers (SCS-CN) method was selected to estimate the runoff from daily rainfall data. This step also requires the weather station files as the input file. Finally, the model was run successfully and saved the output.

The United Nations Food and Agriculture Organization (FAO) have adopted Penman-Monteith method as a global standard for estimating the evapotranspiration [124]. This method has a sound physical basis and therefore suitable for different surface areas and climatic conditions. Penman-Monteith method takes into account the energy needed to sustain evaporation, the strength of mechanism required to remove the water vapor and aerodynamic and surface terms. The details of this method can be found in SWAT theoretical documentation [65]. SCS-CN runoff equation is an empirical model that was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types [65]. This method was developed by the USDA Natural Resource Conservation Service. The SCS-CN method is based on the water balance equation of the rainfall in a known interval of time. The details of this method can be found in SWAT theoretical documentation [65].

4.4. Calibration, Validation and Evaluation of Model

Calibration is the process of tuning the model parameters within recommended ranges to match the simulated output with the observed data. This involves the comparison of model results with the recorded runoff data at selected outlets. In this process, the model parameters are adjusted in such a way that the simulated results are matched to the recorded flow pattern within some accepted criteria. The calibration can be done by trial and error manually or by automatic numerical optimization. After the calibration of the model, validation is done. Validation is the comparison of model output with an independent observed dataset not used in the calibration without further adjustment of model parameters. In this study, the model calibration period is 2003-2005 and validation period is 2006-2007.

Before proceeding the calibration, some influential input parameters have to be identified. Table 6 shows the most influential surface and ground water hydrological parameters with their acceptable ranges [39, 125, 126, 127, 128, 129, 130, 131, 132, 133]. These parameters were used for the sensitivity analysis. During the sensitivity analysis, only one parameter was varied while keeping the other parameters constant. The sensitivity is measured by relative sensitivity index (RSI) which is defined as:

$$RSI = \frac{(y_2 - y_1)}{(x_2 - x_1)} \times \frac{x_a}{y_a} \tag{8}$$

Where *RSI* is the relative sensitivity index, x_1 and x_2 are the minimum and maximum values of input parameter, y_1 and y_2 are the minimum and maximum values of the model output, x_a is the average value of x_1 and x_2; y_a is the average value of y_1 and y_2. If the value of RSI is less than 0.05, the effect of the parameter is considered negligible [134].

Table 6: SWAT input parameter ranges and initial values [39, 125, 126, 127, 128, 129,130]

S.N.	Parameters	Variable Name	Range
1	Runoff curve number	CN2	51 to 94
2	Available soil water capacity(mm H_2O/mm soil)	SOL_AWC	0 to 1
3	Soil evaporation compensation factor	ESCO	0 to 1
4	Groundwater revap coefficient	GW_REVAP	0.02 to 0.2
5	Threshold water level in shallow aquifer for revap	REVAPMN	0 to 500
6	Threshold water depth in shallow aquifer for base flow (mm H_2O)	GWQMN	0 to 5000
7	Surface runoff lag coefficient	SURLAG	1 to 10
8	Baseflow alpha factor (days)	ALPHA_BF	0 to 1
9	Deep aquifer percolation fraction	RECHRG_DP	0 to1
10	Ground water delay time (day)	GW_DELAY	0 to 100
11	Snow melt factor for snow on June 21	SMFMX	1.4 to 8
12	Soil hydraulic conductivity	SOL_K	0 to 100
13	Manning's n value for main channel	CH_N2	0 to 1

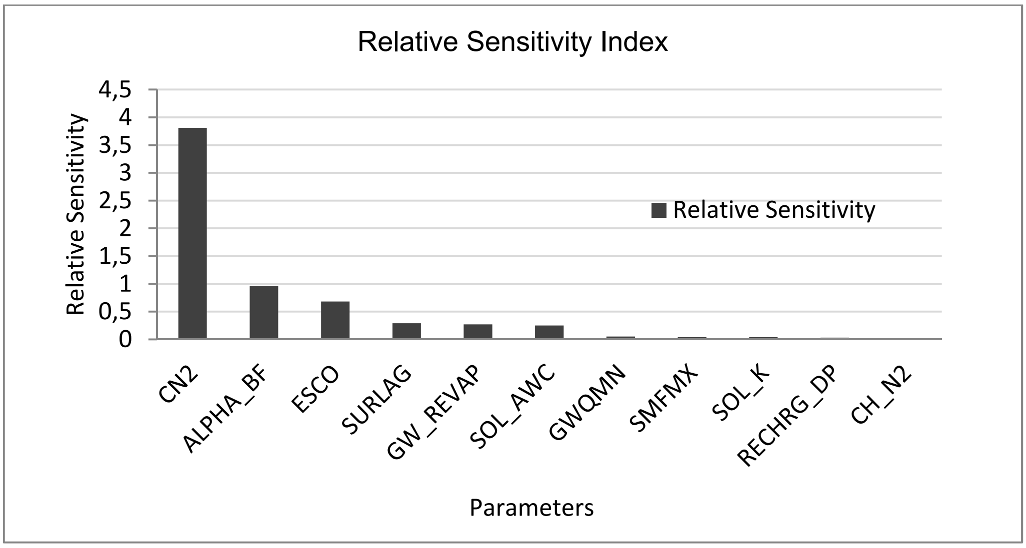

Figure 13: Sensitive parameters and their relative sensitivities in the Koshi basin outlet (Source: Author)

The list of parameters used in SWAT tool for surface and groundwater modeling are provided in the APPENDIX 3. Figure 13 and Figure 14 present the results of the sensitivity analysis. These figures show the sensitive parameters and their relative sensitivities for the Koshi and Karnali basin respectively. Similarly, the sensitive parameters for the Narayani basin are presented in Figure 15. Only these sensitive parameters were used in the model calibration.

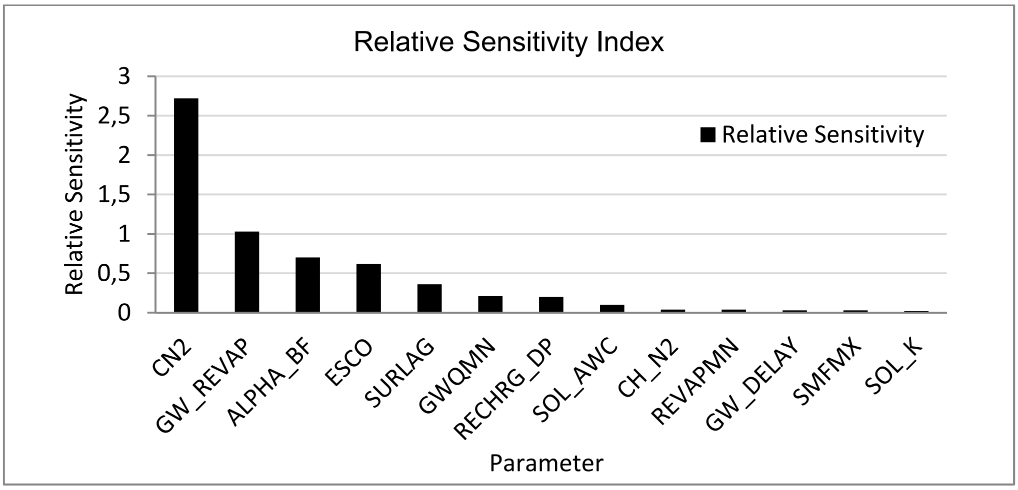

Figure 14: Sensitive parameters and their relative sensitivities in the Karnali basin outlet (Source: Author)

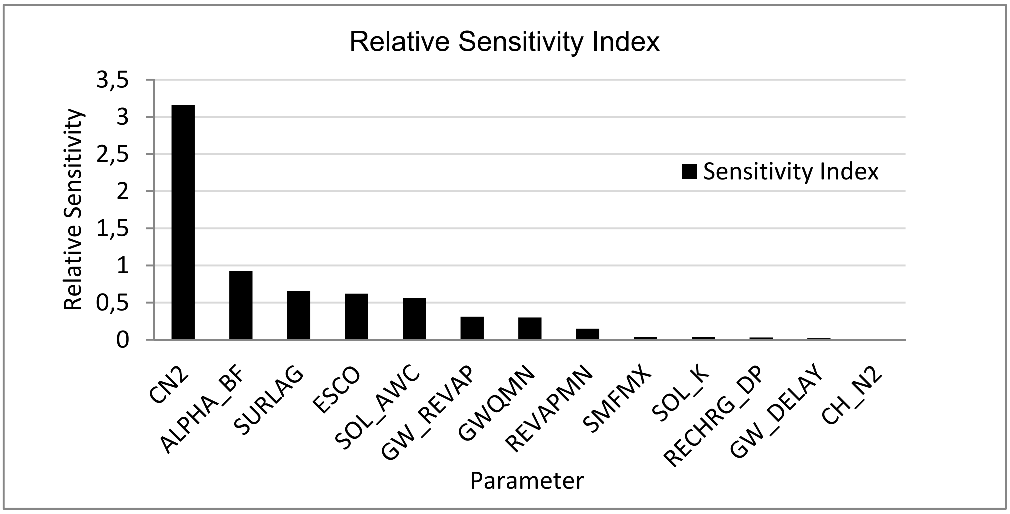

Figure 15: Sensitive parameters and their relative sensitivities in the Narayani basin outlet (Source: Author)

4.4.1. Evaluation of a Model

The performance of a model is evaluated in order to assess how close the model simulated values are with the observed values. There are several statistical techniques for evaluating the performance of a model. They are: coefficient of determination (R^2), Pearson's correlation coefficient (r), percent bias (PBIAS), root mean square error (RMSE), mean square error (MSE), mean absolute error (MAE), Nash-Sutcliffe efficiency (E_{NS}) etc.

[135, 136, 137]. In this study, the performance of this model was evaluated by using the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E_{NS}). Arnold et al. [125], Moriasi et al. [136], Santhi et al. [138] have recommended the quantitative value to evaluate the performance of the model. A model is considered satisfactory and can be used for further application if E_{NS} > 0.5 and R^2 >0.6, adequate if E_{NS} is in between 0.5 and 0.75 and very good if E_{NS} and R^2 > 0.75.

The coefficient of determination (R^2) is the portion of the total variation explained by fitting a regression line and is regarded as a measure of the strength of a liner relationship between observed and simulated data. It is calculated using equation (9):

$$R^2 = \left\{ \frac{\sum_{i=1}^{n}(O_i - O_{av})(S_i - S_{av})}{\sqrt{\sum_{i=1}^{n}(O_i - O_{av})^2}\sqrt{\sum_{i=1}^{n}(S_i - S_{av})^2}} \right\} \tag{9}$$

Where O_i is the i^{th} observed value, O_{av} is the mean of observed value, S_i is the i^{th} simulated value, S_{av} is the mean of simulated value and n is the total number of data. The value of R^2 ranges between 0 and 1 and greater than 0.6 is considered satisfactory [125,136].

Nash-Sutcliffe efficiency (E_{NS}) is a normalized statistics that determines the relative magnitude of the residual variance compared to the measured data variance. E_{NS} indicates how well the plot of observed versus simulated data fits 1:1 line [136]. It is computed by the equation (10).

$$E_{NS} = \left\{ 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O_{av})^2} \right\} \tag{10}$$

Where O_i is the i^{th} observed value, O_{av} is the mean of the observed value, S_i is the i^{th} simulated value and n is the total number of data. The value of E_{NS} varies from 0 to 1 with 1 being the perfect fit and greater than 0.5 is considered satisfactory.

4.4.2. Calibration and Validation of the SWAT Model

Calibration is the most important phase in the modeling process and therefore, well-established calibration procedure should be followed. In this study, the manual calibration procedure was applied. The steps followed are based on the recommendations given in SWAT user manual [65]. First of all, calibration for the water balance and stream flow is done for the average annual conditions. This will take care of the overall flow volume. Then temporal flow calibration is done to fine tune the shape of hydrograph. Figure 16 shows the flowchart of a manual calibration process used in this study as recommended in SWAT user manual [65] and in the literature [136] and [138].

First of all, stream flow is separated into base flow and surface flow for the given observed flow data. The surface runoff is calibrated first by adjusting the parameters within the ranges shown in the figure. Once the surface runoff is within the acceptable range, the base flow is calibrated. In this study, web based SWAT Bflow filter program recommended in SWAT official website [139] is used to separate the daily stream flow into surface runoff and base flow and the results are presented in Table 7 in terms of base flow ratio (baseflow/stream flow) for the selected runoff stations in the Koshi, Narayani and Karnali basin. The base flow ratio shows the contribution of baseflow to the stream flow and is expressed in percentage. Table 7 indicates that on an average, the contribution of base flow to the total flow is 65%. Flow calibration is performed for three years from January 2003 to December 2005 and validation is done for two years from 2006 to 2007. The calibration is first performed for all the tributaries and then is done for the main river outlet.

Table 7: Base flow ratio for the selected runoff stations (Source: Author)

Basin Name	Station No.	Base flow Ratio (%)
Kosi	652	61
	600.1	69
	684	63
	695	68
Narayani	449.91	58
	450	60
	420	61
Karnali	240	64
	269.5	66
	280	70

4.4.2.1. The Kosi Basin

Figure 17 presents the comparison of calibration and validation results for the runoff Station No.652 against the observed runoff in the Koshi basin. For the rest of the stations, the figures are given in the APPENDIX 4.

Using the equations (9) and (10) provided in Section 4.4.2, the calibration and validation statistics were calculated for the selected run-off stations in the Kosi basin. The results of statistics for the four runoff stations, Station No.652 (Sunkosi River), 600.1 (Arun River), 648 (Tamur River) and 695 (Kosi basin watershed outlet) are presented in Table 8. This table shows that during the calibration and validation period, the value of R^2 is greater than 0.6 and that of the value of E_{NS} is greater than 0.5 for all the stations.

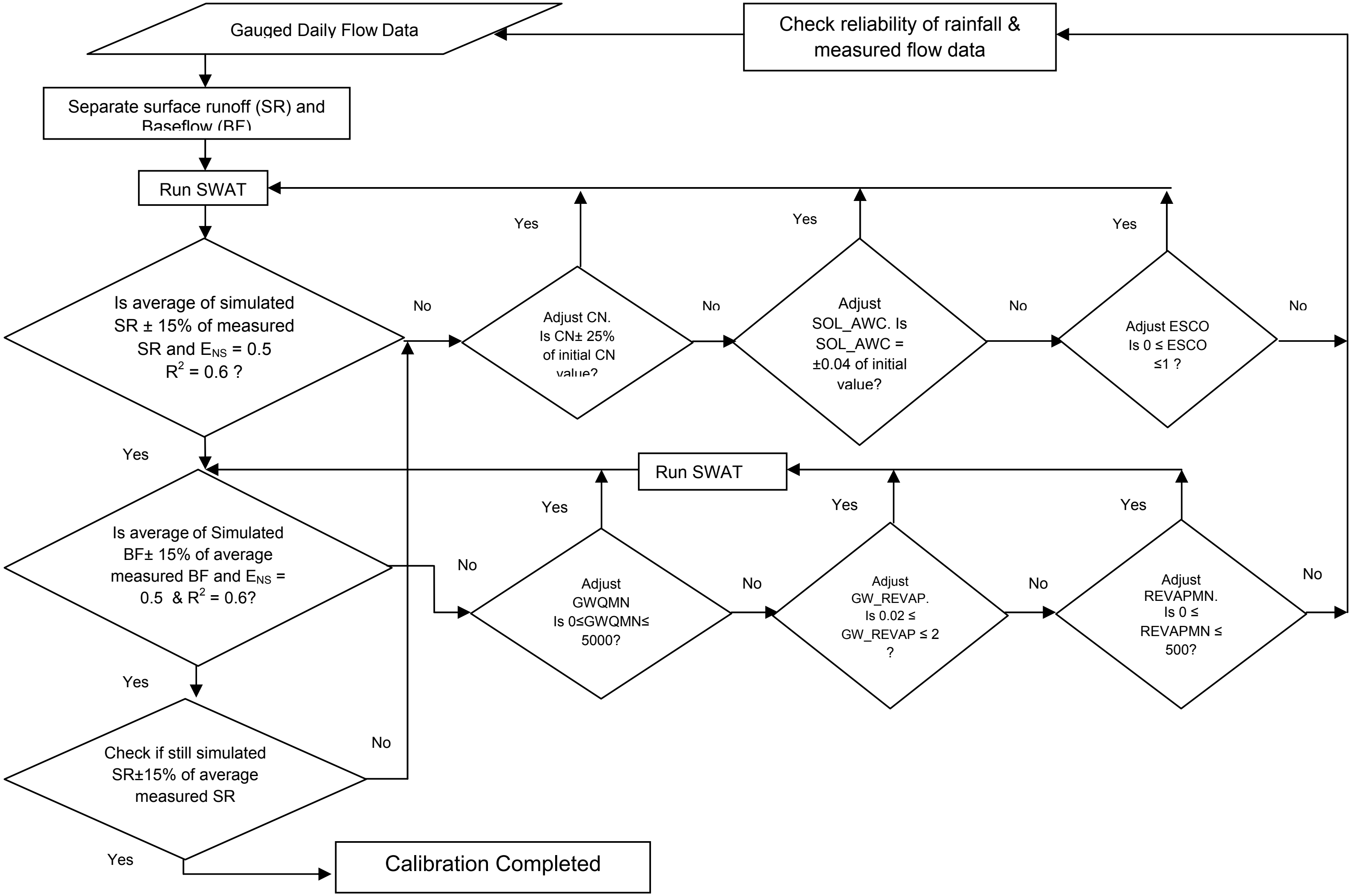

Figure 16: Manual calibration process flowchart used in this study. Diagram extended from [65, 134, 138]

Table 8: Calibration and validation statistics for simulated and observed flow at Koshi basin (Source: Author)

Evaluation Phase	Station No.	Period	Model Evaluation Statistics		% Error between calibration and validation	
			R^2	E_{NS}	R^2	E_{NS}
Calibration	652	2003-2005	0.86	0.75	8.1	2.7
Validation		2006-2007	0.79	0.73		
Calibration	600.1	2003-2005	0.81	0.71	7.4	4.2
Validation		2006-2007	0.75	0.68		
Calibration	682	2003-2005	0.8	0.76	3.8	9.2
Validation		2006-2007	0.77	0.69		
Calibration	695	2003-2005	0.80	0.69	8.75	5.7
Validation		2006-2007	0.73	0.65		

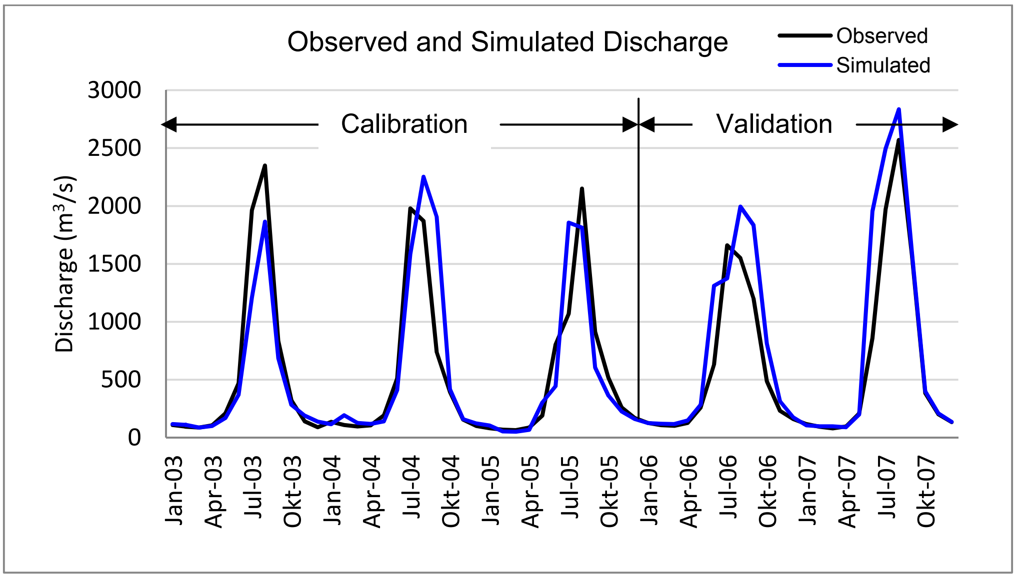

Figure 17: Observed and simulated discharge at station No. 652 in the Koshi basin (Source: Author)

4.4.2.2. The Narayani Basin

For the Narayani basin as well, the calibration and validation statistics were calculated for the selected run-off stations. The calibration and validation statistics are presented in Table 9. The statistics indicate that the model performance is good during calibration period and satisfactory during the validation period for all the stations. This table shows that for the calibration and validation period, the value of R^2 is greater than 0.6 and that of the value of E_{NS} is greater than 0.5. Figure 18 shows the comparison of calibration and validation results for the Station No. 450 in the Narayani basin watershed outlet with reference to the observed runoff. For the rest of stations, the figures are provided in the APPENDIX 5.

Table 9: Calibration and validation statistics for simulated and observed flow in the Narayani Basin (Source: Author)

Evaluation Phase	Station No.	Period	Model Evaluation Statistics		% Error between calibration and validation	
			R^2	E_{NS}	R^2	E_{NS}
Calibration	420	2003-2005	0.81	0.79	9.9	12.7
Validation		2006-2007	0.73	0.69		
Calibration	449.91	2003-2005	0.76	0.75	-9.2	5.3
Validation		2006-2007	0.83	0.71		
Calibration	450	2003-2005	0.73	0.71	-1.4	2.9
Validation		2006-2007	0.74	0.69		

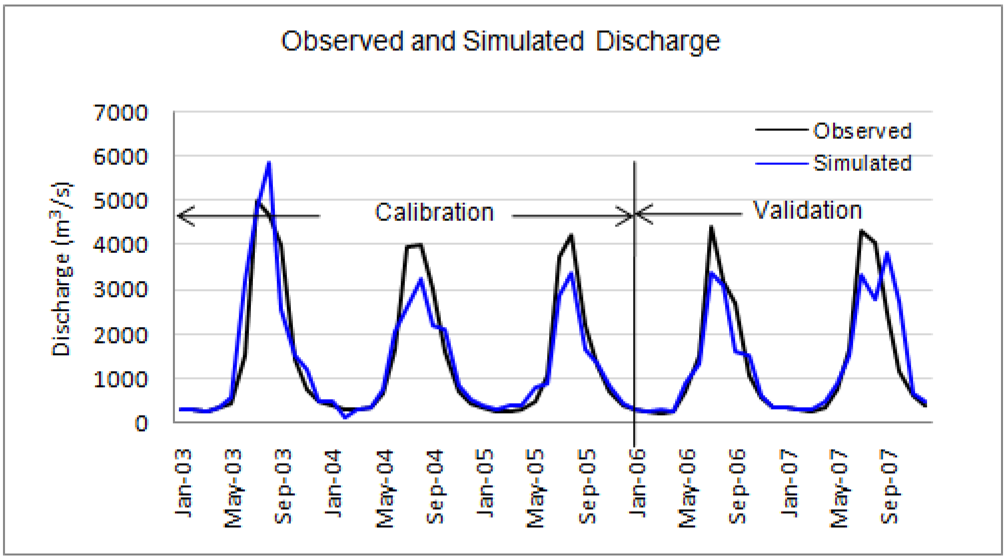

Figure 18: Observed and simulated discharge at station No. 450 in the Narayani basin (Source: Author)

4.4.2.3. The Karnali Basin

The calibration and validation statistics were calculated for the selected run-off stations using equation (9) and (10) and are given in Table 10.

Table 10: Calibration and validation statistics for simulated and observed flow in the Karnali Basin (Source: Author)

Evaluation Phase	Station No.	Period	Model Evaluation Statistics		% Error between calibration and validation	
			R^2	E_{NS}	R^2	E_{NS}
Calibration	240	2003-2005	0.81	0.72	1.2	6.9
Validation		2006-2007	0.80	0.67		
Calibration	269.5	2003-2005	0.83	0.75	8.4	6.6
Validation		2006-2007	0.76	0.70		
Calibration	280	2003-2005	0.74	0.69	2.7	2.8
Validation		2006-2007	0.72	0.67		

Figure 19 presents the comparison of calibration and validation results for the Station No. 240. For the rest of the stations, the figures are provided in the APPENDIX 6. The calculated statistics indicate that the model performance is good during calibration and satisfactory during the validation period for all the stations. This table shows that the value of R^2 is greater than 0.6 and that of the value of E_{NS} is greater than 0.5 for all the stations.

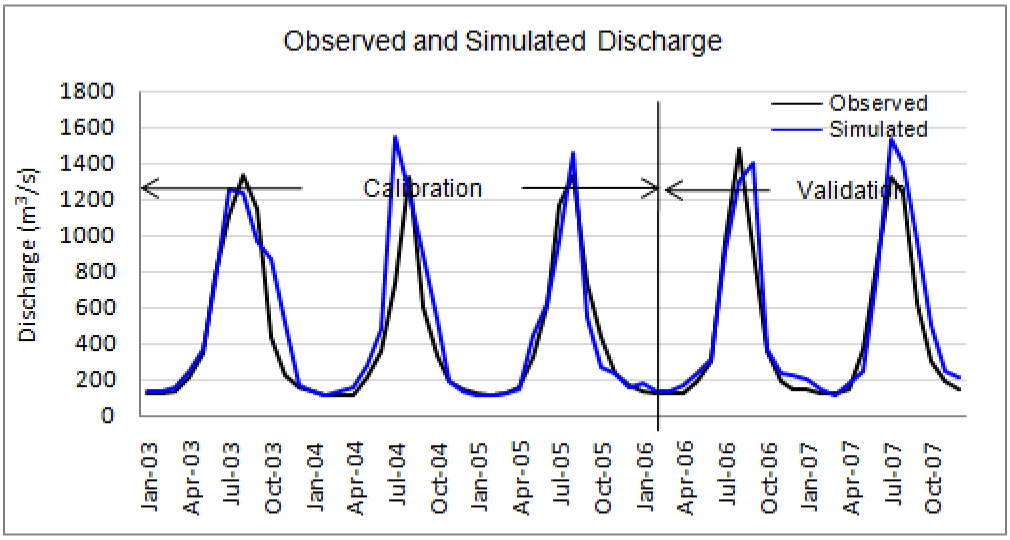

Figure 19: Observed and simulated discharge at station No. 240 in the Karnali basin (Source: Author)

4.4.2.4. Variation of Flow

Figure 20 shows the comparison of observed and simulated flow-duration curve at the station No. 652 in the Koshi basin. This figure shows the close match between the observed and simulated flow at the lower end of the curve, but high flows are little overestimated by the model. The average variation of the flow is about 9.7% for the entire curve. Figure 21 shows the comparison of observed and simulated flow-duration curve at the station No. 420 in the Narayani basin. In this case, the average variation of the flow is 6% for the entire curve. Figure 22 shows the comparison of observed and simulated flow-duration curve at the station No. 280 in the Karnali basin. For rest of the stations, the compared flow-duration curve has been provided in the APPENDIX 7.

In order to estimate the amount of variation of flow in simulated FDC[1] with respect to the flow in observed FDC[2], the percentage of flow difference was calculated for all the flow exceedance ≥ 30% for each runoff stations and all these variations were gathered together and their normality test was done. Since these variations are approximately normally distributed with mean 5.22% and standard deviation 6.92 %, it can be estimated that the flow variation in simulated FDC ranges at ±12.14% at 68 % confidence level and at ±19.06 % at 95% confidence level. Figure 23 shows the error histogram with normality test and

[1] Flow-duration curve drawn from simulated data
[2] Flow -duration curve drawn from observed data

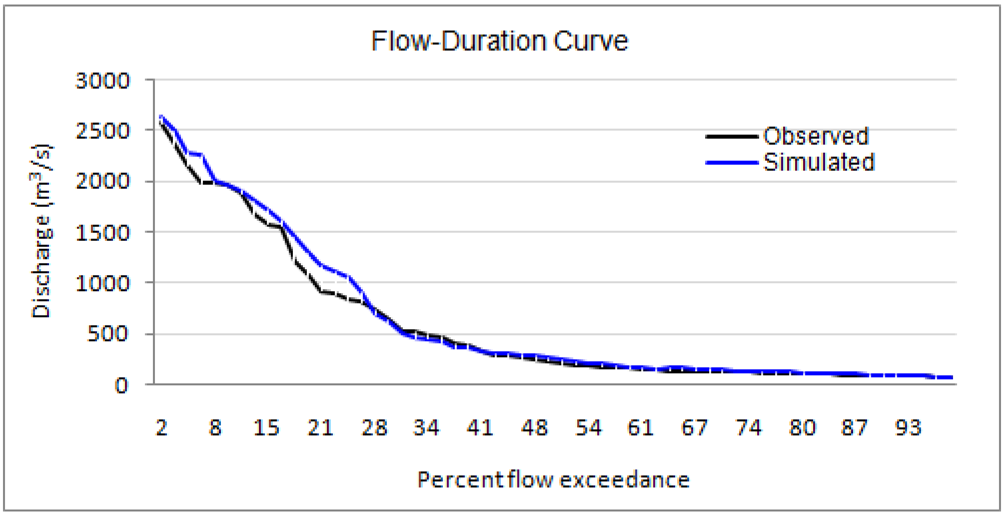

Figure 20: FDC of the observed and simulated flow at station No. 652 in the Koshi basin (Source: Author)

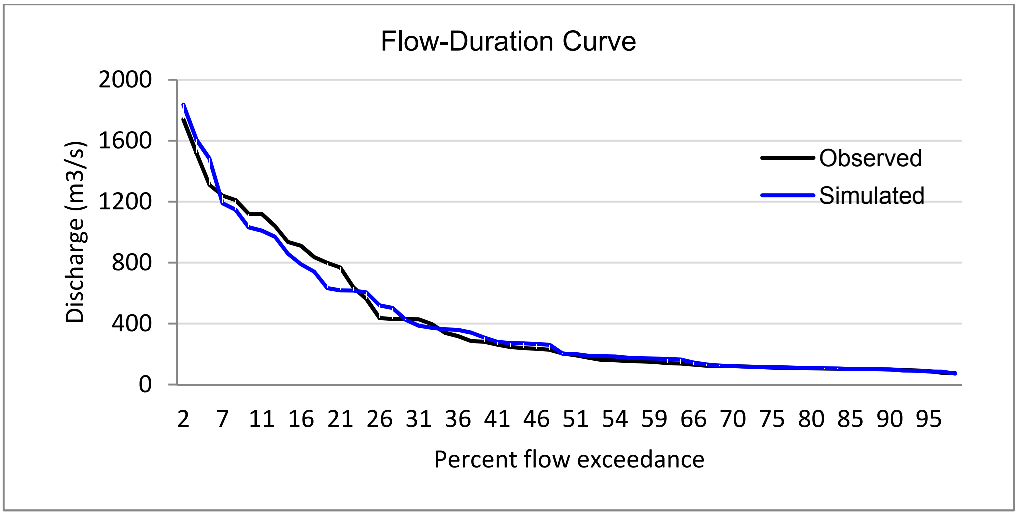

Figure 21: FDC of the observed and simulated flow at station No. 420 in the Narayani basin (Source: Author)

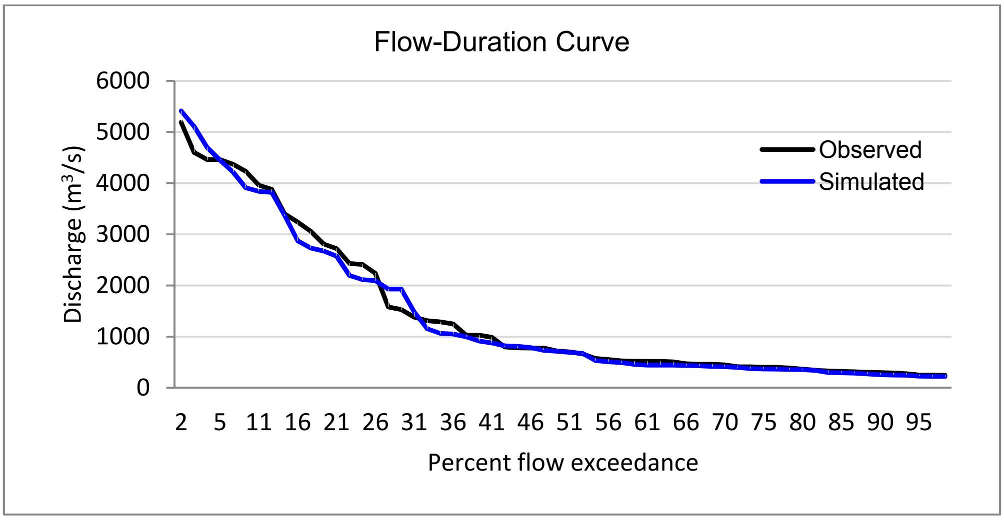

Figure 22: FDC of the observed and simulated flow at station No. 280 in the Karnali basin (Source: Author)

confidence intervals. Similar test was done for the entire FDC curve by gathering all the variations and was found normally distributed with mean 4.39% and standard deviation 11.4%. The error histogram is provided in the APPENDIX 9. Therefore, at 95% confidence interval, the variation of flow in simulated FDC for the entire curve is to the tune of ±27.19%

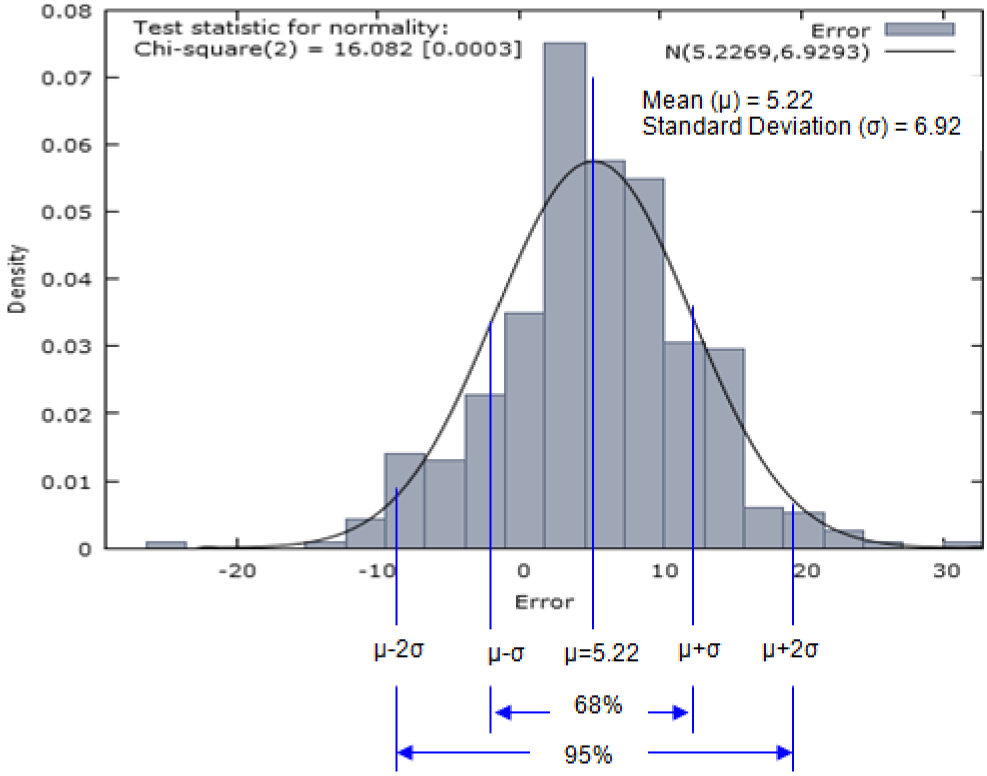

Figure 23: Error histogram with normality test and confidence interval for the flow exceedance ≥ 30% (Source: Author)

4.4.2.5. Model Limitations

All models including SWAT are simplified representation of the reality. Therefore, model output reflects uncertainties. The model output is compared to corresponding measured data to observe the performance of the model. The performance of the model will be the perfect when the value of Nash-Sutcliffe efficiency (E_{NS}) and Coefficient of determination (R^2) is 1. However, due to various reasons the model fails to achieve this target. Some of the basic reasons are the insufficient number of precipitation inputs and their spatial coverage in the simulated watershed. The number of years of precipitation inputs also affects the model results. Likewise measurement uncertainty in precipitation and discharge data also result in poor calibration and validation results. The error in land use and soil data used in the model can affect the model outputs. Likewise, the error level in the DEM and resampling of raster cell size may affect the accuracy of the delineated watershed which in turn affects the model outputs. Insufficient calibration may also lead to model output error.

In this study, there are some limitations regarding the data. In Nepal, most of the precipitation stations are concentrated below 3000 masl and therefore, most of the precipitation data used in this study comes from below 3000 masl and their spatial coverage is not good. For the elevation above 3000 masl, global weather data were used. Also, the length of data period used in this study is only eight years which is relatively short. Local data is more realistic than the global data. However, due to the lack of the local data, land use/land cover data were taken from Global Land Cover 2000 which was published in 2002. Likewise, for the soil data, the digital soil data published in 2007 by Food and Agriculture Organization (FAO) were used.

4.5. Flow Duration Curve

Flow-duration curve (FDC) is the basic tool for ROR hydropower study. The Kosi basin watershed has 1,273 numbers of sub-basins. Out of these, about half of the sub-basins lie in Tibet, China. Among the number of sub-basins that lie in Nepal, only 300 numbers of sub-basins with catchment area ≥ 100 km^2 were selected for the estimation of hydropower potential. Out of these 300 numbers of sub-basins, only 240 numbers of FDCs were generated. The remaining 60 number of sub-basin rivers are intermediate and FDCs of these rivers and their upstream were considered identical. From the FDCs, flow exceedance at 30% was considered to estimate the power potential.

There are 390 numbers of sub-basins in the Narayani river basin. Out of these, 47 numbers of sub-basins lie in Tibet, China. Altogether 205 numbers of FDCs were generated and the remaining 38 numbers of sub-basins are intermediate and therefore, FDC of these rivers and their upstream were assumed identical. Likewise, there are 236 numbers of sub-basins in the Karnali river basin. Out of these, 12 numbers of sub-basins lie in Tibet, China. Out of the remaining sub-basins, 175 numbers of sub-basins were considered for the study. 160 numbers of FDC were produced and the rest 15 numbers of sub-basins are intermediate and their FDC were assumed identical to their upstream sub-basins.

4.6. Potential Head Drop

Estimation of hydropower potential requires the calculation of potential head drop along the river. Head drop was calculated for each selected sub-basin stream using the methodology described in Section 3.1.2, Chapter 3.

4.7. Estimation of Hydropower Potential

As a rough estimation, the potential was initially calculated at annual mean flow and then was estimated at 30% flow exceedance. The estimated total theoretical ROR hydro potential of rivers in Nepal is 103,341 MW at annual mean flow and 119,186 MW at 30%

flow exceedance. The total power potential and their distribution in different river basins are presented in Table 11. This table indicates that the Koshi basin has the highest power potential compared with the Narayani and Karnali basin. The total length of river considered in estimating the power potential is 2,006 km for the Koshi basin while the river length considered is 3,140 km and 2,911 km respectively for the Narayani and Karnali river basins. The major rivers in Koshi, Narayani and Karnali basins are shown in Figure 24.

In this study, the sub-basins of catchment area ≥ 100 km^2 were considered for the estimation of hydro potential. Although the sub-basins with catchment area ≤ 100 km^2 are small, they still have large number of small rivers with discharge 2-5 m^3/s which can be used for the development of micro and small hydropower plants. About 5% to 10% of the entire hydro potential of the country can be estimated to contain in these small sub-basins.

Table 11: Estimated total theoretical hydro potential of Nepal (Source: Author)

S.N.	River Basin	Catchment Area (km^2)	Considered River Length (km)	Estimated Potential (MW)	
				Mean Flow	Q30
1	Koshi Basin	53,902	2,006	35,166	40,888
3	Narayani Basin	36,329	3,140	32,086	37,445
2	Karnali Basin	45,077	2,911	25,755	28,823
4	Rest of small basin			10,334	12,029
Total theoretical ROR Power Potential				103,341	119,185

Shrestha estimated hydro potential of Nepal using the annual mean flow and 80% system efficiency [17]. Therefore, Shrestha's potential figures have been converted into theoretical potential using 100% system efficiency and then comparison has been made with the potential estimated in this study at annual mean flow. Table 12 shows the comparison of author's estimation with Shrestha's estimation. Although there is no significant difference in the total potential of the entire country between the two estimations, there is difference in the distribution of potential among different basins. In the Koshi basin, Shrestha's estimated potential is smaller than the author's estimation by about 7,000 MW. Likewise, in the Narayani basin, Shrestha's estimation is smaller than author's estimated potential by 6,000 MW. In the Karnali basin, the difference between the Shrestha's estimated potential and author's estimation is very large compared to the rest of two basins and Shrestha's estimation is higher than author's estimation by 14,000 MW.

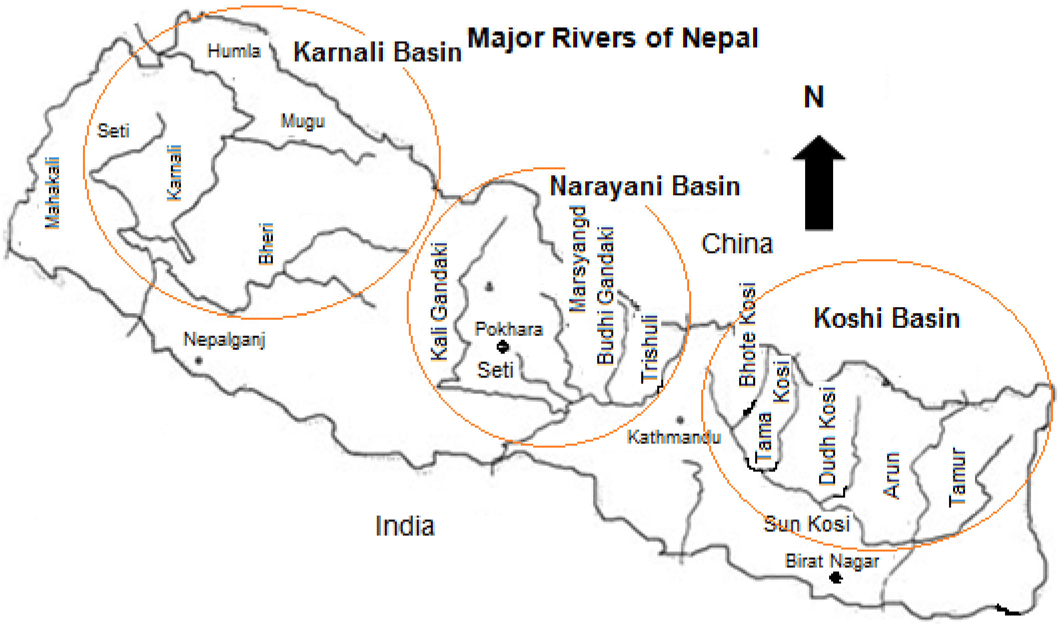

Figure 24: Major Rivers of Nepal Extended from [Source:www.quazoo.com]

Table 12: Comparison of author's estimated potential figures with Shrestha's estimation (Source: Author)

River Basin	Author's theoretical estimation at annual mean flow (MW)	Shrestha's Estimation (MW)	
		At annual mean flow & 80% efficiency	Theoretical estimation at annual mean flow
Koshi Basin	35,166	22,350	27,938
Narayani Basin	32,086	20,650	25,813
Karnali Basin	25,755	32,010	40,013
Rest of small basin	10,334	8,171	10,214
Total ROR Potential	103,341	83,181	103,976

4.7.1. The Koshi Basin Hydro Potential

The Koshi basin has three main sub-basins: Sunkosi, Arun and Tamur. Table 13 shows the distribution of estimated power potential in these sub-basins at different flow exceedance.

Table 13: Estimated theoretical ROR hydro potential in the Koshi Basin (Source: Author)

S.N.	Name of River	Catchment Area (km^2)	Power (MW)		Average Linear Power Density at Q30 (MW/km)
			Mean Flow	Q30[3]	
1	Sunkosi sub-basin	18,287	18,704	22,057	19
2	Arun sub-basin	29,530	8,941	10,455	24
3	Tamur sub-basin	6,085	7,520	8,375	21
Total ROR Potential			35,165	40,887	

[3] Flow available for about 110 days in a year

This table shows that the Sunkosi sub-basin has the highest power potential. The linear power density of river which is the ratio of the total power potential of a river to its total length has been given in this table. The linear power density provides the information of the power potential per unit length of a stream. The higher the linear power density of a stream, the more megawatt will be available per unit length of the stream. This information is useful in the selection of rivers for the development of ROR hydropower plants during the reconnaissance study because more power can be produced from a river with high linear power density.

4.7.1.1. The Sunkosi Sub-Basin

In the Sunkosi sub-basin, the Sunkosi River is the main river and is fed by different tributaries as shown in Figure 24. Indrawati, Tamakosi, Khimti and Dudhkosi are the major tributaries of the Sunkosi River. Table 14 presents the estimated theoretical ROR hydro potential of the Sunkosi River. This table indicates that the Dudhkosi River has the highest power potential compared to other tributaries in this sub-basin.

Table 14: Estimated theoretical ROR hydro potential in the Sunkosi sub-basin (Source: Author)

S.N.	Name of River	Catchment Area (km^2)	Power (MW)	
			Mean Flow	Q30
1	Sunkosi Main River	18,287	2643	2827
2	Bhotekosi River	2,598	826	956
3	Balephi Khola	686.8	1136	1388
4	Indrawati River	1,140	1091	1212
5	Tamakoshi	3,360	3094	3327
6	Khimti	449.3	597	623
7	Likhu	1,054	1477	1966
8	Dudhkoshi	4,087	7839	9758
Total theoretical ROR hydro potential			18,704	22,057

4.7.1.2. The Arun Sub-basin

Table 15 shows the estimated total hydro potential at various flow exceedance in the Arun sub-basin. It is the largest sub-basin in the Koshi basin watershed.

Table 15: Estimated theoretical ROR hydro potential in the Arun sub-basin (Source: Author)

S.N.	Name of River	Catchment Area (km^2)	Power (MW)	
			Mean Flow	Q30
1	Arun main river	29,530	7,490	8,512
2	Arun tributaries		1,451	1,943
Total theoretical ROR hydro potential			8,941	10,455

4.7.1.3. The Tamur Sub-Basin

The Tamur sub-basin is the smallest sub-basin of the Koshi basin. The estimated theoretical hydro potential of this sub-basin is 7,520 MW at annual mean flow and 8,375 MW at 30% flow exceedance. The estimated theoretical ROR hydro power potential of this sub-basin at various flow exceedance is presented in Table 16.

Table 16: Estimated theoretical ROR hydro potential in the Tamur sub-basin (Source: Author)

S.N.	Name of River	Catchment Area (km^2)	Power (MW)	
			Mean Flow	Q30
1	Tamur main river	6,085	3,274	3,592
2	Tamur tributaries		4,246	4,783
Total theoretical ROR hydro potential			7,520	8,375

4.7.2. The Narayani Basin Hydro Potential

The Narayani basin is the third largest river basin and has the abundant hydro potential. The hydro potential of this basin is second highest after the Koshi basin. The distribution of estimated power potential in this basin at different flow exceedance is presented in Table 17. The major tributaries of this basin are: Kali Gandaki, Trishuli, Marsyangdi, Budhi Gandaki, Seti and Rapti which are shown in Figure 24 above. Among these tributaries, the Kali Gandaki River has the highest power potential followed by Trishuli River compared with other rivers. The estimated power potential of the Kali Gandaki River is 9,574 MW at 30% flow exceedance and 9,024 MW at annual mean flow. Likewise, the estimated potential of the Trishuli River is 9,498 MW at 30% flow exceedance and 8,363 MW at annual mean flow respectively. This river has the highest linear density of power potential. The Marsyangdi River has the third highest power potential which is 8,257 MW at 30% flow exceedance.

Table 17: Estimated theoretical ROR hydro potential in the Narayani Basin (Source: Author)

S.N.	Name of River	Catchment Area (km^2)	Power Calculation (MW)		Linear Power Density at Q30 (MW/km)
			Mean Flow	Q30	
1	Kali Gandaki	11,879	9,024	9,574	9.5
2	Trishuli	6,620	8,363	9,498	18
3	Marsyangdi	4,800	6,476	8,257	17.5
4	Budi Gandaki	5,000	5,039	6,743	16
5	Seti	2,955	1,477	1707	6
6	East Rapt	2,499	547	398	1
7	Narayani River		1,161	1,268	13.5
Total theoretical ROR hydro potential			32,087	37,445	

4.7.3. The Karnali Basin Hydro Potential

The distribution of the estimated power potential in the Karnali basin at different flow exceedance is presented in Table 18. The Karnali basin has three major tributaries: Karnali, Thulo Bheri and Seti River and are shown in Figure 24 above. The Karnali River is the biggest river among the three rivers and has the highest power potential. This river has also the highest linear density of power potential as indicated in Table 18.

Table 18: Estimated theoretical ROR hydro potential in the Karnali Basin (Source: Author)

S.N.	Name of River	Catchment Area (km^2)	Power Calculation (MW)		Linear Power Density at Q30 (MW/km)
			Mean Flow	Q30	
1	Karnali River	22,415	14,261	17,179	29
3	Thulo Bheri River	13,335	7,138	7,755	13
5	Seti River	7,653	4,356	3,889	12
Total theoretical ROR hydro potential			25,755	28,823	

4.8. Error Estimation

The errors in head and discharge ultimately lead to the error in the estimation of hydropower potential. The maximum variation of flow in simulated FDC is ±12.14% at 68 % confidence level and at ±19.06 % at 96 % confidence level as explained in Section 4.4.2.4 for the flow exceedance ≥ 30%. The error in head drop calculation comes from the error contained in DEM data. The average vertical accuracy of ASTER DEM has been reported to be 8.68 m and ranges from 7.5 m to 21.19 m depending upon the type of land cover [140]. The elevation of the entire basin considered in this study lies above 500 masl, therefore, the average error in head drop can be assumed to be 2% - 3%. With these variations in flow and head, the variation in estimated power potential can be calculated by using following equation:

$$P_{error} = Q_{error} + H_{error} + Q_{error} \times H_{error} \tag{11}$$

Where,

P_{error}	= Relative error in power estimation = $\Delta P/P$
ΔP	= Error in potential estimation (W)
Q_{error}	= Relative error in discharge = $\Delta Q/Q$
ΔQ	= Error in discharge estimation (m^3/s)
H_{error}	= Relative error in head = $\Delta H/H$
ΔH	= Error in head drop (m)

The derivation of this equation is given in the APPENDIX 10. Using this equation, the maximum error range in estimated power potential is ±15.50% at 68% confidence level and ±22.63 % at 96 % confidence level.

CHAPTER 5

Hydro Resource Utilization

This chapter explains the role of power generation and expansion planning for the utilization of country's hydro resources and supplying power to meet the future electricity demand in Nepal. Next, the hydropower project development in Nepal will be briefly discussed. Lastly, the different types of hydropower plants for harnessing the hydro potential will be explained.

5.1. Role of Power Sector Planning

Power sector planning is the part of a more general problem that is energy and economic development planning [141]. It involves a list of activities such as electrical load forecast, power generation and expansion planning and electrical network planning spanning over several time horizons [142]. The electrical load projection forms the basis of power generation and expansion planning. The primary objective of power sector planning is to determine WHAT, WHEN and HOW MUCH new generation units should be constructed over a long-term planning horizon, so that the future power demand can be met adequately at minimum cost [143]. Basically, the power sector planning involves future demand forecasting and power supply modeling of a region or country and includes the following activities:

a) Projection of future electric load for 5 to 30 years based on the most reliable information.
b) Evaluation of the availability of energy resources in future for electricity generation and foreseeable trend in technical and economical developments.
c) Evaluation of economic parameters such as capital investment cost, fuel cost, operation and maintenance cost, efficiency, construction time etc. of the existing system.
d) Choice of different technologies, their combination and associated cost for the future expansion planning.
e) Choice of the different sources of energy for electricity generation and a suitable electricity mix.

This study is focused mainly on the power generation and expansion planning in Nepal.

5.2. Hydropower Project Planning and Development in Nepal

Hydropower project planning covers a wide range of activities. The project planning requires substantial investment in terms of time, money and efforts to determine the feasible projects for execution [144]. Professional from different fields such as civil, mechanical, electrical, geology, economics, finance, ecology, sociology, environment, etc. are involved in the planning and implementation of hydropower projects. One of the objectives of the hydropower planning is to develop an optimum design considering financial, technical, environmental and social aspects so that the overall cost can be optimized.

The planning of hydropower project is done in three stages. In the first stage, a preliminary investigation is done based on the data collected on topography, hydrology, geology, ecology and if required field visit is arranged. This is called reconnaissance study. If the project is found feasible in this very preliminary study, prefeasibility study is carried out. In this stage, the detailed hydrological study is done, geological investigation is extended and preliminary structural design, layout, plant type are determined. Basic environmental study and economic analysis are carried out. If the project is found feasible, then the detailed feasibility study is carried out based on detailed surveys and investigations of the project area and technical feasibility and financial viability of the project are assessed. If the project is found feasible, it is taken to the implementation phase of project development. While planning the hydropower projects, the important aspects to be considered are: I) estimation of benefits, II) selection of type of project, III) selection of type of structures, IV) selection of type of Electrical & Mechanical (E & M) equipments, V) desilting basin and VI) power evacuation. Figure 25 presents the flow chart for hydropower project development process in Nepal. The project development starts with the legal process and consists of the following five steps:

Step 1: The first step in the hydropower project development is to obtain the survey license from Department of Electricity Development (DOED), Ministry of Energy, Nepal to conduct investigation at a project site to assess its feasibility and preparation of Initial Environment Examination (IEE)/Environment Impact Assessment (EIA). A survey license provides the licensee an exclusive right to study the site for the term of the license period and provides a right-of-first-refusal to develop the projects. The survey license is granted for 5 years [145]. The works related to feasibility study are presented in the Figure 25. At the end of the license period, a detailed feasibility report along with other supporting documents such as topographical, hydrological and geotechnical survey, design of structure, project optimization, financial and economic analysis, IEE report (if the generating capacity is 1-5 MW) and EIA report (if the generating capacity is above 5 MW) [146] have to be submitted to the DOED. EIA is a comprehensive environmental assessment method whereas IEE is a simple checklist of possible environmental and social implications that may arise due to a project. EIA report is very important to get the project approved by DOED and get generation license. If the EIA report is disapproved by the Ministry of Environment, the proponent cannot apply for the generation license.

One of the major parts of the EIA is to study socio-economic and cultural environment of project site, impact of project on the local people and possible barriers from the local communities and various mitigation opportunities. If the project is found feasible economically and environmentally but local people are against the project, such project will be difficult to implement during the construction phase even if the project gets approved by DOED. However, if the possible social barriers are identified during the feasibility study, in this case the proponents have to convince the local people regarding the benefits and opportunities of the projects, for example, the jobs that will be created from the projects, offer of equity share to the public, other social benefits like schools to the community, offer of concession on electricity use etc. If such social problems are identified early in the project phase, then problems can be solved in the beginning and such project will likely face less social barriers during construction. Nowadays, most of the hydroelectric projects offer equity share to the local people which makes them feel ownership of the project and helps mitigate the social barriers.

Step 2: Before applying for the generation license, a number of documents and work has to be completed. At the end of the feasibility study, if the project is found feasible, then the company applies for grid connection agreement with Nepal Electricity Authority (NEA) to evacuate the power. Once the grid connection agreement is finalized, promoters apply for Power Purchasing Agreement (PPA) with NEA. In PPA, the price of electricity along with the amount of energy that NEA will buy during each month is finalized. The price of electricity depends on the size of the project. Projects below 25 MW get the rate declared by NEA which is Nepalese currency NRs. 4.8 per kWh (Approx. NRs. 100 = 1 US$) for eight months including rainy season and NRs. 8.8 per kWh for the rest four months during dry season. However, for the price of electricity for the plants greater than 25 MW, negotiation is done between NEA and the promoters of the project and the rate is determined based on the cost per megawatt of the project and will not be lower than the rate declared by NEA. The duration of this PPA rate is for 30 years from the date of commercial operation of project. PPA document is required for the company to apply for loan in the financial institutions.

Step 3: A generation license is required to build and operate the hydropower plant after the completion of feasibility survey. The maximum period of a generation license is 35 years for the projects meant for domestic consumption and 30 years for the export oriented projects [147]. After the expiry of license period, the project has to be handed over to the government at well operating condition. There is no opportunity to renew the generation license. The company has to apply for generation license to the Secretary of Ministry of Water Resources (MOWR) through the DOED [148]. The required documents to apply for the generation license are: I) Detailed feasibility report along with the approved IEE/EIA report and grid connection agreement, II) Detail financing plan, including estimated cost of the project, the financial capability of investors, commitment of financial institutions, debt equity ratio and liability of investors, III) PPA with NEA, and IV) other legal documents regarding the company.

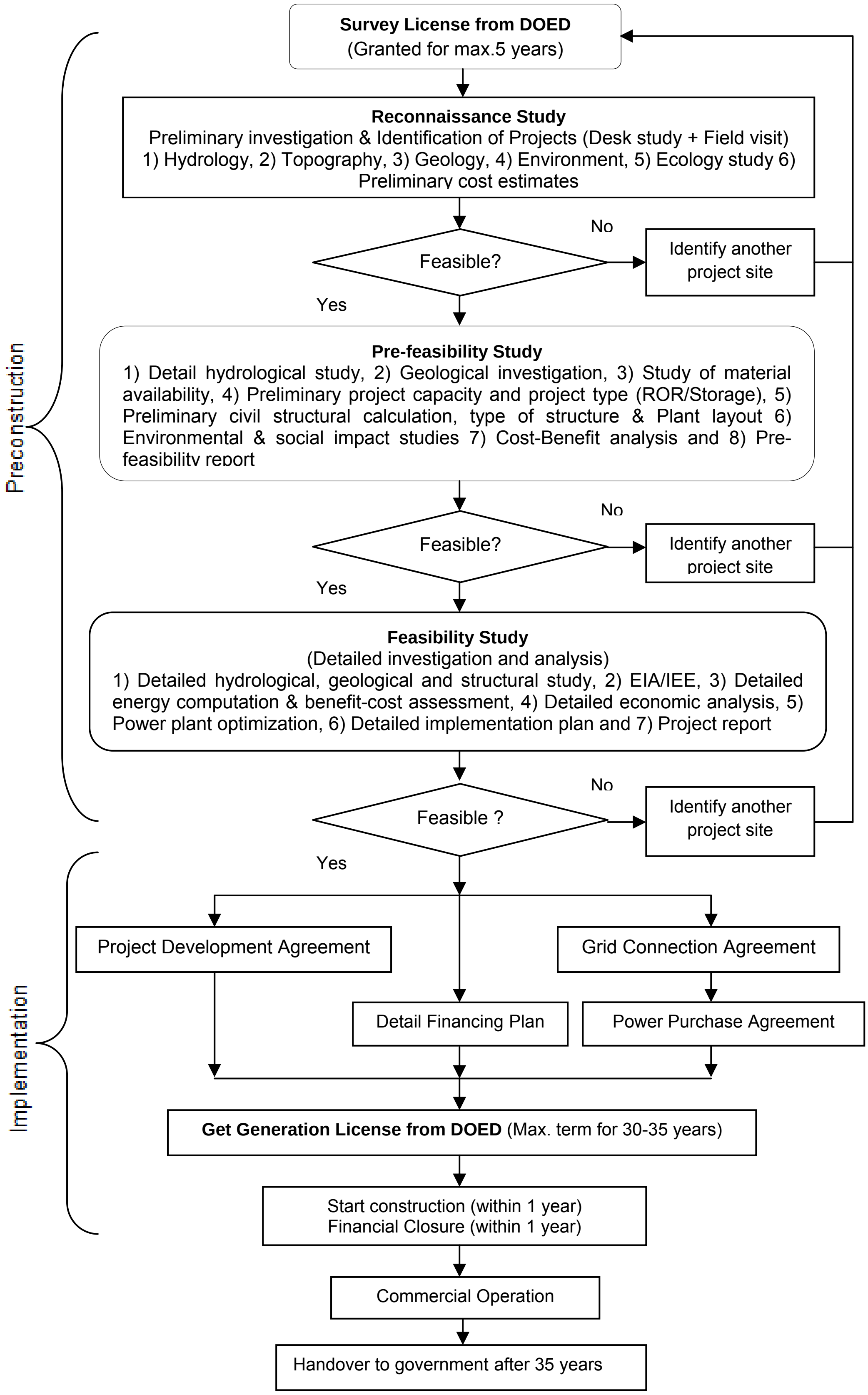

Figure 25: Flowchart for hydropower project development process in Nepal [149, 150]

Step 4: After obtaining the generation license, the company has to start the actual construction within 1 year. Also the company has to complete the financial closure within 1 year of license issued date [149]. The company has to submit the bi-annual progress report until construction is completed. Once the construction is completed, the plant is tested and commissioned. Then starts the commercial operation till the end of the license period and pays royalties to the government of Nepal.

Some of the important points to be highlighted here is the grid connection agreement with NEA which is mandatory to apply for the generation license. This agreement provides the right for the promoters to connect the power to the grid operated by NEA which is the only sole power purchaser and distributer in Nepal as of now. This agreement is also an obligation to NEA to provide the grid facility to evacuate the power generated by private power developers. Unfortunately, NEA is signing the grid connection agreement with the projects where no transmission line exists based on the under-construction and planned transmission line projects. However, due to delay in the completion of the transmission line on stipulated time, some of the privately built hydropower projects have failed to evacuate the power incurring them huge losses. The only penalty for NEA in this case is to pay 5% compensation of total project investment to the promoters.

Various problems and difficulties arise during the implementation of above steps. One major problem is the disruption created by local communities. As soon as some developers begin survey works, local community members come forward with various demands such as donations to schools, for building roads etc. Unless their demand is satisfied, it is difficult to work at the project site. In order to mitigate such problems, nowadays project developers involve the local leaders and community people from the beginning of the projects. Developers have started providing the equity share of the project to the local people and it is working well as well.

Another difficulty is to get financing from the Banks. Commitment from the financial institutions is required to be submitted to apply for the generation license. However, it takes from a year to number of years to find the financer. Bankers hesitate to invest in the hydropower because of the delay in transmission line construction. Therefore, the project gets delayed. In order to get license for power generation, environmental clearance is required and this process is very lengthy as various ministry and government department such as Department of Energy Development, Ministry of Energy, Ministry of Forests and Soil Conservation and Ministry of Environment, are involved in this process. This results in a lengthy process to get Environmental Approval which ultimately delays the project implementation.

Project Duration: Depending upon the capacity of the project, generally it takes about 6 to 9 years to complete the construction of the projects from initial feasibility study till the completion of the project. However, it may take longer time if the financial closure gets delayed. Also, the interruption from local people may lengthen the construction time of the project. Most of the projects handled by NEA in the past have taken longer time to complete the projects. For example, the detailed feasibility study of Kali Gandaki Hydropower project (144 MW) was started in 1993, but the actual construction started only in 1996 and completed after six years in 2002 [151,152]. Likewise, the construction of Middle Marsyangdi Hydropower project (70 MW) took 7 years to complete. It was started in 2001 and completed in 2008 [153]. However, the projects handled by private promoters have taken lesser time to complete the project. For example, Khimti Hydropower Project (60 MW) took 2 years for its feasibility study and 4 years to construct the project. The construction was started in 1996 and completed in 2000 [154]. Similarly, Bhotekosi Hydropower Project (45 MW) took 4 years to complete its construction. The construction was started in 1997 and completed in 2001 [155].

Cost: The cost required for the feasibility study varies from project to project. However, the approximate cost involved for ROR hydro projects (30 MW- 50 MW) are as follows [156]: The licensing fee is Nepalese currency NRs. 10,000 per megawatt per year. The approximate costs involved in the feasibility study are:

- Pre-feasibility study : Approximately NRs. 70,000 to 100,000 per megawatt
- Detailed feasibility study: Approximately NRs.1 million per megawatt
- Tender stage design update and tender documents: Approximately NRs. 140,000 to 170,000 per megawatt.
- Detailed engineering design: Approximately NRs. 1 million per megawatt

This cost is considered approximately 1-2 % of the total project cost. The promoters have to bear this feasibility study cost. Generally, the licensee has to complete the feasibility study within 5 years and in case the work is not completed within the period, licensee may request for renewal of license prior to its expiry by submitting copies of all progress reports and a complete description of the status of the remaining works.

5.3 Types of Hydropower Plant

Hydropower technology utilizes the potential energy possessed by water body between two elevation levels, which is proportional to the rate of flow of water and elevation difference, referred to as the head. Therefore, hydropower planning and design are focused towards increasing these two parameters by selecting proper sites and construction measures. Various types of hydropower plants have been developed depending upon the availability of head and control of discharge. They are as follows:

a) Run-of-river (ROR) / Peak Run-of-river (PROR) hydropower plants
b) Storage hydropower plants

c) Pumped storage plants

a) Run-of-river (ROR) hydropower plant

The ROR hydropower plants have very little or no control of the natural flow of water and therefore, generates electricity as and when the water is available in the stream. When the flow in the river recedes, the power produced by the plant also decreases. It has almost constant head and is usually operated as a base load plant. These plants are normally designed to utilize the flows in the river during the dry season and the installed capacity shall be based on the dependable flow available in the river throughout the year. ROR plants are designed with discharge at certain percentile of available flow in the river. In Nepal, ROR plants are usually designed at 40 % dependable flow. A barrage or weir is constructed to divert the water to the conveyance which delivers the water to the powerhouse through the penstock pipe. The ROR plants can have various possible layouts: I) ROR plant with the canal system, II) ROR plants with pipe system and III) ROR plants with tunnel system and IV) ROR plants with waterways. Figure 26 presents the typical ROR plants with open channel system in Nepal.

PROR hydropower plants are similar to the ROR plants, but with some control over the discharge. A small pondage is constructed to collect the daily flow available in the river so that some regulation is possible during peak hours to generate more power during dry season when the flow in the river recedes below the design flow. During the rainy season, when the river discharge exceeds the design flow, the plant operates like a ROR plant.

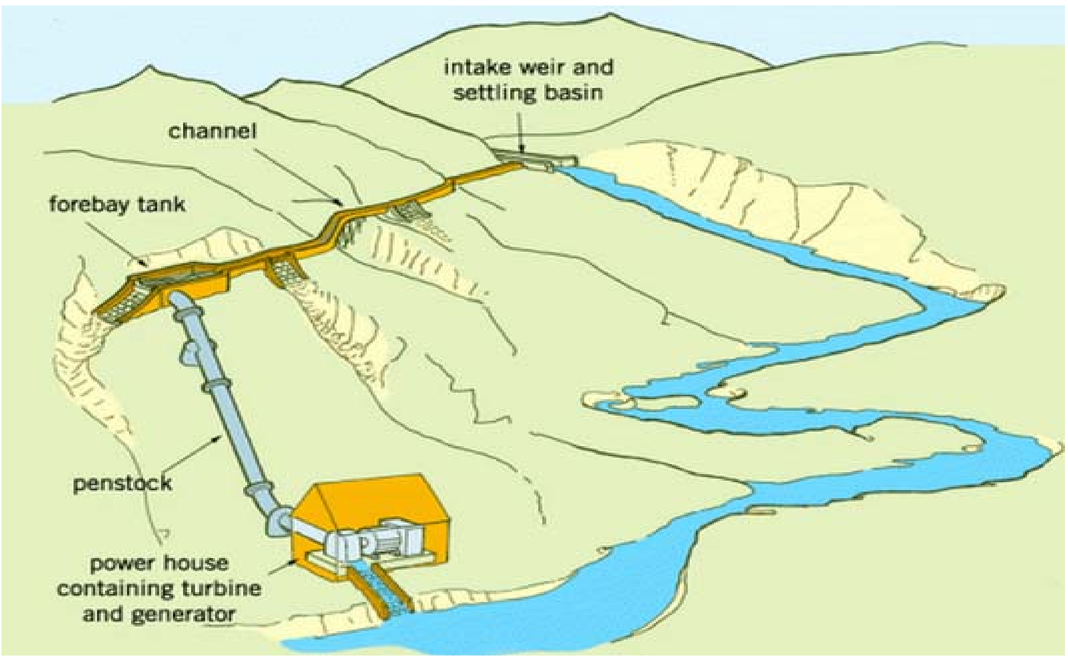

Figure 26: Typical ROR plant with open channel [157]

b) Storage hydropower plant

The storage power plants are constructed with a high dam across a river to create a reservoir and therefore, flow regulation is possible according to the power demand. In such power plant, the gross head is not constant, but varies according to the immediate past power generation, volume of reservoir and natural water inflow [142]. For a country like Nepal, where the wide fluctuation occurs in the river flow during rainy and dry seasons, storage power plants are the most suitable one. The excess water flow during the rainy season can be stored in the reservoir and can be operated throughout the year.

The main components of the storage plants are dam to store water, spillway, headrace tunnel, surge tanks, penstock and powerhouse. Based on the layout, the storage plant may be two types: I) Storage plant with powerhouse at dam toe and II) Storage plant with powerhouse at a certain distance from the dam. In the first type of storage plant, powerhouse is constructed at the toe of the dam. This type of plant layout is preferred for the location where there is a wide river at dam axis. In the second type of storage plant, powerhouse is constructed at a certain distance downstream from the dam. This layout provides additional head to the system. Figure 26 shows the typical storage type hydropower plant with powerhouse at dam toe.

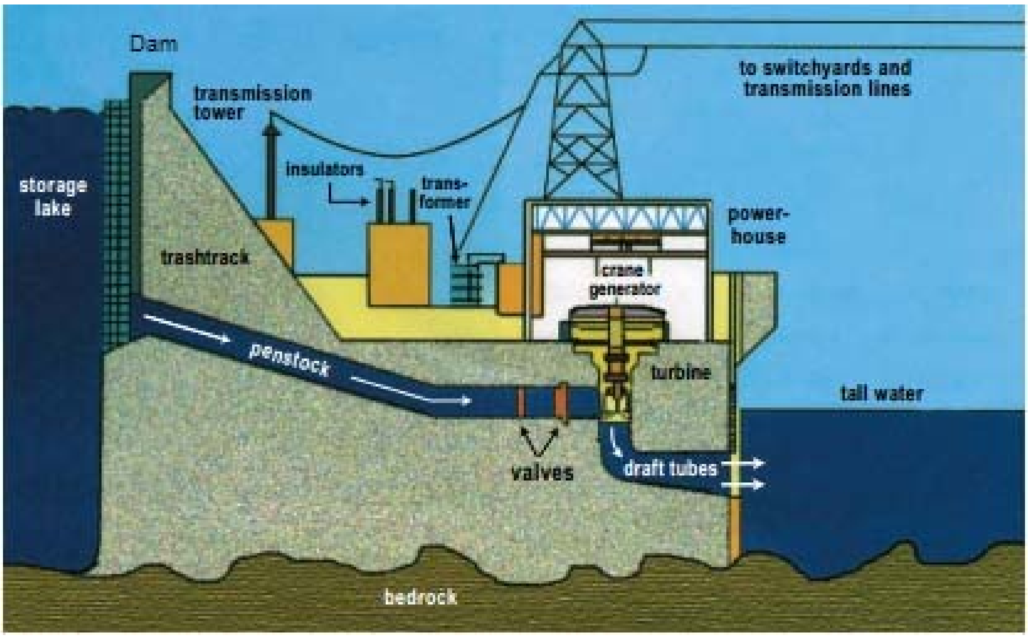

Figure 27: Typical storage hydropower plant with powerhouse at dam toe [158]

c) Pumped storage plant

The pumped storage plants generally employ two reservoirs located at different elevations. The lower reservoir is usually an existing reservoir or natural lake. Water is pumped from a lower reservoir to the higher reservoir using low cost off-peak electric power. During the periods of high power demand, the stored water is released through the turbine to generate electric power. The same turbine acts as a pump as well as the turbine. The economy of pumped storage plant is achieved by selling electricity during peak hours when the price of electricity is high. Pumped storage plants provide a speedy response to the large variation in load and surplus electricity can be used to pump the water to the higher reservoir. Figure 27 shows the typical pumped storage hydropower power plant.

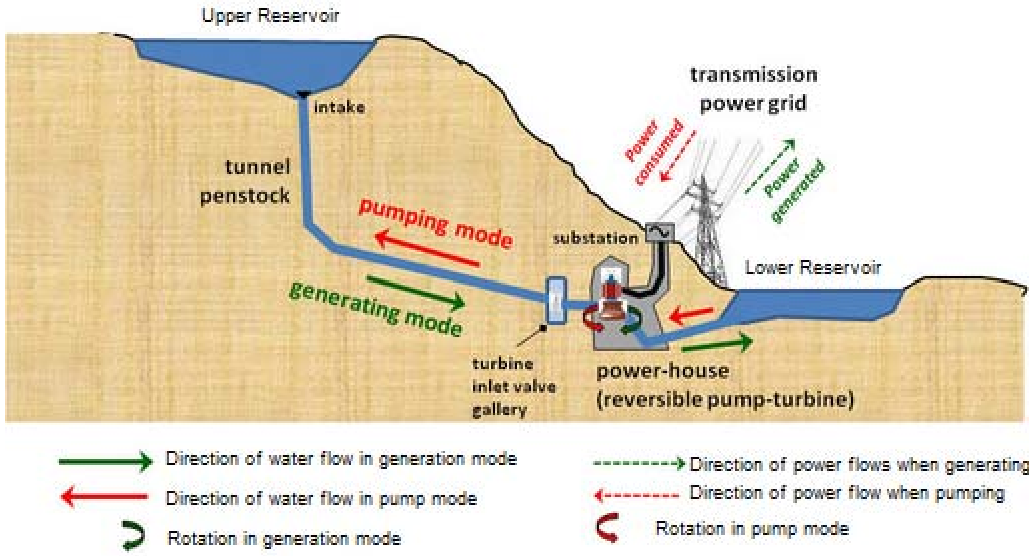

Figure 28: Typical pump storage hydropower plant [159]

CHAPTER 6

Power Generation and Expansion Planning

Harnessing country's hydro potential calls for the power sector planning which involves the demand projection and power supply modeling. This chapter begins with the analysis of the characteristics of electricity demand and supply in Nepal. Next, the present status of hydropower plants will be discussed. Likewise, present status of grid development in Nepal will be briefly explained. Finally, the development of LEAP power supply model for the Nepalese power sector will be described.

6.1. Characteristics of Electricity Demand and Supply in Nepal

Historically, because of low industrial base, the use of electricity in Nepal was limited only to the residential sector and in the residential sector, it was used mainly for lighting purpose. However, this pattern has not changed significantly till date due to poor progress in industrial development. Figure 29 presents the electricity use pattern in Nepal in 1974/75 and 2013/14. Though the electricity consumption in the industrial sector has increased in 2013/14 compared with 1974/75, the share of residential sector is still dominant. Due to this dominance of the residential sector in electricity use pattern (mainly for lighting and using some household appliances), the system load in Nepal has typical characteristics exhibiting substantial variation in hourly demand and shows peaking demand during evening time. Figure 30 presents the hourly variation of the system load in Nepal in 24 hours for different days in wet and dry seasons. This figure shows that the peak load demand occurs in the evening, which is almost double the base load demand. Also, this figure shows the difference of evening peak timing in winter and summer season. This is due to the difference in the sunshine hours in summer and winter season. People shift their evening activities in summer time. Figure 31 presents the monthly system load curve for the year 2012 and 2013 in Nepal. This figure indicates that the monthly variation of peak power demand is within 50 MW except in the month of October-November. This indicates that the power demand in Nepal has only hourly variation and monthly and seasonal variations are very small.

On the one hand, the system load has a wide fluctuation in hourly demand, but on the other hand, NEA does not have the supply system capability to respond to this hourly variation. Figure 32 illustrates the structure of the electricity mix in the Integrated Nepal Power System (INPS). This figure indicates that about 68% of the total capacities of INPS are ROR hydro designed at 40% dependable flow (Q40). Therefore, these plants operates at full capacity only at monsoon season when the river flow is high, but generates less than 40% of the installed capacity during dry season (Nov-June) when the flow recedes in the river. Due to this large share of ROR hydro in the power supply system, there is a large seasonal variation of power generation in Nepal

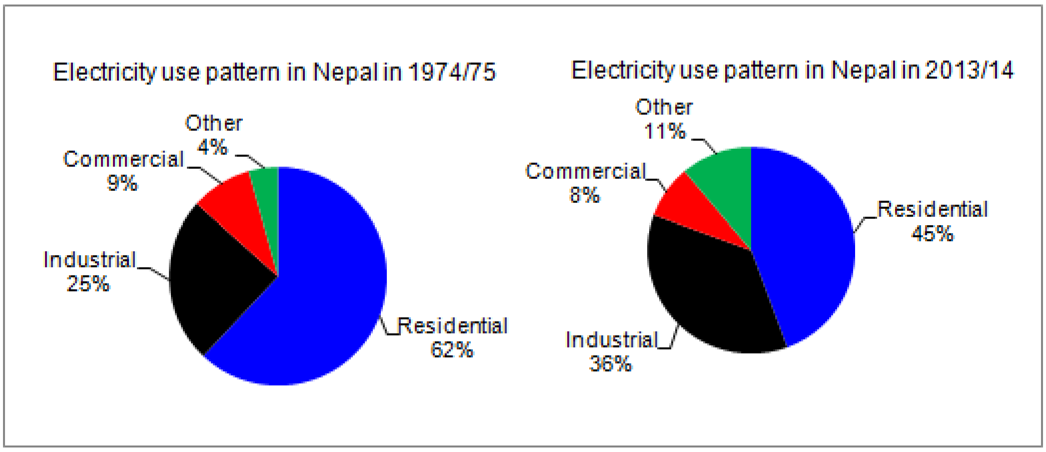

Figure 29: Electricity use pattern in Nepal in 1974/75 and 2013/14 (Source: Economic Survey, 2012)

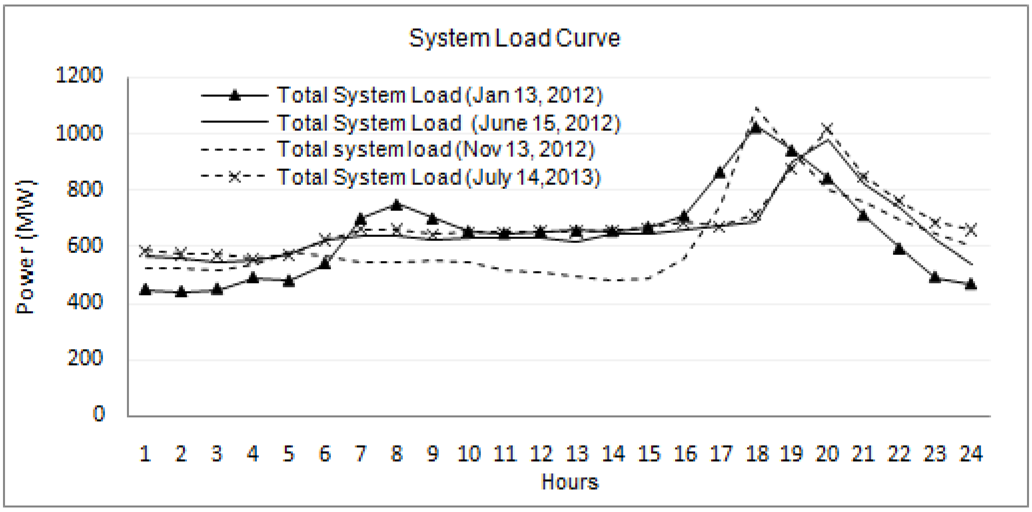

Figure 30: Hourly system load curve of peak load day in Nepal (Source: NEA)

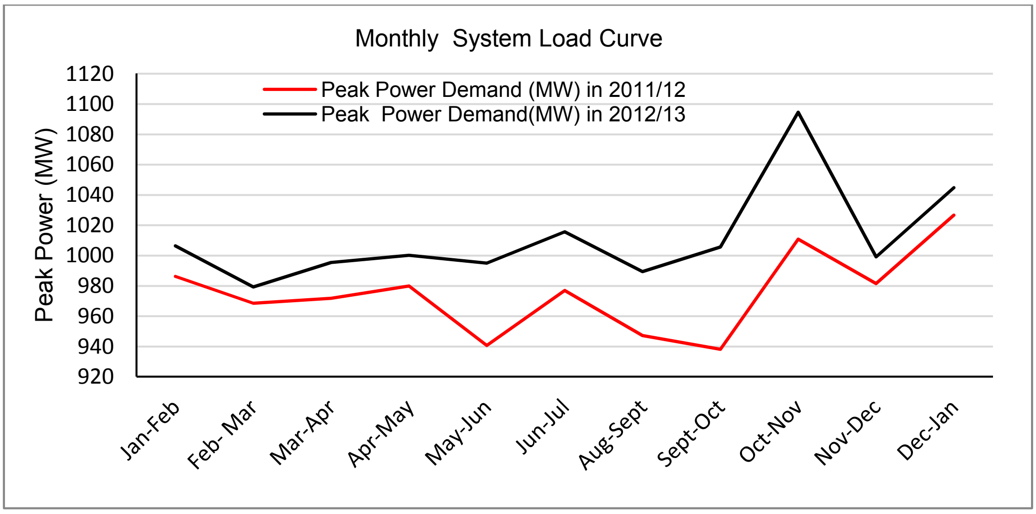

Figure 31: Monthly peak power demand curve (Source: NEA)

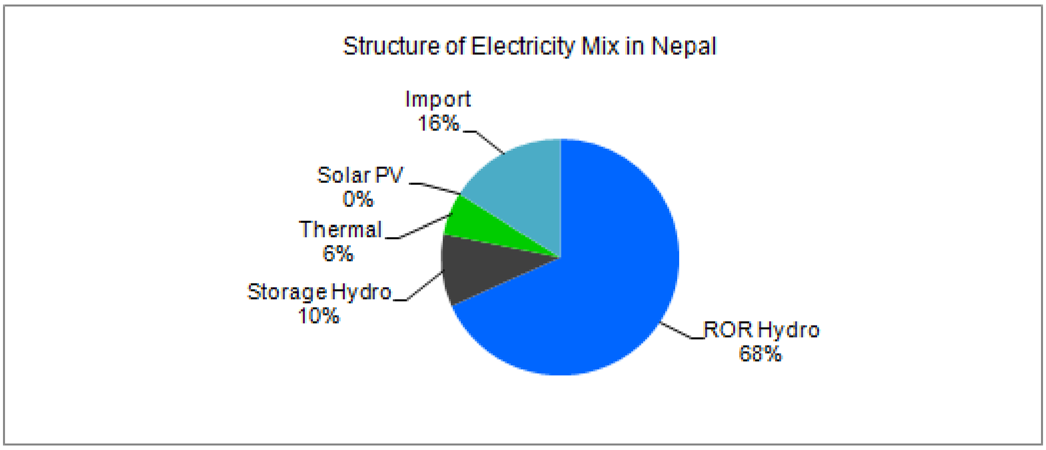

Figure 32: Structure of Electricity Mix in Power System of Nepal (Source: NEA)

According to the data published by the NEA, on an average, power demand and number of consumers are increasing each year at a rate of 9.34% and 10.87% respectively since 2000 [160]. However, the rate of capacity addition is almost stagnant compared to the growth of electricity demand. Figure 33 shows the development of hydropower plants and peak power demand in Nepal.

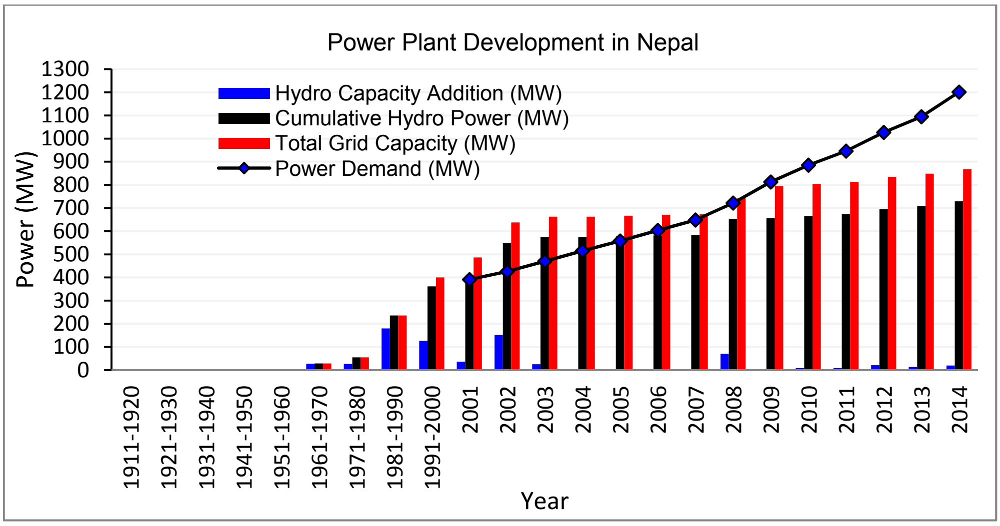

Figure 33: Power Plant Development in Nepal [73, 161, 162]

This figure indicates the widening gap between the power demand and system capacity. No big power plants were added after 2003. As a result, power crisis surfaced in 2006 and each year the problem aggravated. Although NEA is importing few megawatts from India, it cannot bridge the huge gap between demand and supply. The peak demand for the year 2013 (November 3) was 1,200.98 MW, however, the INPS grid connected power capacity, including thermal and import from India was only 890 MW during rainy season [163]. Therefore, the current power crisis in Nepal is caused by: i) huge capacity gap between demand and supply but, a stagnant power plant expansion, ii) large seasonal variation of power production due to large share of ROR hydro plants and iii) wide fluctuation of hourly demand. The only solution to address this problem is to construct new power plants which can match the characteristics of power demand. The construction of new power plants requires in the first place, the development of new transmission lines where the hydro projects are being developed and long term power generation and expansion plan.

6.2. Electricity Demand Projection

In this study, the future electricity demand was taken from Bhattarai (Chapter 4) [164]. Bhattarai [164] projected the future electricity demand using end-use and econometric approach for three different cases: i) Base case demand (BC), ii) Medium growth demand (MG) and iii) High growth demand (HG). Table 19 presents the future electricity demand projected for three different cases. These projected demands were used for power generation and expansion planning. The base case demand was projected using 3.9 % annual GDP. Medium growth demand was projected using 5.6% annual GDP growth rate and high growth electricity demand was projected using 6.5% annual GDP growth.

Table 19: Projected electricity demand [164]

Year	Load Forecast (GWh)		
	Base Case	Medium Growth	High Growth
2015	4163	4573	4790
2016	4463	5020	5317
2017	4767	5477	5863
2018	5087	5953	6430
2019	5413	6443	7017
2020	5750	6953	7623
2021	6143	7580	8400
2022	6553	8233	9207
2023	6973	8907	10043
2024	7413	9610	10910
2025	7863	10337	11810
2026	8383	11227	12950
2027	8917	12143	14133
2028	9473	13097	15350
2029	10043	14080	16620
2030	10633	15100	17933

6.3. Current Status of Hydropower Plant in Nepal

Although the hydropower potential of Nepal is substantial, only a small fraction of it has been utilized yet. As of now, the total installed hydropower capacity is 729 MW, which is 93% of country's installed power capacity. Out of this, the capacity of storage hydro plant is only 92 MW and the rest is ROR hydro plant. Table 20 presents the existing hydropower plants capacity in Nepal. The list of the existing hydropower plants is provided in the APPENDIX 11.

As of now, 1,625 MW of hydropower plants are under-construction and is expected to be completed by 2020. Out of this, the capacity of storage hydropower plant is only 154 MW (Kulekhani III-14 MW, Tanahu Hydropower Project-140 MW) and the rest are all ROR projects, designed at Q40 dependable flows. The list of the under-construction hydropower plants are given in the APPENDIX 12. Likewise, the generation license has been granted to 1,663 MW of hydro projects and out of which, 535 MW of projects are in different stages of development [165]. Similarly, 5,237 MW of hydropower projects are waiting for generation license [166]. Figure 34 presents the power development map of Nepal exhibiting the existing, under-construction, generation license granted and generation license waiting hydropower projects in Nepal.

Table 20: Existing Hydropower Capacity in Nepal (Source: NEA)

Type of Power Plant	Capacity (MW)
ROR Hydro	637
Pure ROR	334
PROR	303
Storage Hydro	92
Thermal	53
Total	782

6.4. Current Status of Transmission Line in Nepal

6.4.1. Existing and Under-Construction Transmission Line

In Nepal, the existing high voltage transmission line consists of 132 kV-2,130 km (national grid) and 66 kV-399 km length of transmission circuit [20]. The 132 kV transmission line, mostly being single circuit besides in a few places, extends from Anarmani, the eastern part to Mahendranagar, to the western part of Nepal and runs through the southern plain land of Nepal. The 66 kV transmission line, also mostly being single circuit, connects the power plants to the national grid. Figure 34 shows the existing, under-construction, planned and proposed transmission line in major power corridors in Nepal. Currently, 132 kV-972 km, 220 kV-373 km (double-circuit) and 400 kV-570 km (double-circuit) length of transmission circuit are under-construction.

The NEA has also planned and proposed to expand another 4,084 km length of transmission line circuit which includes 220 kV-1,236 km, 132 kV-1,540 km and 400 kV-1,308 km length of transmission line circuit in coming ten years. These lines will cover major power generation corridors of Nepal. This plan also includes the construction of 78 km long 400 kV Dhalkebar-Muzzaffarpur, Duhabi-Jogbani, Bardaghat-Gorakhpur cross border transmission line. The construction of these cross-border transmission lines will enhance the power exchange between India and Nepal and will open the avenue to export the power to India.

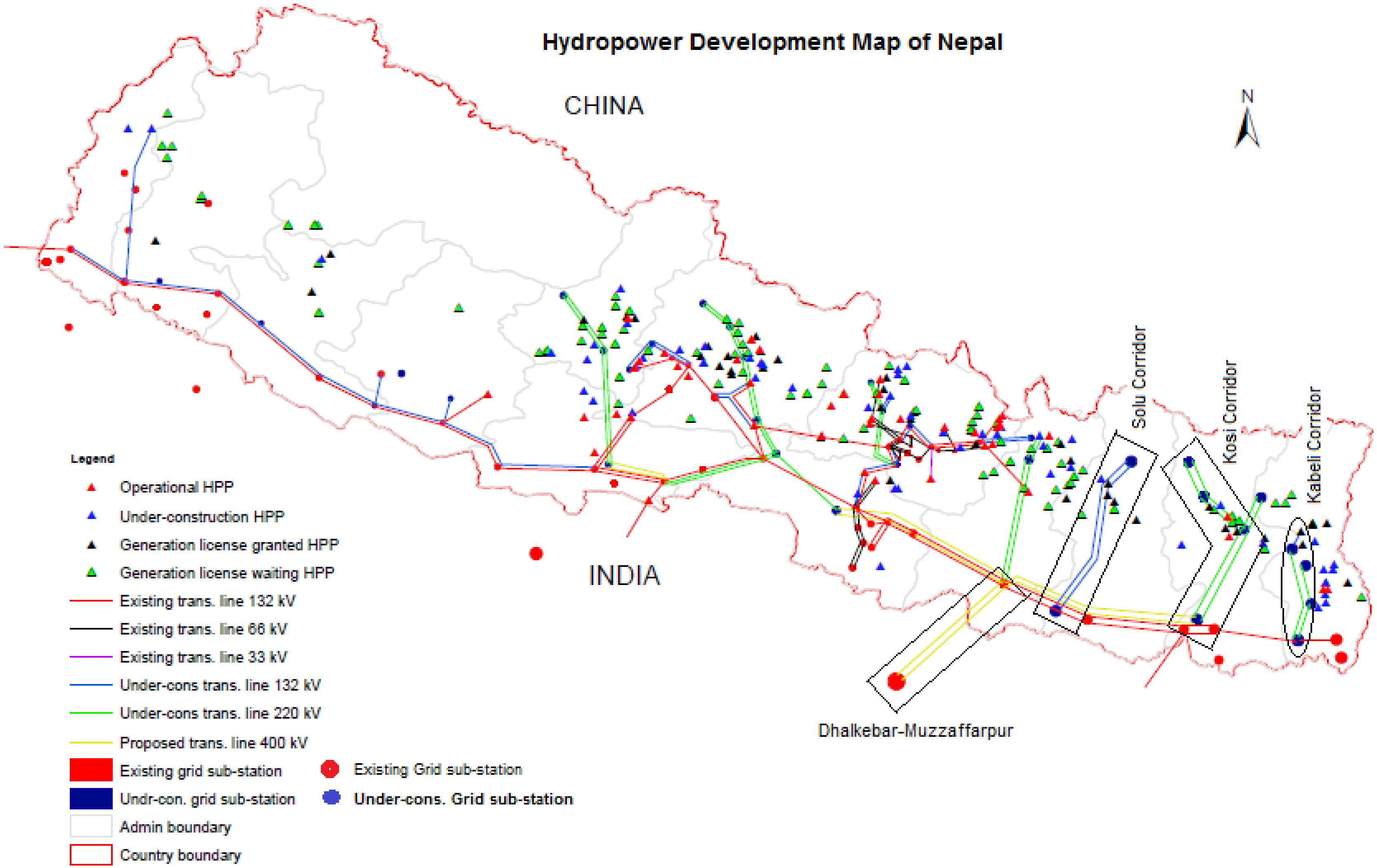

Figure 34: Hydropower development map of Nepal Diagram extended from Annual Review, NEA, 2014

Currently, the power exchange is limited to 145 MW due to low capacity transmission line.

Government of Nepal and NEA (public utility company) are responsible for the development of transmission line in Nepal. NEA plans, constructs and operates the transmission line whereas government provides the funding for the construction of transmission line. Small projects are fully funded from government's development budget but, to construct large transmission line projects, government approaches the international financial institutions like World Bank, Asian Development Bank etc to finance the projects. Some projects are funded by government of India as well.

6.4.2. Progress of Transmission Line Development in Nepal

The transmission line is very important in the power sector for two reasons: i) power evacuation and ii) system stability. However, the importance of the transmission line development has been undermined by both government and NEA in Nepal. There is an imbalance between the development of hydropower and the expansion of the transmission line in the country. Although there is a boom in the development of hydropower, the development of a transmission is not satisfactory. The progress of under-construction transmission lines is briefly discussed.

The construction of 75 km-220 kV Khimti-Dhalkebar transmission line (single circuit) was started in 2002 and scheduled to be completed in 2010/11, however, so far only about 85% work has been completed [167, 168, 169]. Likewise, the stringing of second circuit on 220 kV Khimti-Dhalkebar transmission line was started in the same year the stringing of the first circuit, however, so far only 50% work has been completed. This transmission line will directly connect the hydro plants being developed in the Tamakosi-Khimti basin to the national grid by shortening existing 300 km route to 75 km. Figure 35 shows the location of New Khimti-Dhalkebar 220 kV transmission line.

The construction of 90 km-132 kV Kabeli-Damak corridor transmission line was started in 2005 in order to facilitate the evacuation of power from hydro plants being developed in Kabeli corridor. However, so far 90% works has been completed and yet to complete 10% work. As a result, some of the already completed hydropower plants have not been able to evacuate the power. For example, Sanima Mai Hydro plant was completed in August, 2014, however, it could not evacuate the power because of the delay in transmission line completion [170]. Figure 35 shows the location of this transmission line.

The construction of 208 km-132 kV Butwal-Kohalpur-Mahendranagar second circuit transmission line was started in 2008 with the purpose of evacuating the power from the hydro projects developing in the Karnali basin and providing the adequate power in the Western part of Nepal. This project was scheduled to be completed in 2010/11, however, so far about only 80% work has been completed [169, 171]. Figure 36 shows the location of this transmission line.

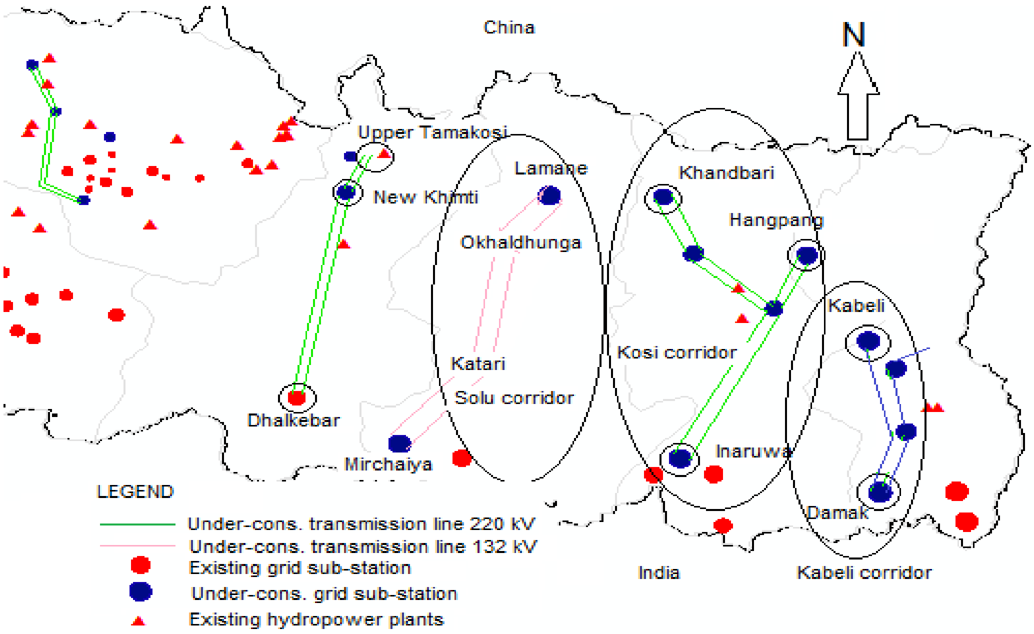

Figure 35: Location of different under-construction transmission line (Source:NEA)

Likewise, 73 km-220 kV Hetauda-Bharatpur transmission line was started in 1998 in order to enhance the transmission line capacity and reliability of INPS grid. However, so far hardly 35% work has been completed. The 75 km- Bharatpur-Bardaghat transmission lines was also started in 1998 and was scheduled to be completed in 2011/12, however, so far hardly 15% work has been completed [169]. Figure 37 shows the location of these transmission lines in Nepal.

The 40 km-220 kV Marsyangdi corridor transmission line was started in 2008 with the objective of increasing the power evacuation capacity of the hydropower projects being developed in Marsyangdi corridor and was initially planned to be completed in 2016/17. However, this project is still on very infant stage. Figure 37 shows the location of this transmission line from Marsyangdi to Manang.

The 220 kV-Kosi corridor transmission line was started in 2008 in order to evacuate the power from the hydro projects being developed in the Kosi corridor and was scheduled to be completed by 2019. However, so far the project is still on infant stage and takes at least another 2 years to start the actual construction work [169]. Figure 38 shows the location of this transmission line.

The 39 km-400 kV Dhalkebar-Muzzaffarpur cross border transmission line (Nepal portion) was scheduled to be completed by December, 2014. However, the construction was just started on last July and is anticipated to be delayed by nine months than the scheduled time [172]. The completion of this transmission line will facilitate the power trading between Nepal and India to the extent of 1200 MW [173]. The location of this transmission line has been shown in Figure 38. The 90 km-132 kV Solu corridor transmission lines were scheduled to be completed on 2016/17 in order to evacuate the power from the hydropower plants being developed in Solu corridor. So far the work progress is the completion of feasibility study and survey work. Figure 38 above shows the location of this transmission line.

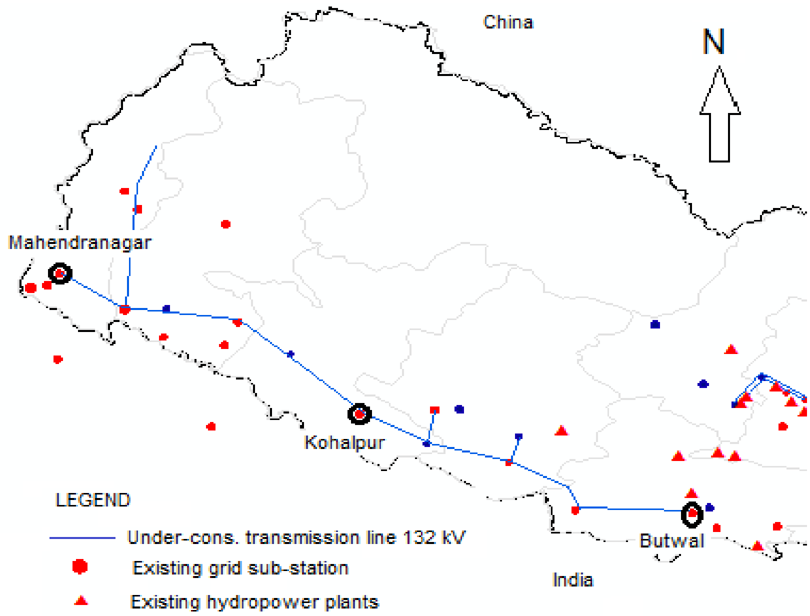

Figure 36: Location of Butwal-Kohalpur-Mahendranagar transmission line (Source:NEA)

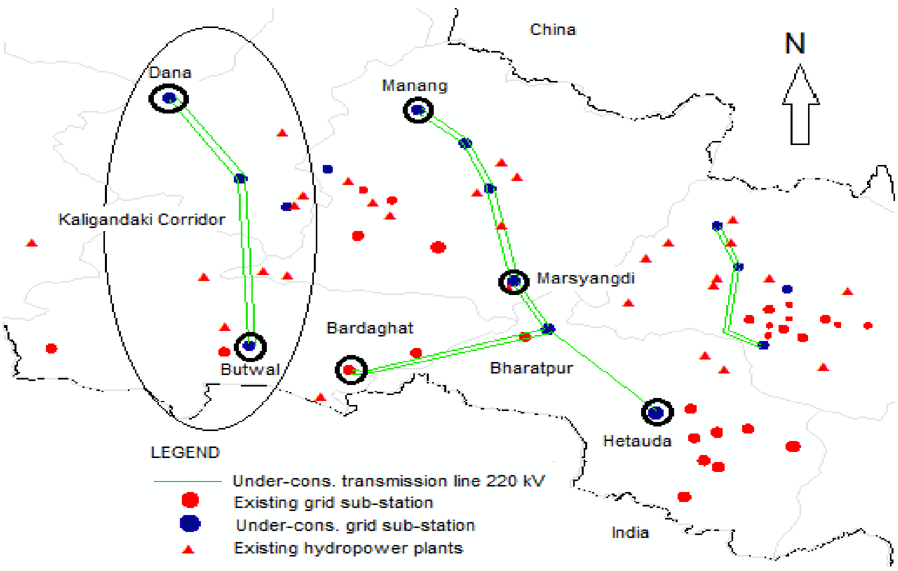

Figure 37: Location of 220 kV under-construction transmission line (Source: NEA)

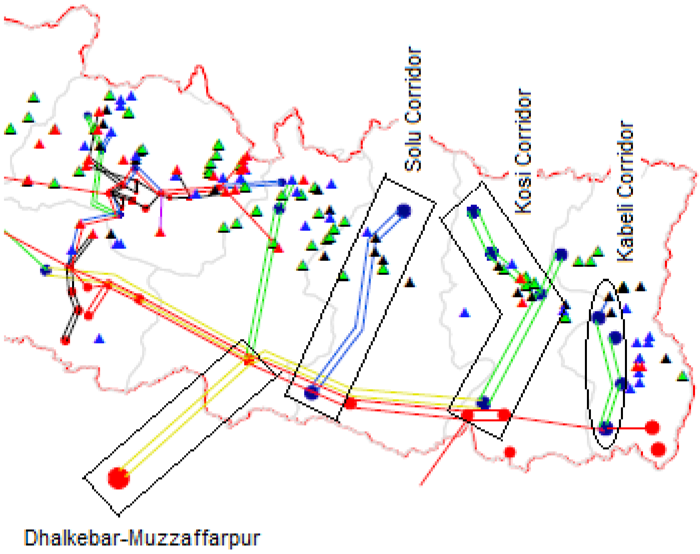

Figure 38: Location of Dhalkebar-Muzzaffarpur and Solu corridor transmission lines (Source: NEA)

6.4.3. Problems in Transmission Line Construction

Transmission line is the fundamental requirement in the development of entire power sector. However, its importance has been overlooked by the government, politicians, NEA and other related government bodies in Nepal. Figure 34 above shows that the transmission lines do not exist in the major power corridors where the new generation license granted and license waiting hydro projects are concentrated and the new hydro projects are currently under-construction. The under-construction transmission lines in these power corridors are getting delayed due to various problems. Due to the delay in the transmission line construction, many investors have delayed their PPA concluded and funding secured projects for construction, for example, Maya Khola (14.9 MW), Solu HEP (23.5 MW), Tallo Solu HEP (82 MW) and Mewa Khola HEP (50 MW) [174]. The existing transmission line is already overloaded. NEA could not fully utilize the electricity generated during the wet season due to insufficient capacity of the existing transmission lines [175]. If the under-construction transmission lines are not completed within 2020, not only the hydro projects which are currently under-construction will be out of national grid, but also, many investors who have got generation license will delay their projects. This will further aggravate the power crisis in the country. The major hindrances in the development of transmission lines are discussed below:

One of the major problems is the obstruction from local people during the land acquisition for the right of way to construct the transmission lines. This issue is politicized by political parties and becomes a critical problem later on. The main reasons behind these problems are:

- First, according to the Land Acquisition Act, 1977, government and public institutions can acquire the land to build public infrastructure by providing compensation to people. However, the compensation rate quoted in compensation rule (only 10% of the value of the land valued by government) of Nepal is very minimal compared to the prevailing market rate of land. The locals demand compensation at the market rate.
- Second, in Nepal, government has not categorized the land as residential areas and farmlands and therefore, people build their houses wherever they want in their land and therefore, scattered over a wide areas. They do not want the transmission lines running nearby their houses and on and above their lands.
- Third, land is considered as the important property in Nepal. People have acquired the land either by investing the earnings of their whole life or inherited from their forefather. When the transmission line runs over through the middle of their land, it restricts the usage of land and therefore, decreases the economic value and marketability of the land. Therefore, the landowners want NEA to acquire the whole land at the prevailing market price rather than the scanty compensation for the right of way.
- Fourth, according to the prevailing law and rule, the project-affected people do not get any direct benefit in any kind from the government. Therefore, they refuse to provide their land for right of way at scanty amount.

In order to mitigate this land related issues, the following measures can be done by government:

- First of all, government should understand the socio-economic aspect of people linked with the land.
- The government should periodically review its legal and administrative provisions regarding the usage of land, compensation amount and amend them with respect to the changing time in order to increase its acceptability by the people.
- Usually government authorities forget to treat the land owners as the major stakeholders and key participants in the entire process of infrastructure development such as transmission line. Since they are not involved in the process, they feel that their land is being forfeited by government. So, local people should be provided some kind of economic benefits so that they do not feel they are losing their valuable land.
- The affected people should be provided some kind of economic benefits so that they do not feel they are losing their valuable land.

Another major problem is getting environmental clearance. Various government departments and ministries such as Department of Energy Development, Ministry of Energy, Department of Forest, Ministry of Forest and Soil Conservation, Ministry of Environment, are involved in the process of providing environmental clearance and there is no coordination among them and therefore, take very long time to expedite the process. The forest guidelines and rules are very cumbersome in Nepal. For example, for every tree that is cut down, the project has to plant 25 and for clearing one hectare of forest for transmission line, the project has to compensate the forest department with 16 hectares [174]. Such cumbersome forest guidelines should be amended for the construction of public utility infrastructures.

Public procurement act, tender act etc. are also not conducive for the infrastructure development works including the transmission line development and delay the project. For example, according to tender act, tender is given to the parties who bid the lowest amount. So, parties bid at very low amount to get the project contract. After winning the contract, they start raising claims against higher costs and stop working which delays in the construction of transmission line. The aforementioned problems cannot be solved by NEA alone, even by government alone. It needs the combined effort of government, all political parties and public.

6.5. Development of LEAP Model for Power Supply Modeling

Figure 39 shows the power supply model development in LEAP. First of all, the primary source of fuel is specified. In this study, the primary source of fuel is hydro, solar, wind and diesel (for existing plant). Then the electricity generation technologies are specified based upon the primary source of energy supplied. In this study, the generation technologies used are ROR hydro, Storage hydro, Solar PV, Wind Turbines and Diesel plant. Generated electricity is provided to the consumers through transmission and distribution lines to satisfy the demand.

6.5.1. Major Variables

The major parameters required for the power supply modeling in LEAP are shown in Figure 40. Each parameter is briefly described below.

Energy Resources

In Nepal, there exist no proven reserves of fossil fuels such as coal, oil and natural gas reserves. Substantial solar energy potential exists in Nepal. The theoretical potential of solar energy has been reported to be 26,000 MW [176], out of this 2,100 MW is considered commercial potential for grid connection [177]. Existence of some wind energy potential has been reported in Nepal. According to SWERA report [178], the total feasible wind energy potential of Nepal is 3,000 MW. Therefore, hydro, solar and wind resources were considered in this study.

Transmission and Distribution Losses

The transmission and distribution loss is an important parameter in LEAP. The transmission and distribution loss is very high in the power supply system of Nepal compared to the neighboring countries. For example, the transmission and distribution losses in Bangladesh are only 10% [179]. Based upon the NEA's annual report published since 2009, on an average system loss is about 27%. This loss consists of both technical and non-technical losses. Technical loss is considered about 20% in Nepal's transmission and distribution system [180]. In this study, the total transmission and distribution loss of 27% was considered.

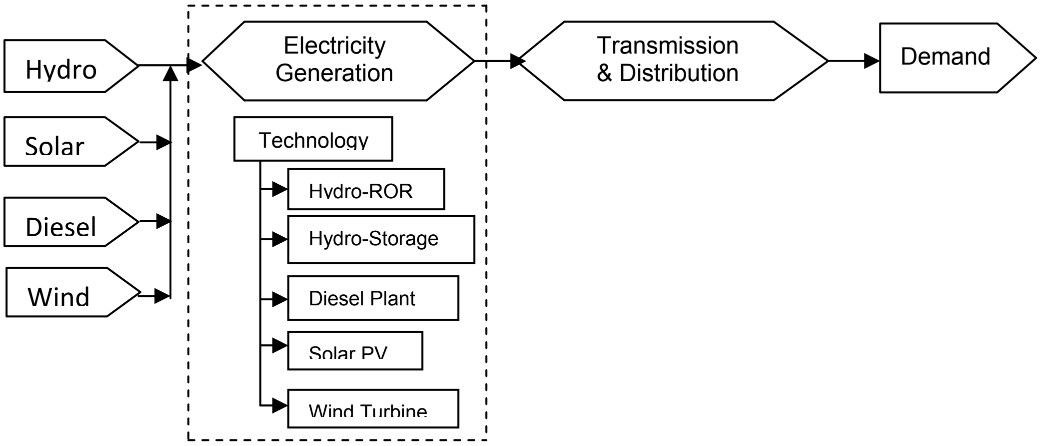

Figure 39: Development of power supply model in LEAP (Source: Author)

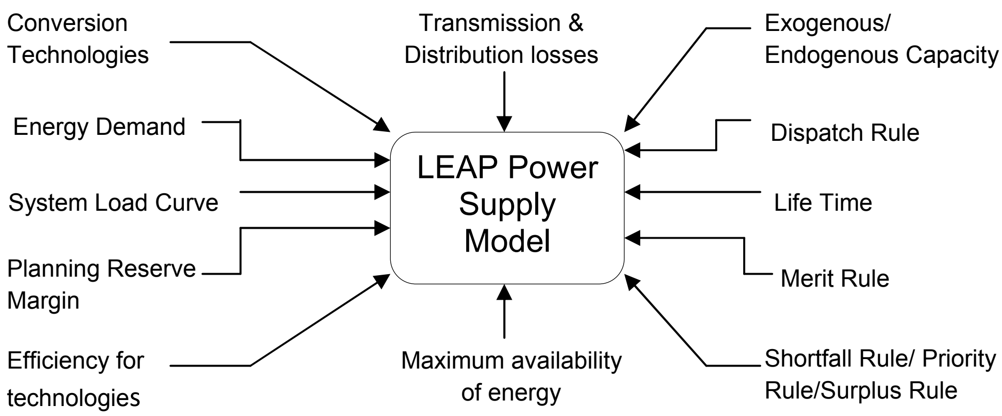

Figure 40: Major LEAP parameters for power supply modeling (Source: Author)

Load Duration Curve (LDC)

Load duration curve has to be specified in LEAP so that LEAP can simulate both annual demand for energy and dispatch the power plants to meet the instantaneous demand for power. A load duration curve is a graphical representation of the variation of demand for energy or power with respect to the time arranged in a descending order of magnitude. The load duration curve shows the relationship between the percent of time or number of hours over a day or a year, for which a particular load exists in the system. The hourly load data was obtained from NEA for the year 2012 and LDC was prepared. Figure 41 illustrates the hourly LDC specified in LEAP in this study.

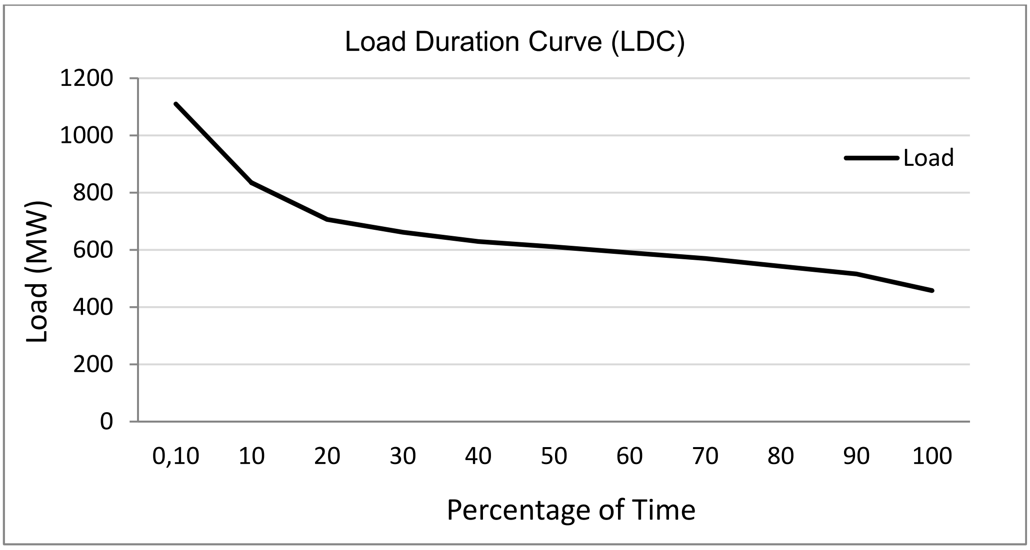

Figure 41: Load duration curve for the year 2012 (Source: NEA)

Maximum Availability of Energy

This parameter has to be specified in LEAP by the user. It is used to put an upper limit on the availability of energy from the power plant. The maximum availability is the ratio of the maximum energy produced to what would have been produced if the plant ran at full capacity for a given period [181]. This variable is equivalent to a capacity factor and termed as maximum availability of energy in LEAP. If the availability does not vary within a year, a single value is specified. If maximum availability varies by season or by month, a yearly shape describing the availability profile is defined. For ROR hydropower plants, the availability varies by season. Likewise, for solar PV as well, availability varies within a day and by season.

Figure 42 shows the availability of energy from ROR hydropower plant in Nepal in each month. This profile was drawn based on the energy generated by ROR hydropower plants in Nepal in various months. Likewise, the energy produced from Solar PV and Wind farms depends upon the sunshine hours and wind speed. Since the grid connected solar PV and Wind turbine do not exists in Nepal as of now, the availability profile for these sources could not be drawn and therefore, a single average annual value based on literature was taken. Based on the literature review, the availability of wind power varies from 20% to 60 % in different countries [182]. In this study, a conservative value of 20% was assumed. Likewise, the availability value solar PV varies from 10% to 25% depending upon the locations [183]. In this study, average annual value of 15% was assumed.

Planning Reserve Margin

In LEAP, capacity can be added by two ways. In exogenous method, existing and as well planned/committed capacity additions are specified. In addition to this, LEAP also uses endogenous method in which LEAP adds the required capacity automatically to maintain the planning reserve margin specified by the user. First LEAP utilizes the exogenous capacity specified by the user to meet the given load and then adds the endogenous capacity automatically to maintain the reserve margin.

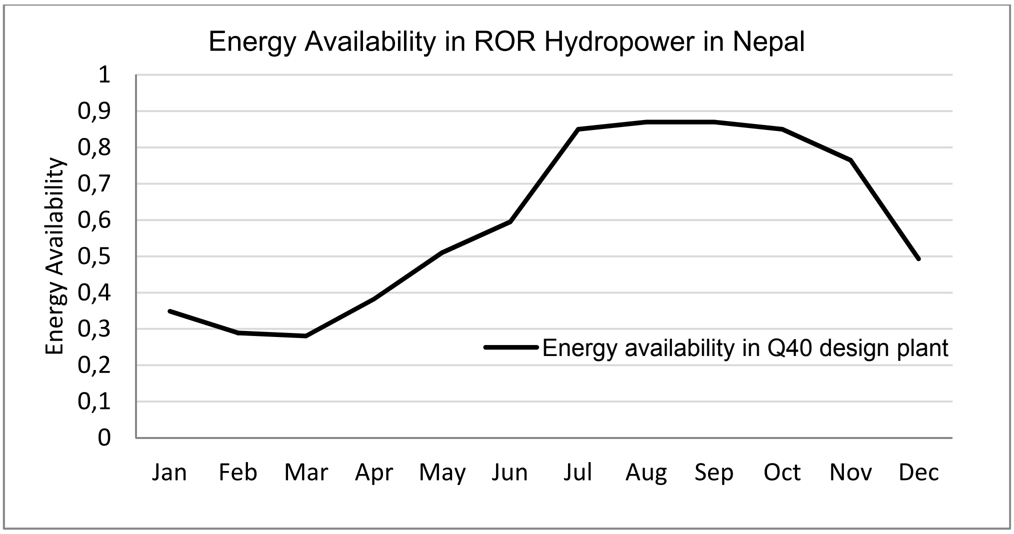

Figure 42: Average energy availability from ROR hydropower plant in Nepal (Source: NEA)

Planning reserve margin is the difference between the available capacity and the peak demand expressed in percentage value. It is specified to provide the amount of generation capacity available to meet the expected peak demand in the planning horizon [184]. Therefore, some additional capacity above and beyond the expected peak load is needed so that sufficient capacities are available at all times to meet load. In some countries, the value of reserve margin is fixed by government. For example, 14% is the reserve margin in Panama [185]. North American Electric Reliability Corporation (NERC) recommends 15% reserve margin for predominantly thermal system and 10% for predominantly for hydro system [184]. In this study, a planning reserve margin of 10% was considered.

Capacity Credit

Capacity credit is defined as a fraction of the rated capacity that can be considered firm for meeting the peak load during worst condition. When referring to intermittent renewable sources such as wind and solar, the capacity credit is the amount of conventional generation that can be avoided or replaced by wind or solar [186]. This value is normally higher for thermal power plants than for renewable power plants reflecting their lower availability.

LEAP recommends a first order approximation and defines that the capacity credit of a renewable plant can be assumed to be equal to the ratio of the availability of the renewable plant to the availability of a standard thermal plant. The capacity credit of ROR hydro is high during rainy season when maximum flow is available but decreases during dry season. Consideration has to be made for the worst case. In Nepal, there is no thermal plant to compare the availability of ROR hydro plant with it. Therefore, the availability of hydro during the dry season was considered as the capacity credit which is 30%, the minimum power than can be generated during dry season of the rated capacity to meet the peak load. The capacity credit of storage hydro is higher than ROR hydro and ranges from 62 % to 95 % [185]. In this study, capacity credit for storage hydro was taken 85%.

Ensslin et al.[187] and Voorspools et al. [186] discuss various method of estimating the capacity credit of intermittent resources like solar and wind using the probability value based on the observation on these system over a time series. As there is no grid connected solar and wind system in Nepal, this method is not possible. There are number of studies done in different countries to calculate the capacity credit of wind and these value ranges from 5% to 35%. For example, the capacity credit of wind power was reported in the range of 5% to 30 % in Germany [188]. In US, the capacity credit was reported in the range of 8% to 20% [189]. In this study, a conservative value of 10% was assumed as a capacity credit of wind. Likewise, the capacity credit of solar PV varies from less than 10% to 60% [190]. Since average sunshine day in Nepal is 300 days, the capacity credit for solar PV was assumed 20%.

Merit and Dispatch Rule

The merit order indicates the order in which the power plants are dispatched. The plants with the lowest value are dispatched first (base load plants) and those with the highest merit order values are dispatched later (peak load plants). Plants with equal merit order are dispatched together in proportion to their available capacity. In this study, ROR hydro plants, solar PV and wind power were used as the base load plants and storage hydro and diesel plants were used as the peak load plants. Table 21 shows the dispatch of power plants based on their merit order. Merit order 1 indicates the base load plant, merit order 2 indicates the power plants for the middle load and merit order 3 indicates the power plant for the peak load.

Shortfall /Priority Rule

In this study, the shortfall in domestic electricity production was specified to be met by import and the priority was specified as the domestic use first.

Table 21: Dispatch of Power Plants (Source: Author)

Types of Power Plant	Merit order
ROR Q 40 Hydro	1
ROR Q 60 Hydro	1
Solar PV	1

Wind Turbine	1
Storage Hydro	2
Diesel Plant	3

Cost and Efficiency of Technology

The cost and efficiency data have been provided to the model. Country specific data was used when it is available. In the absence of country specific data, data were collected from various sources like general data from U.S. Energy Information Administration (EIA) and International Energy Agency (IEA). Table 22 presents the cost data used in this study. Likewise, the efficiency of hydro and solar PV was assumed 80% and 20% respectively, and that of diesel plant was assumed 30%. The economic life of the hydro plants was assumed 40 years and that of the solar PV and diesel plants were assumed 20 years and 50,000 hours respectively. Similarly, the life and efficiency of wind turbine was assumed 25 years and 30% respectively [191].

Table 22: Capital and operating cost of different power generation technologies

Conversion Technology	Cost at 2014 Price			Reference
	Capital Cost/ MW (US $ Mill.)	Fixed Operation & Maintenance (O & M) Cost/kW-yr (US$)	Variable O & M cost / kWh (US$)	
ROR Hydro Plant	2.0	14	0	[192, 193, 194, 195]
Storage Hydro Plant	3.3	18	0	[192, 196, 197]
Solar PV	2.3	25	0	[198, 199]
Diesel Power Plant	1	18	0.30	[200, 201, 202]
Wind Turbine	2.2	40	0	[203]

6.5.2. Assumptions and Boundaries of the Study

In this study, following general assumptions were made during the power supply modeling in LEAP:

a) This study covers only the grid connected power system of Nepal to identify the capacity requirements and timing of construction of power plants.
b) Least cost optimization is not covered in this study.
c) All the existing and operating power plants will continue to exist throughout the study period.
d) This study covers only the electricity need for domestic consumption.
e) There is no constraint regarding the availability of financing means due to the international financial institutions, foreign direct investment (FDI) and private sector investment in the power sector.
f) Daily load fluctuations are not considered.
g) All the under-construction transmission lines will be completed by 2020.

6.6. Development of Scenarios

Scenarios are used to predict the future events within a possible range of existence. In this study, four scenarios were developed to supply the power for each projected electricity demand. The year 2015 is the first scenario year. The following section describes each scenario briefly.

1. Planning Scenario for Electricity Generation (PS)

In this scenario, all the hydropower projects currently under-construction are considered for the power generation and expansion planning. All of these projects are run-of-river hydro based on 40% dependable flow (hereafter ROR Q40 Hydro) and all of them are expected to be completed by 2020. Likewise, 154 MW of storage hydro projects are under-construction and are expected to be completed by 2018 and NEA is constructing 25 MW grid-connected solar PV in 2015 The detailed feasibility study of Budhigandaki storage hydro project (600 MW) has been completed and government of Nepal has planned to start the civil construction of this project within 2017. All of these under-construction and planned projects were considered in this scenario. Therefore, this scenario is named Planning Scenario. There are two purposes of this scenario:

- To study whether these under-construction projects when added to the existing system, will be able to meet the projected electricity demand during the period 2015 to 2020.
- To study the plant capacity requirement and year of addition of capacity to meet projected electricity demand and investment requirement for the period 2015 to 2030

Up to the year 2020, the capacity of under-construction hydro projects and their expected year of addition are known. After 2020, there are only few planned projects. Therefore, it was assumed that the current trend will follow which only includes the development of run-of-river hydro plants at 40% dependable flow and therefore, only ROR Q40 hydro will be built in this scenario to meet the projected electricity demand. This scenario was developed for all of the three projected demand cases (Base case, Medium growth and High growth electricity demand)

2. Energy Mix Scenario for Electricity Generation(EMS)

In this scenario, apart from the ROR Q40 hydro plants, various sources of electricity such as solar, wind, and storage hydro are developed at a suitable electricity mix and used to supply the power. The result of this scenario is compared with the result obtained from PS. Since NEA is preparing to implement the ROR hydropower at 65% flow exceedance (hereafter ROR Q65 hydro), this is also included in this scenario.

3. Transmission & Distribution Loss Reduction Scenario

a. Transmission and Distribution Loss Reduction Scenario 1 (TDLRS 1)

Transmission and distribution losses are very high in Nepal. Therefore, this scenario is made to know how much capacity will be required to meet the demand if the losses are reduced over a period of time. Table 23 shows the assumed transmission and distribution loss reduction plan. This loss reduction plan is combined with the Planning Scenario to see the capacity and investment requirement if the losses are reduced gradually over a period of time. This scenario is called Transmission and Distribution Loss Reduction Scenario 1 (TDLRS1). This scenario was developed for all of the three projected electricity demand cases.

b. Transmission and Distribution Loss Reduction Scenario 2 (TDLRS 2)

The same transmission and distribution loss reduction plan given in Table 23 is combined with Electricity Mix Scenario to see the capacity requirement if the losses are reduced. This scenario is called Transmission and Distribution Loss Reduction Scenario 2 (TDLRS 2). This scenario was built for all of the three projected electricity demand cases.

Table 23: Loss reduction plan (Assumption) (Source: Author)

Year	2015	2016-2017	2018-2019	2020-2021	2022-2023	2024-2025	2026-2027	2028-2030
Loss Reduction (%)	26	25	22	19	16	13	10	8

6.7. Results

The very first requirement in order to develop the power projects is the existence of transmission lines in the country. However, the major corridors where the new hydro projects are being constructed have no transmission lines. The under-construction transmission lines in these corridors are getting delayed due to the less effort put forth by the government. Therefore, the first priority has to be given to complete the under-construction transmission lines in time by resolving all the problems associated with it. If these transmission lines are not completed in time, the power crisis will further worsen in the country.

The simulated results for various aforementioned scenarios are presented. The results show the capacity requirement and timing of capacity addition to satisfy the future electricity demand. The evaluation of each scenario in terms of their actual realization is also described. The result illustrates that it is not possible to meet even the base case electricity demand in Planning Scenario. Therefore, if the current trend of power capacity development continues in the country which only includes the development of run-of-river hydro plants at 40% dependable flow, the power crisis will continue till 2030. However, if the emphasis is given towards the development of various sources of electricity such as storage hydro, grid-connected solar PV and wind power at suitable electricity mix, then there is possibility of developing the required power capacity to meet the base case electricity demand. It will be much easier to develop the required power capacity and meet the electricity demand if the current level of transmission and distribution loss is reduced to some lower level. Therefore, besides building new power plants, the emphasis has to be given on the reduction of transmission and distribution losses as well. This includes the completion of under-construction transmission lines as early as possible, construction of new proposed transmission lines on time, reinforcement of distribution system to reduce losses in the distribution system and reducing the non-technical losses such as theft of electricity.

If the electricity demand increases in the country higher than the existing demand and reaches the medium growth demand, the results of various scenarios have shown that it will be very difficult to meet such demand. No scenarios have shown the easy solution to build the required power capacity to meet the demand. However, the result has indicated that if the transmission and distribution losses are reduced from the current level at 27% to 8% by 2030 and power capacities are developed at suitable electricity mix, then there will be some possibility to meet the demand. Therefore, transmission and distribution loss reduction is the most important job. Both government and NEA should work together to perform this job.

If the electricity demand further increases from medium growth demand to high growth demand, then there is no possibility of meeting such demand by developing the required power capacity level. No scenarios are feasible in this case. The only solution in this case will be to accelerate the development of whole power sector which includes the rapid development of various sources of power plant as per the required capacity level and at the same time rapid expansion of new transmission and distribution lines, timely completion of under-construction lines and reduction of losses in transmission and distribution system. The results of each scenario are described below.

6.7.1. Electricity Supply Planning for Base Case Electricity Demand

In order to supply the base case electricity demand, four electricity supply scenarios were developed and the result of each are described below.

a) Planning Scenario (PS)

Figure 43 illustrates LEAP output of power plant capacity requirement in each year starting from 2015 through 2030 to meet the base case electricity under this scenario. This figure also exhibits the expected power plant capacity development (sum of expected addition from the under-construction projects and existing plant capacity) from 2015 to 2020. A big gap can be seen between the required power plant capacity[4] and expected power capacity development. Therefore, the current power crisis will continue till 2020 as well even all the under-construction plants are added to the system. Figure 44 shows the peak power required for the base case electricity demand projected by LEAP. LEAP tries to meet both energy and peak power demand while calculating the power plant capacity.

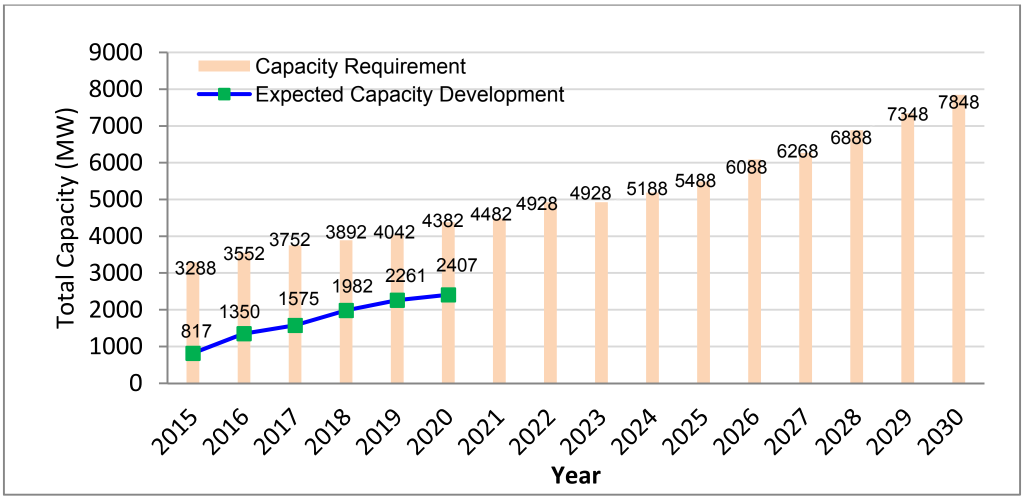

Figure 43: PS power plant capacity requirement (Source: Author)

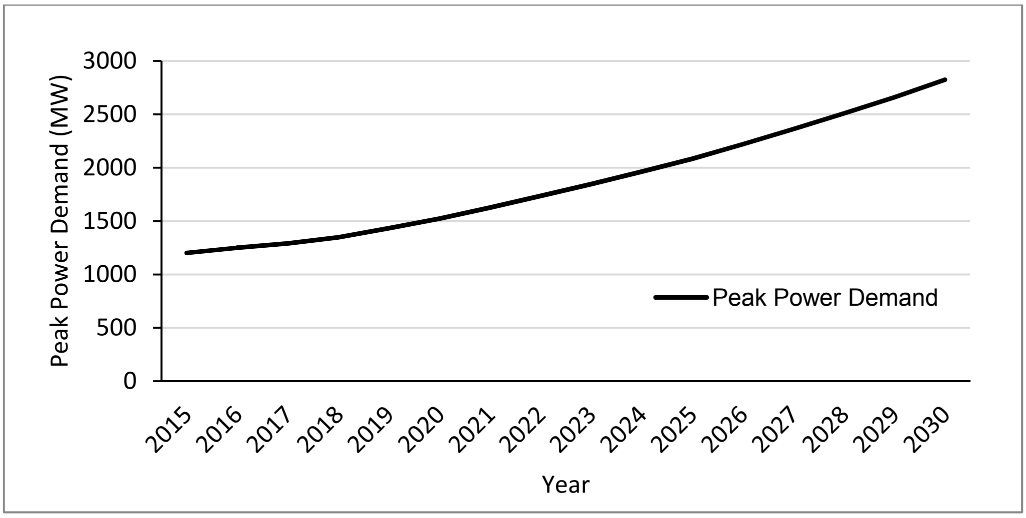

Figure 44: Peak power for base case electricity demand (Source: Author)

Table 24 presents LEAP model output of the power plant capacity requirement and year of addition to satisfy the base case electricity demand under this PS. This table shows that by 2020, the ROR Q40 hydro plant capacity requirement will reach 4,057 MW, however, the maximum expected ROR Q40 hydro capacity development will reach only 2,110 MW (including the existing ones) by then.

[4] LEAP calculates the required power plant capacity to meet both the energy demand and peak power requirement considering energy availability from the plant, system load curve, efficiency of technology, transmission and distribution loss and planning reserve margin if specified. Therefore, depending upon the primary source of fuel supplied, the required power plant capacity may differ to meet the same load.

Table 24: Power plant capacity requirement for Base case electricity demand in PS (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Hydro	3,117	3,567	4,057	4,157	4,417	5,317	6,117	7,077
Storage Hydro	92	246	246	692	692	692	692	692
Solar PV	25	25	25	25	25	25	25	25
Diesel Plant	53	53	53	53	53	53	53	53
Total	3,288	3,892	4,382	4,928	5,188	6,088	6,888	7,848

Since 1,663 MW of ROR Q40 hydro projects have been granted generation license and out of which 535 MW are in different stages of development and ready for of civil construction. Therefore, this 535 MW (more optimistic value) can be expected to be added in the system besides the currently under-construction projects by 2020. With this extra megawatt, the total ROR Q40 hydro capacity will be 2,645 MW which is less by 1,412 MW than the required ROR Q40 capacity by 2020. At the current rate of development, it is not possible to build 1,412 MW within coming five years. Therefore, it will be not possible to build the required ROR Q40 hydro capacity by 2020.

Since government has already committed to go into the construction of Budhigandaki storage project (600 MW) by 2017, it is expected to come into operation by 2022/2023. However, it seems difficult to reach the required ROR Q40 hydro capacity by 2030 because even the entire generation license granted projects are constructed also, the ROR Q40 hydro capacity will reach only 3,773 MW which is just 53% of the required capacity in 2030. Therefore, under this planning scenario, it will not be possible to develop the required capacity to meet the base case electricity demand. So, the current power crisis will continue till 2030.

b) Electricity Mix Scenario (EMS)

Table 25 presents the LEAP output of power plant capacity requirement and the year of addition to meet the base case electricity demand in this scenario. Figure 45 presents the structure of electricity mix in this scenario. By 2020, ROR Q40 hydro plant capacity requirement will reach 3,617 MW, however, the most optimistic capacity that can be expected by 2020 is 2645 MW as mentioned earlier which is less by 972 MW than the required ROR Q40 hydro capacity by 2020. Therefore, it will not be possible to develop the required RORQ40 hydro capacity by 2020 under this scenario also.

By 2030, the capacity requirement of ROR Q40 hydro will reach 3,817 MW. As discussed earlier, if the entire generation license granted projects are constructed, the ROR Q40 hydro capacity will reach 3,773 MW including the existing ROR Q40 hydro plants which is nearly equal to the capacity requirement. Right now 1,470 MW of ROR Q40 hydro plants are under-construction and will be completed by 2020. All of these projects were started after the year 2010 only. On this basis, it can be said that it is possible to construct 1,663 MW of generation license granted ROR Q40 hydro within the year 2020 to 2030 provided that the under-construction transmission lines are completed before 2020.

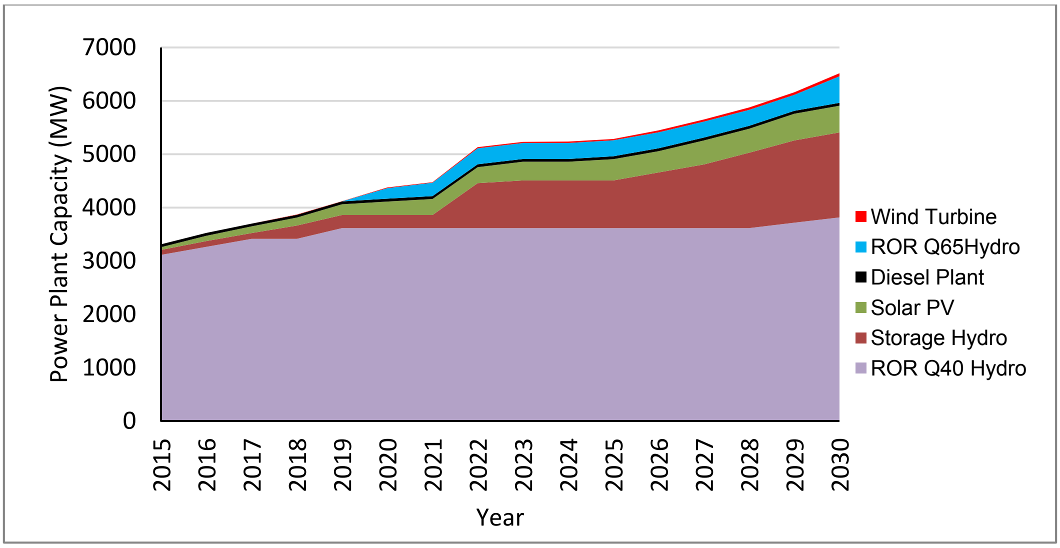

Figure 45: Structure of Electricity Mix Scenario (Source: Author)

Table 25: EMS capacity requirement for Base case electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,117	3,417	3,617	3,617	3,617	3,617	3,617	3,817
Storage Hydro	92	246	246	842	892	1,042	1,412	1,592
Solar PV	50	150	250	300	350	400	450	500
Diesel Plant	53	53	53	53	53	53	53	53
ROR Q65 Hydro	0	0	200	300	300	300	300	500
Wind Turbine	0	5	10	20	25	35	45	55
Total	3,313	3,872	4,377	5,133	5,238	5,448	5,878	6,518

Regarding the requirement of storage hydro plant capacity, 154 MW is currently under-construction and is expected to be completed before 2020. Therefore, together with the existing storage plants, the total capacity of storage will be 246 MW by 2020. As mentioned before, government of Nepal is committed to complete the construction of Budhigandaki storage project (600 MW) by 2020 [204]. The progress of this project is satisfactory as of now and the Exim Bank of India has agreed to provide US$ 1 billion loan for this project [205],[206]. Therefore, we can expect this project to come into operation by 2022/2023 even if few years get delayed. With this project, the total expected storage hydro capacity will reach 846 MW by 2022/2023 which is enough to meet the storage capacity requirement of the year 2024. Likewise, Korea Water Resource Corporation and NEA have agreed to construct jointly the Upper Modi and Upper Modi A storage projects in cascade format with an installed capacity of 62.5 MW by 2020. The detailed feasibility and design of this project have been already completed. NEA and Korea Water Resource

Corporation have agreed to start the civil construction of these projects by 2017. Korea Exim Bank and ADB have already agreed to finance these projects [207]. Therefore, we can expect that this project will be completed around 2021/2022. With this, the expected capacity of storage hydro capacity will reach about 908 MW by 2022/2023. For the year 2030, the total storage hydro capacity requirement is 1,592 MW. Since 908 MW is expected to be developed by 2022/2023, the required additional capacity to be developed is still 684 MW. Government of Nepal is developing Nalsingh Gadh storage project- 410 MW and its feasibility study has been already completed and the project has acquired the land for the power house and other physical infrastructure [208]. So, this project can be expected before 2030. If this project is built before 2030, the total expected capacity of storage hydro will reach 1318 which is near to the capacity requirement by 2030.

Regarding the grid connected Solar PV, NEA has planned to install 25 MW by the end of 2015 and has already identified the location [177] and got the loan sanctioned by World Bank for the project [209]. Therefore, 25 MW of solar PV can be expected at the end of 2015. Government of Nepal is interested to develop the grid connected solar PV in the country to end the current power crisis and therefore, has announced to install 100 MW solar plants within 2018. Also, government has announced to purchase the solar power from private sector by signing power purchase agreement (PPA) with them [210]. As of now, survey license has been issued to three companies with a total capacity of 67 MW [161]. This shows the positive direction towards the development of solar PV in Nepal. Therefore, we can expect 150 MW to 200 MW by the end of 2020 and further development can be expected by 2030.

NEA is preparing to sign PPA agreement with only those hydropower projects that are developed under 65% flow exceedance model [211] which can produce electricity in full capacity for 65% time of a year or 237 days of a year. Therefore, it can be expected that there will be development of ROR hydropower at 65% flow exceedance in future. However, the prospective regarding the development of grid-connected wind power is not optimistic as of now. So far survey license has been issued for only 5 MW of wind power [161].

In this scenario, the capacity requirement of RORQ40 hydro can be realized by 2030. The realization of storage hydro capacity requirement seems little difficult by 2030. However, if government constructs Nalsingh Gadh storage hydro project on time, it may be possible to realize the required storage capacity by 2030. Regarding the solar PV, the positive initiation has already started. However, government should further boost up towards the development of sufficient capacity. For the development of ROR Q65 hydro, NEA is preparing the framework to implement it. Some positive development can be expected in future. However, the development of wind power is not positive as of now.

c) Transmission and Distribution Loss Reduction Scenario 1 (TDLRS1)

Table 26 presents the LEAP output of power plant capacity requirement and the year of addition to meet the base case electricity demand in this scenario. By 2020, ROR Q40 hydro plant capacity requirement will reach 3,857 MW which is less than in PS (4,057 MW), however, as mentioned before an optimistic capacity of ROR Q40 hydro that can be expected by 2020 is only 2,645 MW which is still less by 1,212 MW to reach the required capacity in 2020. Therefore, it is not possible to realize the required ROR Q40 hydro plant capacity by 2020. Although the ROR Q40 hydro capacity requirement has reduced from 7,077 MW in PS to 5,217 MW in this scenario, still it seems difficult to reach the required capacity by 2030 because even all of the generation license granted projects are constructed, the ROR Q40 hydro capacity will reach only 3,773 MW which is less by 1,444 MW than the required capacity by 2030. Therefore, under this scenario also, it is very difficult to achieve the required capacity to meet the base case electricity demand at the current rate of development.

Table 26: TDLRS1 capacity requirement for Base case electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,067	3,467	3,857	3,917	3,917	4,117	4,717	5,217
Storage Hydro	92	246	246	692	692	692	692	692
Solar PV	25	25	25	25	25	25	25	25
Diesel Plant	53	53	53	53	53	53	53	53
Total	3,238	3,792	4,182	4,688	4,688	4,888	5,488	5,988

d) Transmission and Distribution Loss Reduction Scenario 2 (TDLRS2)

The power plant capacity requirement and year of addition to meet the base case electricity demand in this scenario is presented in Table 27. By 2020, 3,317 MW of ROR Q40 hydro capacity is required and as discussed earlier, the most optimistic capacity of ROR Q40 hydro that can be expected within 2020 is 2,645 MW. Therefore, the required ROR Q40 hydro capacity will not be realized by 2020. If 2,645 MW of ROR Q40 hydro capacity is built by 2020, another 672 MW has to be developed to reach the required capacity by 2030. Since there are large number of generation license granted projects at different stages of development, 672 MW capacity can be realized by 2030.

Likewise, the requirement of storage hydro can be realized by 2030. As mentioned before, about 908 MW of storage hydro capacity can be expected by 2022/2023. By 2030, 1,092 MW of storage hydro capacity is required. Since 908 MW is expected by 2022/2023, the additional capacity to be developed to reach the capacity requirement is only 184 MW. Since NEA is studying number of storage projects of different capacity, at least one of them may be assumed to be developed by 2030. Therefore, the required storage hydro capacity may be realized in this scenario. Similarly, some development of grid-connected solar PV and ROR Q65 hydro capacity can be expected by 2030. In totality, the required power capacity level can be realized in this scenario.

Table 27: TDLRS2 capacity requirement for base case electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q 40 Hydro	3,067	3,317	3,317	3,317	3,317	3,317	3,317	3,317
Storage Hydro	92	246	246	692	692	792	992	1,092
Solar PV	50	150	200	250	250	300	300	350
Diesel Plant	53	53	53	53	53	53	53	53
ROR Q65 Hydro	0	0	200	250	250	300	300	500
Wind Turbine	0	5	10	20	25	35	45	55
Total	3,263	3,772	4,027	4,583	4,588	4,798	5,008	5,368

e) Total System Cost Perspective

The cost factor is very important and should be carefully analyzed in choosing the technology in power generation and expansion planning. Table 28 presents the capital cost at 2014 price in different scenario for the selected years. Also, the cumulative cost from the year 2015 to 2030 at 2014 price is given in this table.

Table 28: Capital cost in different scenarios at 2014 price (Source: Author)

Scenario	Capital Cost at 2014 price (US$ Mil.)								Cumulative Cost[5] at 2014 price (US$ Mil.)
	2016	2018	2020	2022	2024	2026	2028	2030	
PS	546	462	680	1,472	520	1,200	1,240	1,000	14,958
EMS	461	531	526	999	586	1,177	737	776	13,741
TDLRS1	446	462	480	1,472	-	400	700	500	11,238
TDLRS2	661	531	411	1,494	11	452	506	411	10,672

f) Comparison of Scenario

The results of above four scenarios are compared and are presented in Table 29. At the current trend of power plant development which consists of only ROR Q40 hydro, it will not be possible to develop the required capacity even by 2030 to meet the base case electricity demand under the PS. The required power capacity has decreased when the transmission and distribution loss is reduced but, not to the extent that can be developed by 2030. When the power capacities are developed at suitable electricity mix (EMS), the capacity requirement has reduced compared to the requirement in PS but, still it might be difficult to realize the required capacity by 2030. Since the perspective for the development of solar PV is positive in the country, future development can be expected by 2030 but still uncertainty exists. The development of ROR Q65 hydro is also underway but cannot be

[5] Cost added from 2015 to 2030 at 2014 price.

predicted for sure. In totality, it will be difficult to realize the required power capacity in this scenario at the current rate of development.

Table 29: Comparison of scenarios (Source: Author)

Scenario	Technology Type	Capacity Requirement (MW) by 2030	Possibility of required capacity development by 2030	Cumulative Cost at 2014 price (US$ Mil.)	Remarks
PS	ROR Q40 Hydro	7,848	Not possible at today's rate of development	14,958	The problem will continue till 2030. So, alternatives should be found.
EMS	ROR Q40 Hydro, Storage Hydro, Solar PV, Wind	6,518	Difficult to develop the required capacity	13,741	The required capacity has reduced. Realization of both ROR Q40 hydro and storage hydro capacity is difficult but possible. Positive sign towards solar PV development. ROR Q65 hydro development is underway . Uncertainty in wind power.
TDLRS1	ROR Q40 Hydro with loss reduction in transmission & distribution system	5,988	Difficult to reach the required capacity at today's rate of development	11,238	Required capacity has reduced compared with planning scenario but not to the extent that can be realized by 2030.
TDLRS2	ROR Q40 Hydro, Storage Hydro, Solar PV, Wind + Transmission & distribution loss reduction plan	5,368	Required capacity realization is possible	10,672	Required capacity can be realized in this scenario, Transmission and distribution losses have to be reduced.

When the power capacities are developed at a suitable electricity mix and at the same time the transmission and distribution losses are reduced (TDLRS2), the required capacity decreases significantly compared to the rest of the scenario. In this scenario, the ROR Q40 hydro and storage hydro capacity are realizable by 2030. Also, the capacity requirement of solar PV and ROR Q65 hydro have reduced compared to the rest of scenarios. Therefore, it will be easy to realize these capacities also. In totality this scenario is more realistic. Based on the aforementioned results and discussion, the following recommendation can be provided to end the current power crisis in the country:

1. First and foremost, transmission and distribution losses have to be reduced.
2. Apart from the development of ROR hydro projects which is the current trend in the country, focus should be made towards the development of various sources of electricity such as storage hydro, RORQ65 hydro, grid-connected solar PV and wind power at suitable electricity mix.

6.7.2. Electricity Supply Planning for Medium Growth Electricity Demand

In order to supply the medium growth electricity demand, four electricity supply scenarios were developed and the result of each are described below.

a) Planning Scenario (PS)

Figure 46 shows LEAP output of power plant capacity requirement in each year starting from 2015 through 2030 to meet the medium growth electricity demand under this scenario. This figure also shows the expected power plant capacity development (sum of expected addition and existing plant capacity) from 2015 to 2020. A large gap can be seen between the required power plant capacity and anticipated power capacity development. This gap is larger than the gap in PS for base case electricity demand. Figure 47 shows the peak power required for the medium growth electricity demand.

Table 30 presents the PS capacity requirement for medium growth electricity demand. As discussed before, the most optimistic capacity of ROR Q40 hydro that can be expected within 2020 is 2,645 MW which is only 52 % of the required capacity by 2020. By 2030, the required ROR Q40 hydro capacity will reach 10,817 MW. Even the entire generation license granted and generation license waiting projects (generation license granted: 1,663 MW, generation license waiting: 5,237MW) are constructed also, the total ROR Q40 hydro capacity will be only 9,010 MW which is less than the required ROR Q40 hydro capacity by 2030. It is highly unrealistic and improbable to assume that the entire generation license granted and waiting projects will go into construction. Therefore, it is not possible to reach the required power capacity to meet the medium growth electricity demand under this scenario.

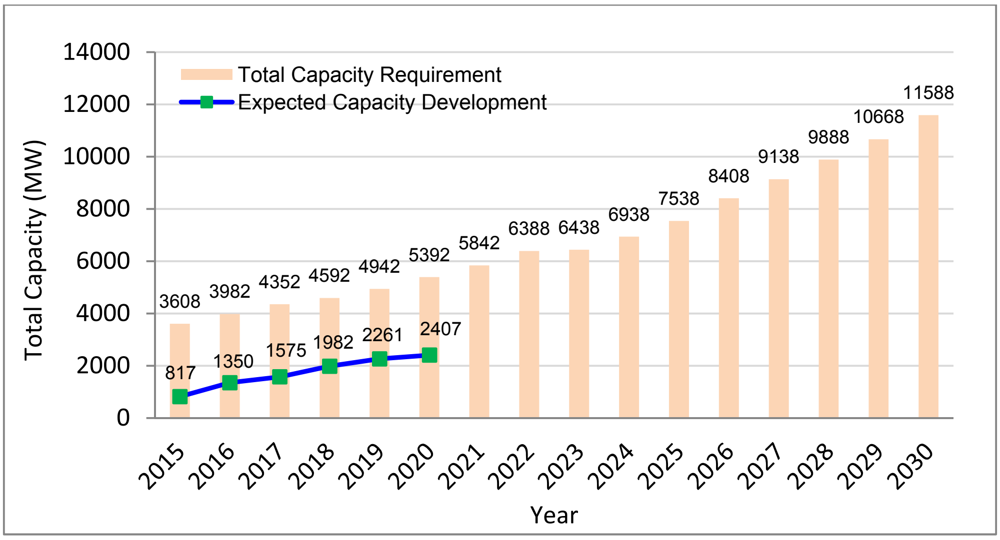

Figure 46: PS capacity requirement for medium growth electricity demand (Source: Author)

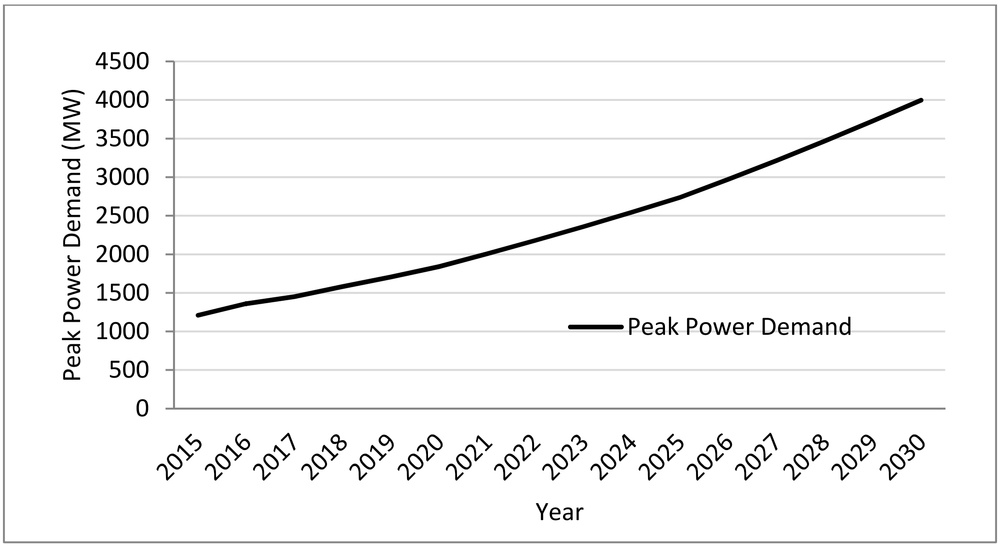

Figure 47: Peak power demand for the medium growth electricity demand (Source: Author)

Table 30: PS capacity requirement for medium growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,437	4,267	5,067	5,617	6,167	7,637	9,117	10,817
Storage Hydro	92	246	246	692	692	692	692	692
Solar PV	25	25	25	25	25	25	25	25
Diesel Plant	53	53	53	53	53	53	53	53
Total	3,608	4,592	5,392	6,388	6,938	8,408	9,888	11,588

b) Electricity Mix Scenario (EMS)

Table 31 shows the LEAP output of the power plant capacity requirement and the year of addition to meet the medium growth electricity demand in this scenario. By 2020, ROR Q40 hydro plant capacity requirement will reach 4,217 MW, whereas, the most optimistic capacity of ROR Q40 hydro that can be expected within 2020 is 2,645 MW and this capacity is just 63% of the required capacity by 2020. If 2,645 MW of ROR Q40 hydro capacity is developed by 2020, still 2,172 MW of ROR Q40 hydro capacity has to be developed by 2030 to reach the required capacity which is not possible at the current rate of development.

As discussed before, 908 MW storage hydro capacity can be expected by 2022/2023. By 2030, the total storage hydro capacity requirement will reach 2,192 MW. Since 908 MW is expected to be developed by 2022/2023, the required additional capacity to be developed is still 1,284 MW. To realize this capacity, at least three storage projects that have been planned by NEA (Dudhkosi- 640 MW, Upper Arun-335 MW and Uttar Ganga -300 MW) [20], have to be constructed on time. One of them can be expected by 2030 but, it may be unrealistic to assume that all of these will be constructed. Therefore, the storage hydro power capacity requirement will not be realized in this scenario.

Although the perspective for the development of grid connected solar PV is optimistic in the country, the development of 600 MW by 2030 may be difficult. Likewise, although Nepal Electricity Authority is preparing to implement Q65% model, it might be difficult to reach the required capacity level by 2030. In totality, the realization of required power capacity under this scenario is not possible to meet medium growth electricity demand.

Table 31: EMS capacity requirement for medium growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,417	3,817	4,217	4,217	4,417	4,617	4,617	4,817
Storage Hydro	92	246	246	842	992	1,292	1,742	2,192
Solar PV	50	250	300	300	350	500	600	600
Diesel Plant	53	53	53	53	53	53	53	53
ROR Q65 Hydro	0	230	410	410	550	700	1000	1200
Wind Turbine	0	5	10	20	25	35	45	55
Total	3,613	4,602	5,237	5,843	6,388	7,198	8,058	8,918

c) Transmission and Distribution Loss Reduction Scenario 1 (TDLRS1)

Table 32 shows the power plant capacity requirement and the year of addition to meet the medium growth electricity demand in this scenario. In this scenario, ROR Q40 hydro plant capacity requirement will reach 4,717 MW by 2020 which is less than in PS (5067 MW). However, as mentioned earlier the most optimistic capacity of ROR Q40 hydro that can be expected within the year 2020 is 2,645 MW which is nearly half of the required capacity by 2020. Therefore, it is not possible to build the required ROR Q40 hydro capacity by 2020. Afterwards also, there is no possibility of reaching the required capacity by 2030. Although the capacity requirement has reduced from 10,817 MW in PS to 8,217 MW in this scenario, still it will not be possible to reach the required ROR Q40 hydro capacity by 2030 because all of the generation license granted and license waiting projects have to be constructed to reach the required capacity by 2030 which is not possible at the current rate of development.

Table 32: TDLRS1 capacity requirement for medium growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q 40 Hydro	3,397	4,017	4,717	4,867	5,217	6,117	7,217	8,217
Storage Hydro	92	246	246	692	692	692	692	692
Solar PV	25	25	25	25	25	25	25	25
Diesel Plant	53	53	53	53	53	53	53	53
Total	3,568	4,342	5,042	5,638	5,988	6,888	7,988	8,988

d) Transmission and Distribution Loss Reduction Scenario 2 (TDLRS2)

The power plant capacity requirement and the year of addition to meet the medium growth electricity demand in this scenario are given in Table 33. By 2020, 3,867 MW of ROR Q40 hydro plant capacity is required, whereas, the most optimistic capacity of ROR Q40 hydro that can be expected within the year 2020 is 2,645 MW and this capacity is less by 1,222 MW than the capacity requirement by 2020. If 2,645 MW of ROR Q40 hydro capacity is developed by 2020, still 1,572 MW of ROR Q40 hydro capacity has to be developed by 2030 to reach the required capacity of 4,217.

By 2030, the total storage hydro capacity requirement will reach 1,592 MW. Since 908 MW is expected to be developed by 2022/2023, the required additional capacity to be developed is only 684 MW. To realize this capacity, among the various storage projects planned by NEA, Dudhkosi storage project-640 MW, has to be constructed on time. This is possible if NEA puts this project on priority.

Due to initiation taken by government for the development of grid connected solar PV in the country, about 150 MW to 200 MW (maximum) can be expected by 2020. Since the requirement by 2030 is only 350 MW, we can expect this capacity by 2030. Although NEA is preparing to implement Q65% model, not much can be expected before 2020. However, if NEA implements this model on time, we can expect some development by 2030 but still it might be difficult to realize the required capacity of 950 MW by 2030 at the current rate of development. In totality, the realization of required power capacity under this scenario is also difficult.

Table 33: TDLRS2 capacity requirement for medium growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,367	3,867	3,867	3,867	3,867	3,867	3,967	4,217
Storage Hydro	92	246	308	842	892	1,292	1,492	1,592
Solar PV	50	225	300	350	350	350	350	350
Diesel Plant	53	53	53	53	53	53	53	53
ROR Q65 Hydro	0	210	300	400	400	450	750	950
Wind Turbine	0	5	10	20	25	35	45	55
Total	3,563	4,607	4,839	5,533	5,588	6,048	6,658	7,218

e) Total System Cost Perspective

Table 34 presents the capital cost at 2014 price for different scenario for the selected years. These tables indicate that the Planning Scenario incurs the highest cost and TDLRS2 incurs the lowest cumulative cost.

Table 34: Capital cost in different scenarios at 2014 price (Source: Author)

Scenario	Capital Cost at 2014 Price (US$ Mil.)								Cumulative Cost[6] at 2014 Price (US$ Mil.)
	2016	2018	2020	2022	2024	2026	2028	2030	
PS	766	662	900	1,672	1,000	1,740	1,500	1,840	22,438
EMS	876	1,048	506	1,784	821	1,197	1,201	1,271	19,427
TDLRS1	686	502	800	1,472	700	1,240	1,300	1,040	17,238
TDLRS2	819	893	273	1,784	11	1,012	1,071	641	14,977

f) Comparison of Scenario

The results of above scenarios are compared and are presented in Table 35. The results indicate that if the demand for electricity increases in the country higher than base case electricity demand in future, it will be very difficult to supply the power to meet the demand and there are no easy ways to mitigate this difficulty.

Table 35: Comparison of Scenarios (Source: Author)

Scenario	Technology Type	Capacity Requirement (MW) by 2030	Possibility of required capacity development by 2030	Cumulative Capital Cost at 2014 Price (US$ Mil.)	Remarks
PS	ROR Q40 Hydro	11,588	Impossible at today's rate of development	22,438	The problem continue till 2030. Therefore, alternatives should be found.
EMS	ROR Q40 Hydro, Storage Hydro, Solar PV, Wind	8,918	Not possible to develop the required capacity at today's rate of development	19,427	The required capacity has reduced but not to the extent that can be realized by 2030. ROR Q40 hydro and storage hydro cannot be realized. Uncertainty exist in the realization of solar PV and ROR Q65 hydro due to their high capacity requirement by 2030.
TDLRS1	ROR Q40 Hydro with loss reduction in transmission & distribution system	8,988	Not possible to reach the required capacity at today's rate of development	17,238	Required capacity has reduced compared to planning scenario but not to the extent that can be developed by 2030.
TDLRS2	ROR Q40 Hydro, Storage Hydro, Solar PV, Wind + Transmission & distribution loss reduction	7,218	Possible but difficult to reach the capacity requirement	14,977	ROR Q40 hydro can be realized, possibility exists for the realization of storage hydro. Required capacity of solar PV can be realized but difficult to realized RORQ65 hydro. Top priority has to be given to reduce system losses

[6] Cost added from 2015 to 2030 at 2014 price.

6.7.3. Electricity Supply Planning for High Growth Electricity Demand

In order to supply the high growth electricity demand, four electricity supply scenarios were developed and the result of each are described below.

a) Planning Scenario

Figure 48 shows the LEAP output of power plant capacity requirement in each year to supply the high growth electricity demand. This figure also illustrates the gap between the expected power plant capacity development from 2015 to 2020 and the required power plant capacity. A huge gap can be seen and this gap is larger than the gap in PS for medium growth electricity demand. Figure 49 shows the peak power requirement for high growth electricity demand projected by LEAP.

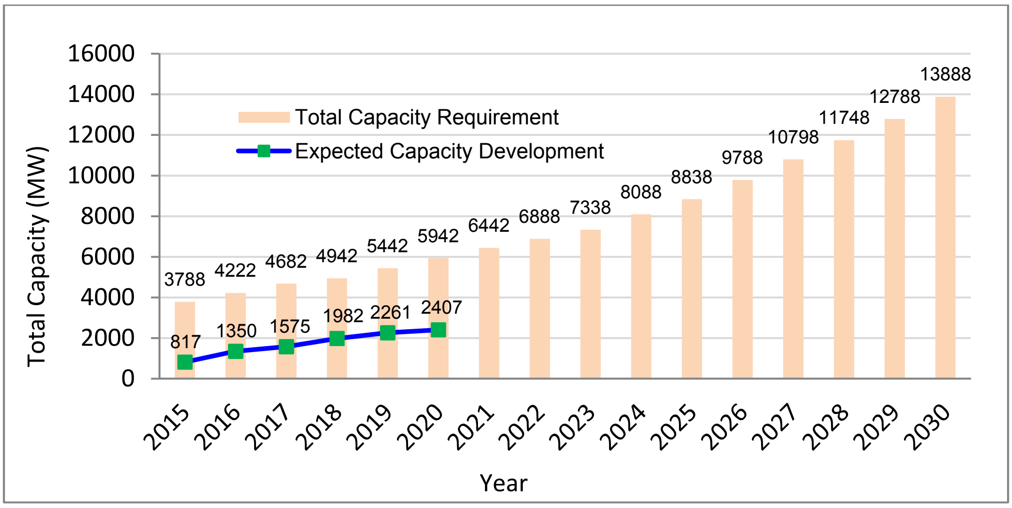

Figure 48: PS capacity requirement and expected capacity development till 2020 (Source: Author)

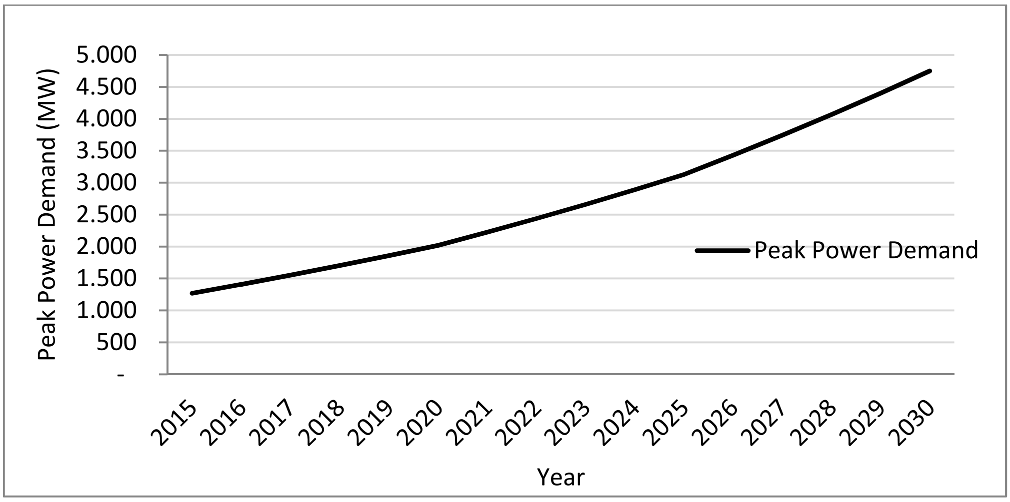

Figure 49: Peak power demand for high growth electricity demand (Source: Author)

Table 36 shows the PS capacity requirement for high growth electricity demand. As mentioned before, the most optimistic capacity of ROR Q40 hydro than can be expected by 2020 is 2,645 MW which is just about 43 % of the required power capacity by 2020. Likewise, by 2030, the ROR Q40 hydro power capacity requirement will reach 13,117 MW. Even the entire generation license granted and license waiting projects are constructed also, the total ROR Q40 hydro capacity will be only 9,010 MW which is less than the required capacity by 2030. Therefore, the required power capacity cannot be developed in this scenario.

Table 36: PS capacity requirement for high growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,617	4,617	5,617	6,117	7,317	9,017	10,977	13,117
Storage Hydro	92	246	246	692	692	692	692	692
Solar PV	25	25	25	25	25	25	25	25
Diesel Plant	53	53	53	53	53	53	53	53
Total	3,788	4,942	5,942	6,888	8,088	9,788	11,748	13,888

b) Electricity Mix Scenario (EMS)

Table 37 shows the power plant capacity requirement and the year of addition to supply the high growth electricity demand in this scenario. This table shows that by 2020, ROR Q40 hydro plant capacity will be required 4,777 MW, whereas, the most optimistic capacity that can be developed by 2020 is only 2,645 MW and this capacity is less by 2,132 MW than the required capacity of ROR Q40 hydro by 2020. Therefore, it will not be possible to develop the required ROR Q40 hydro capacity by 2020. Likewise, by 2030, 6,217 MW of ROR Q40 hydro capacity is required. If 2,645 MW is developed by 2020, still 3,572 MW has to be developed by 2030 to reach the required capacity level. At the current rate of development, it will not be possible to develop this much capacity by 2030.

Table 37: EMS capacity requirement for high growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,617	4,167	4,777	5,017	5,017	5,017	5,417	6,217
Storage Hydro	92	246	246	742	1,142	1,712	2,202	2,592
Solar PV	50	250	350	400	550	600	700	700
Diesel Plant	53	53	53	53	53	53	53	53
ROR Q65 Hydro	0	230	410	400	495	700	900	1150
Wind Turbine	0	5	10	20	25	35	45	55
Total	3,813	4,952	5,847	6,633	7,283	8,118	9,318	10,768

Likewise, as mentioned earlier, about 908 MW of storage hydro can be expected by 2022/2023. By 2030, 2,592 MW of storage hydro capacity will be required. Therefore, if 908 MW is developed by 2022/2023, still 1,684 MW has to be developed by 2030. To reach this capacity level, entire projects (Dudhkosi-640 MW, Tamor-530 MW, Upper Arun-335 MW and Uttar Ganga-300 MW) planned by NEA have to be constructed which is not possible at the current trend of development.

Although the perspective for the development of grid-connected solar PV is optimistic in the country, still uncertainty exists regarding how much will be developed till 2030 because the capacity requirement is high. Regarding development of Q65 ROR hydro, if NEA implements this model on time, we can expect some development by 2030 but still it might be difficult to reach the required capacity level. Therefore, the realization of required power capacity under this scenario is not possible.

c) Transmission and Distribution Loss Reduction Scenario 1 (TDLRS1)

Table 38 shows the power plant capacity requirement and the year of addition to meet the high growth electricity demand in this scenario. By 2020, 5,217 MW of ROR Q40 hydro plant capacity is required in this scenario which is less than the requirement in PS (5,617 MW). However, this capacity cannot be realized by 2020 because only an optimistic capacity of 2,645 MW of ROR Q40 hydro can be expected by 2020 which is just half of the required capacity by 2020. After 2020 also, there is no possibility of meeting the required capacity by 2030. By 2030, 10,067 MW of ROR Q40 hydro capacity is required. As mentioned before, even the entire generation license granted and license waiting projects are constructed also, the total ROR capacity will be only 9,010 MW, less than the capacity requirement by 2030. Therefore, it is not possible to realize the required capacity by 2030.

Table 38: TDLRS1 capacity requirement for high growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,567	4,417	5,217	5,517	6,167	7,347	8,817	10,067
Storage Hydro	92	246	246	692	692	692	692	692
Solar PV	25	25	25	25	25	25	25	25
Diesel Plant	53	53	53	53	53	53	53	53
Total	3,738	4,742	5,542	6,288	6,938	8,118	9,588	10,838

d) Transmission and Distribution Loss Reduction Scenario 2 (TDLRS2)

The power plant capacity requirement and the year of addition to meet the high growth electricity demand are given in Table 39 for the selected years. By 2020, 4,317 MW of ROR Q40 hydro capacity is required, but the most optimistic capacity that can be expected by 2020 is only 2,645 MW. Likewise, 4,717 MW of ROR Q40 hydro capacity is required by 2030. If 2,645 MW is developed by 2020, still 2,072 MW of ROR Q40 capacity has to be developed by 2030 which is also not possible at the current rate of development.

As mentioned earlier, about 908 MW of storage hydro can be expected by 2022/2023. By 2030, 2,092 MW of storage hydro capacity will be required. Therefore, if 908 MW is developed by 2022/2023, still 1,184 MW has to be developed by 2030. To reach this capacity level, the two projects (Dudhkosi-640 MW, Tamor-530 MW) planned by NEA have to be constructed which is very difficult at the current trend of development. Some development can be expected about the grid-connected solar PV. However, it might be difficult to develop the required capacity by 2030 because the requirement is high. Similar is the case for ROR Q65 hydro plants. Therefore, the realization of required power capacity under this scenario is not possible.

Table 39: TDLRS2 capacity requirement for high growth electricity demand (Source: Author)

Technology Type	2015	2018	2020	2022	2024	2026	2028	2030
ROR Q40 Hydro	3,557	4,167	4,317	4,317	4,317	4,317	4,417	4,717
Storage Hydro	92	246	246	592	1,192	1,452	1,852	2,092
Solar PV	50	200	350	400	500	600	700	700
Diesel Plant	53	53	53	53	53	53	53	53
ROR Q65 Hydro	0	200	410	410	410	500	700	900
Wind Turbine	0	0	10	20	25	35	45	55
Total	3,753	4,867	5,387	5,793	6,498	6,958	7,768	8,518

e) Total System Cost Perspective

Table 40 shows the capital cost at 2014 price for different scenario for the selected years. These tables indicate PS incurs the highest cost and TDLRS2 incurs the lowest cost.

Table 40: Capital cost in different scenarios at 2014 price (Source: Author)

Scenario	Capital Cost at 2014 Price (US$ Mil.)								Cumulative Cost[7] at 2014 Price (US$ Mil.)
	2016	2018	2020	2022	2024	2026	2028	2030	
PS	886	702	1,000	1,472	1,500	1,900	1,900	2,200	27,038
EMS	976	1,048	1,026	1,659	1,206	1,323	1,449	1,873	23,502
TDLRS1	866	702	1,000	1,267	1,200	1,660	1,700	1,340	20,938
TDLRS2	916	862	857	847	341	960	1,318	973	18,572

f) Comparison of Scenarios

The results of above scenarios are compared and are shown in Table 41. The results indicate that the required power capacity cannot be realized in any scenarios to meet the high growth electricity demand. Even when the transmission and distribution loss reduction is reduced from 27% at present level to 8% by 2030, no scenarios produced the realistic capacity level. Therefore, the only solution in this case will be to accelerate the development of whole power sector which includes the rapid construction of various

[7] Cost added from 2015 to 2030 at 2014 price.

sources of power plant to reach the required capacity level and at the same time expansion of new transmission and distribution lines, rapid reduction of transmission and distribution losses in the system.

Table 41: Comparison of different scenarios (Source: Author)

Scenario	Technology Type	Capacity Requirement (MW) by 2030	Possibility of required capacity development by 2030	Cumulative Capital Cost at 2014 Price (US$ Mil.)	Remarks
PS	ROR Q40 Hydro	13,888	Not possible	27,038	Not possible
EMS	ROR Q40 Hydro, Storage Hydro, Solar PV, Wind	10,768	Not possible	23,502	Although the capacity requirement has decreased compared to Planning Scenario, still it will not be possible to realize the required capacity.
TDLRS1	ROR Q40 Hydro with loss reduction in transmission & distribution system	10,838	Not possible	20,938	Required capacity has reduced compared to planning scenario but not to the extent that can be developed by 2030.
TDLRS2	ROR Q40 Hydro, Storage Hydro, Solar PV, Wind + Transmission & distribution loss reduction	8,518	Not possible	18,572	Required capacity has reduced compared to the rest of scenarios but, not to the extent that can be developed by 2030.

CHAPTER 7

Conclusion and Recommendation

The various methods of run-of-river hydropower potential estimation and power supply modeling were reviewed. In this study, a GIS-based spatial tool was selected for estimating hydro power potential. Long Range Energy Alternative Planning (LEAP) was selected for power supply modeling as it is the widely used energy modeling tool around the world for integrated energy planning and supply side management.

The theoretical run-of-river hydropower potential was estimated by developing the hydrological model for the three major river basins of Nepal: the Kosi, the Narayani and the Karnali basin. The estimated total theoretical ROR hydro potential of Nepal is 77,810 MW at 40% flow exceedance. In this study, the power supply model was developed using the hydro as the major source of energy for three projected electricity demand cases: base case, medium growth and high growth electricity demand. Besides hydro, solar PV and wind power were also incorporated. The major problems associated with the construction of the transmission line in Nepal, were discussed.

The finding of this research provides valuable insights. The estimated theoretical hydro potential in this study has provided the new potential figure for the major rivers of Nepal. This will provide the fundamental information to the government and concerned stakeholders to formulate plans and policies to develop hydropower in the country. Furthermore, this information is also valuable for the power developers to select the particular river of high potential during the desk study.

This study has shown that the timely development of transmission lines is the key to end the power crisis in the country besides developing the new power plants. Therefore, the first priority has to be given towards the completion of under-construction transmission lines and the expansion of new lines in the major power corridors as soon as possible where the hydro projects are being constructed and new hydro projects are planned to be built. The construction of transmission lines not only connects the hydro projects currently under-construction, but also, many hydro projects which have been postponed due to delay in transmission line completion will be constructed. Therefore, the problems related to the transmission line development should be solved immediately by the government and politicians.

The reduction of transmission and distribution losses plays a significant role in the power generation and expansion planning. The plant capacity requirement would decrease significantly when the transmission and distribution loss is reduced from the current level of 27 % to 8% by 2030. This includes the completion of under-construction transmission lines as early as possible, rehabilitation of the existing distribution system and stoppage of theft of electricity by the public.

The concept of electricity mix is useful in the power supply planning to meet the future electricity demand. It will not only reduce the power capacity requirement, but also, improves the energy security. Therefore, the current trend of run-of-river based hydropower development has to be changed and priority should be given towards the development of storage type hydropower. Other sources of renewable energy that are available in the country such as solar and wind, have to be developed sufficiently to meet the future electricity demand.

For the future work, the following proposals are recommended:

1. In this dissertation, only theoretical ROR hydro potential has been estimated. The information about the technical and economical potential is very important in the development of hydropower in the country. So, the present work can be extended to estimate the technical and economical potential of hydropower in the future.
2. The information regarding the potential of storage hydro is also paramount important and has not been covered in this study. The present work can be extended to estimate the storage potential as well.
3. Next, this study has been done using only the power supply simulation. This study can be further extended to find the least cost electricity mix using least cost optimization.
4. This study covers only the power supply side. The effect of demand side management on power supply could not be studied. The present work can be extended to cover the demand side as well, so that the effect of policy intervention on the demand side can be studied on power generation and expansion planning

APPENDIX

APPENDIX 1

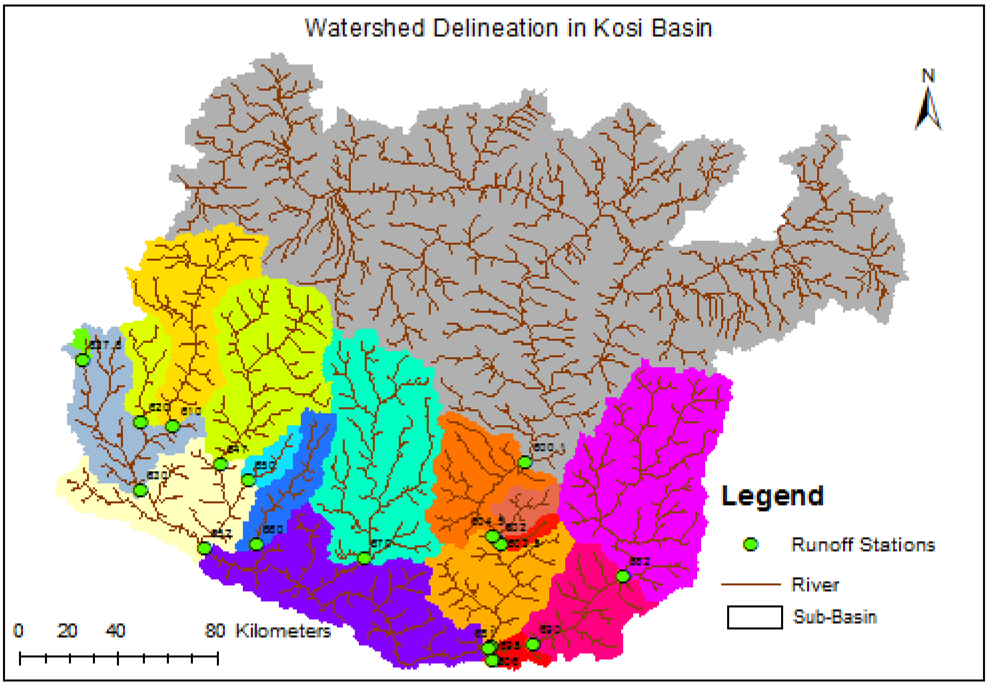

Figure A-1: Delineated watershed in the Kosi basin

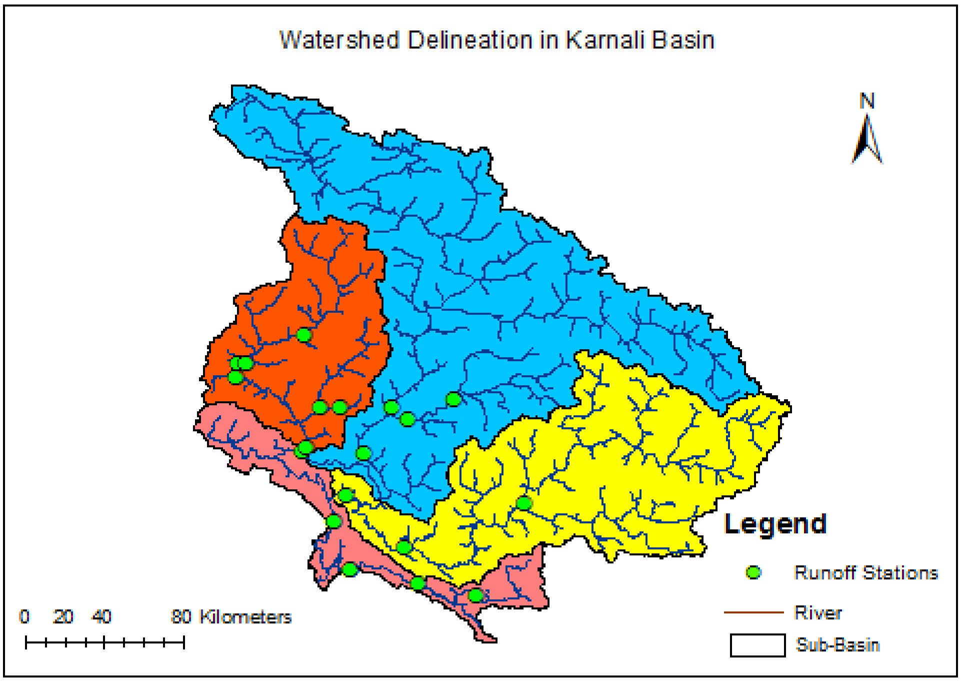

Figure A-2: Delineated watershed in the Karnali Basin

APPENDIX 2

Table A-1: HRU Report created by SWAT for the Kosi Basin (Source: Author)

	SWAT code for landuse	Area [ha]	%Watershed
Landuse	GRAS	940670.13	17.45
	MIGS	1715234.1	31.82
	SHRB	197592.86	3.67
	BSVG	384323.25	7.13
	WATR	234969.17	4.36
	CRGR	565712.42	10.5
	FODB	316311.71	5.87
	CRIR	510253.87	9.47
	CRDY	435007.74	8.07
	FOMI	14937.03	0.28
	SAVA	5697.08	0.11
	FOEN	69497.65	1.29
	Soil Type	Area [ha]	%Watershed
Soil	Od1-a-3215	13481.16	0.25
	I-Bh-U-c-3717	3284265.9	60.93
	GLACIER-6998	482691.79	8.95
	Bd34-2bc-3663	1567159.69	29.07
	Ah12-2bc-3639	40874.21	0.76
	WATER-6997	386.34	0.01
	Je77-1-2a-3761	1347.9	0.03
	Slope Bands	Area [ha]	% Watershed
Slope	0-15	552611.36	10.25
	15-35	955172.94	21.19
	35-9999	3090000.24	68.55

Table A-2: HRU Report created by SWAT for the Narayani Basin (Source: Author)

	SWAT code for landuse	Area [ha]	%Watershed
Landuse	BSVG	270646.7	7.45
	SHRB	199225.97	5.48
	GRAS	467458.56	12.87
	MIGS	532372.43	14.65
	WATR	135090.24	3.72
	CRGR	604552.24	16.64
	SAVA	75974.05	2.09
	CRIR	491180.36	13.52
	CRDY	153631.1	4.23

	FOEN	143115.71	3.94
	FODB	118736.92	3.27
	FOMI	320774.27	8.83
	CRWO	90234.13	2.48
	FOEB	29977.33	0.83
Soil	Soil Type	Area [ha]	% Watershed
	I-Bh-U-c-3717	1359477.12	37.42
	Bd34-2bc-3663	1620353.43	44.6
	GLACIER-6998	324402.94	8.93
	Bk38-1-2b-3693	21337.93	0.59
	Je76-2a-3760	115402.23	3.18
	Rd30-2b-3851	168135	4.63
	Bh18-2b-3692	20883.89	0.57
	Je75-2a-3759	2977.46	0.08
Slope	Slope Bands	Area [ha]	% Watershed
	0-15	282150.39	7.77
	15-35	330060.85	9.09
	35-9999	3020758.75	83.15

Table A-3: HRU Report created by SWAT for the Karnali Basin (Source: Author)

	SWAT code for landuse	Area [ha]	%Watershed
Landuse	SHRB	685177.59	15.2
	TUWO	80681.03	1.79
	BSVG	330332.37	7.33
	MIGS	559520.58	12.41
	WATR	58705.26	1.3
	GRAS	761398.35	16.89
	CRGR	944264.8	20.95
	FOMI	464893.96	10.31
	FODB	61906.3	1.37
	FOEB	66425.38	1.47
	SAVA	69566.08	1.54
	FOEN	173405.14	3.85
	CRDY	138916.52	3.08
	CRWO	12043.23	0.27
	CRIR	100422.41	2.23
Soil	Soil Type	Area [ha]	%Watershed
	I-Bh-U-c-3717	1588870.8	35.25
	GLACIER-6998	557908.56	12.38
	Bd34-2bc-3663	1783055.93	39.56
	Bd35-1-2b-3664	385272.09	8.55

	Je75-2a-3759	77525.81	1.72
	Bd29-3c-3661	102709.83	2.28
	I-X-2c-3731	10243.11	0.23
	Rd30-2b-3851	2072.86	0.05
Slope	Slope Band	Area [ha]	%Watershed
	0-15	366923.44	8.14
	15-35	690573.36	15.32
	35-9999	3450162.2	76.54

APPENDIX 3

The list of parameters used in SWAT tool for surface and groundwater modeling are

CN2 Moisture condition II curve number

PRECIPITATION Daily precipitation (mm H2O)

CNCOEF Weighting coefficient used to calculate the retention coefficient for daily curve number calculations dependent on plant evapotranspiration

CLAY % clay content

SAND % sand content

SOL_BD Moist bulk density (Mg/m3)

SOL_K Saturated hydraulic conductivity of first layer (mm/hr)

OV_N Manning's n value for overland flow

SLSUBBSN Average slope length (m)

CH_L(1) Longest tributary channel length in sub-basin in (km)

CH_S(1) Average slope of tributary channels (m/m)

CH_N(1) Manning's n value for tributary channels

SURLAG Surface runoff lag coefficient

SUB_KM Area of the sub-basin (km2)

CH_K(1) Effective hydraulic conductivity (mm/hr)

CH_W(1) Average width of tributary channel (m)

CH_L(1) Longest tributary channel length in sub-basin (km)

ESCO Soil evaporation compensation coefficient

CANMX Maximum canopy storage

WND_SP Daily wind speed (m/s)

VPDFR Vapor pressure deficit

SOL_AWC Available water capacity

SOL_CRK Potential crack volume for soil profile

DEPIMP_BSN Depth to impervious layer (mm)

LAT_TTIME Lateral flow travel time (days)

SLSOIL Hill slope length (m)

HRU_SLP Average slope of the sub-basin (m/m)

GW_DELAY Delay time for aquifer recharge (days)

GWQMN Threshold water level in shallow aquifer for base flow (mm H2O)

APLHA_BF Baseflow recession constant

REVAPMN Threshold water level in shallow aquifer for revap (mm H2O)

GW_REVAP Revap coefficient

RCHRG_DP Aquifer percolation coefficient

GW_SPYLD Specific yield of the shallow aquifer (m/m)

SNOCOVMX Threshold depth of snow, above which there is 100% cover

SMTMP Threshold temperature for snow melt (0C)

SMFMX Melt factor on June 21 (mm H2O/day-0C)

SMFMX Melt factor on December 21 (mm H2O/day-0C)

APPENDIX 4

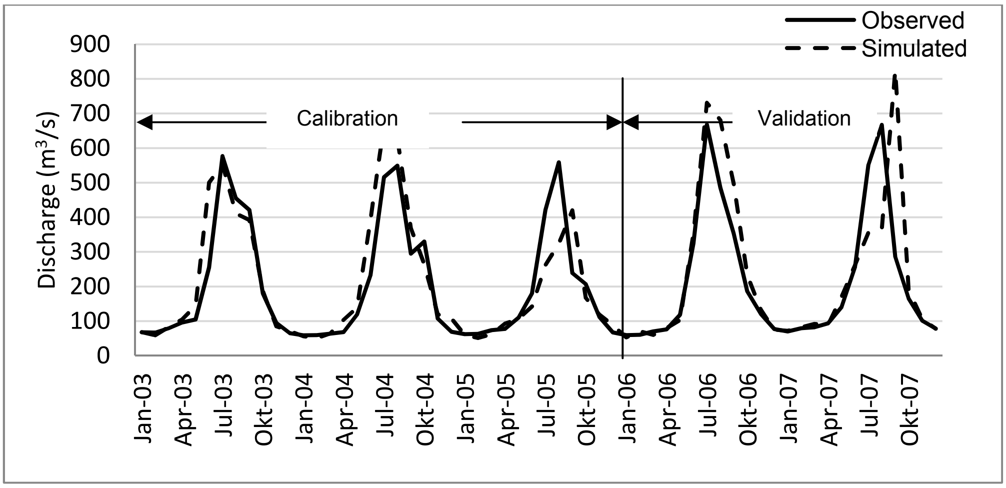

Figure A-3:Observed and simulated discharge at station No. 600.1 in the Koshi basin (Source: Author)

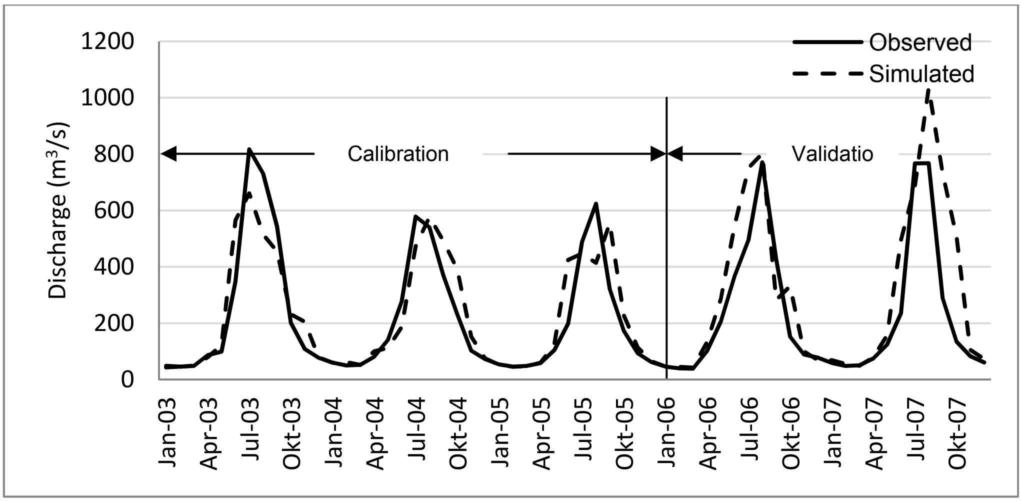

Figure A-4 Observed and simulated discharge at station No. 684 in the Koshi basin (Source: Author)

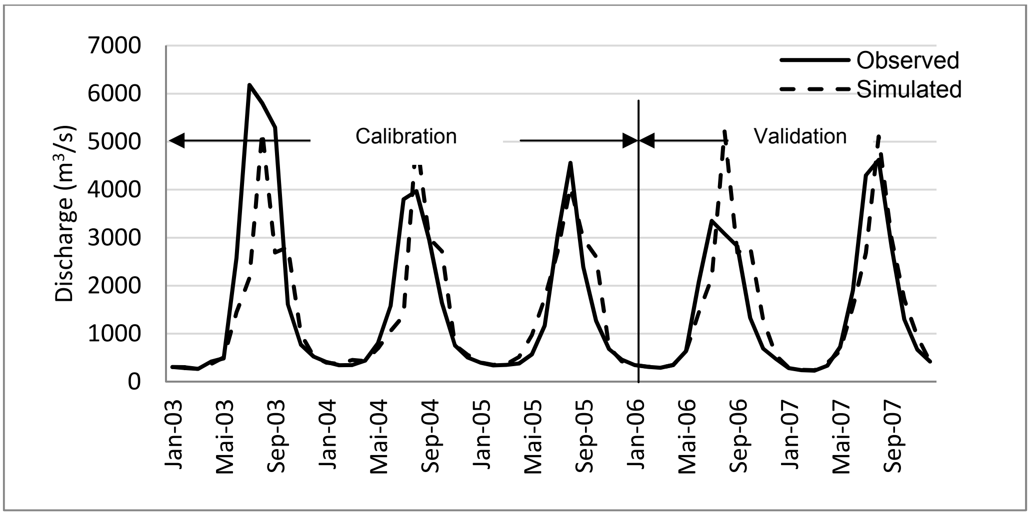

Figure A-5: Observed and simulated discharge at station No.695 in the Koshi basin (Source: Author)

APPENDIX 5

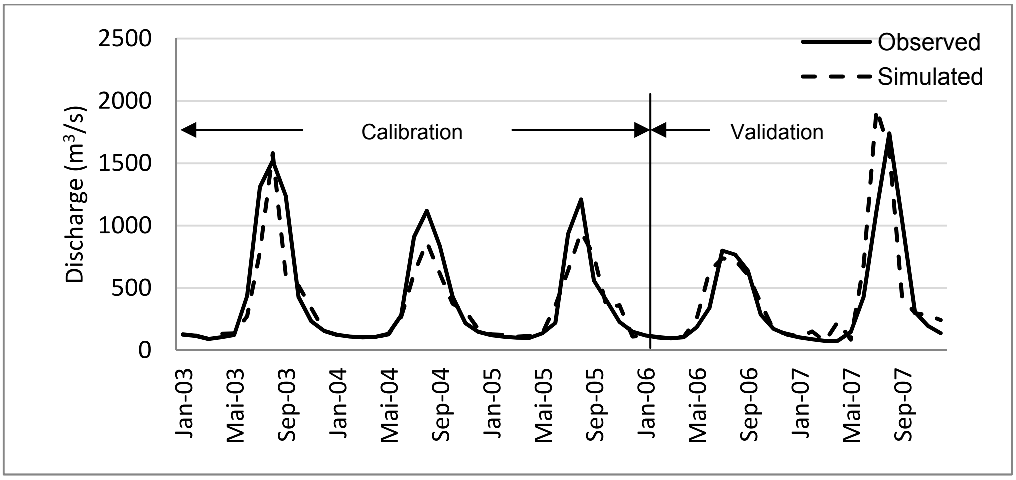

Figure A-6: Observed and simulated discharge at station No.420 in the Narayani basin (Source: Author)

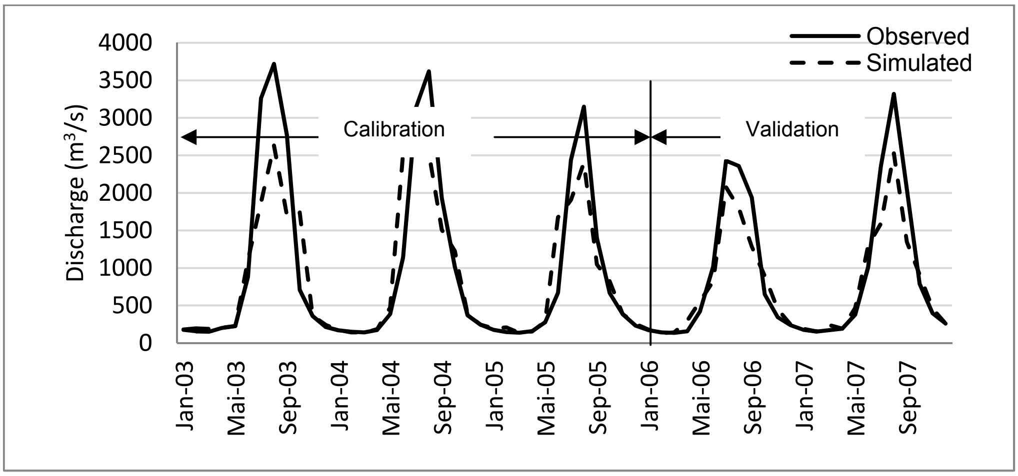

Figure A-7: Observed and simulated discharge at station No.449.91 in the Narayani basin (Source: Author)

APPENDIX 6

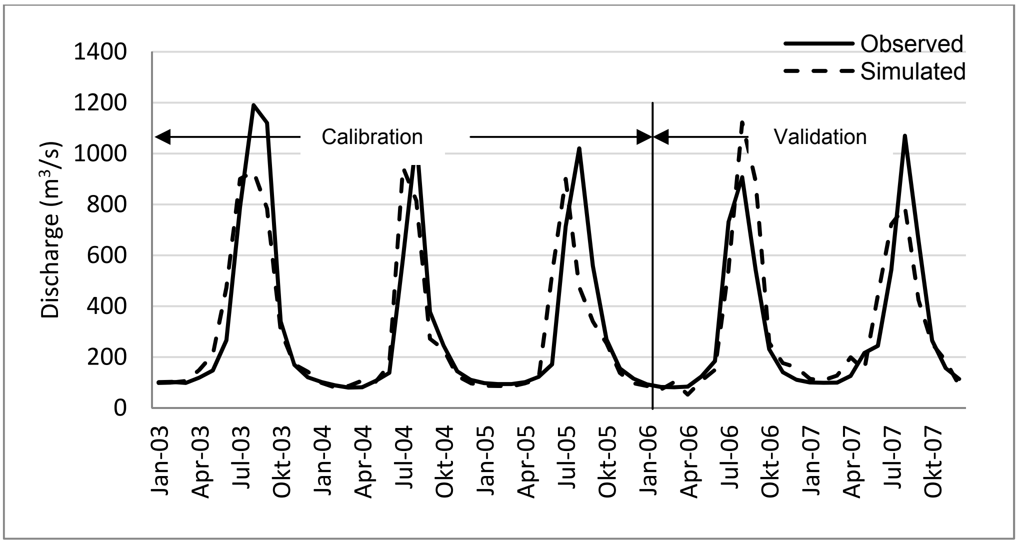

Figure A-8: Observed and simulated discharge at station No.269.5 in the Karnali basin (Source: Author)

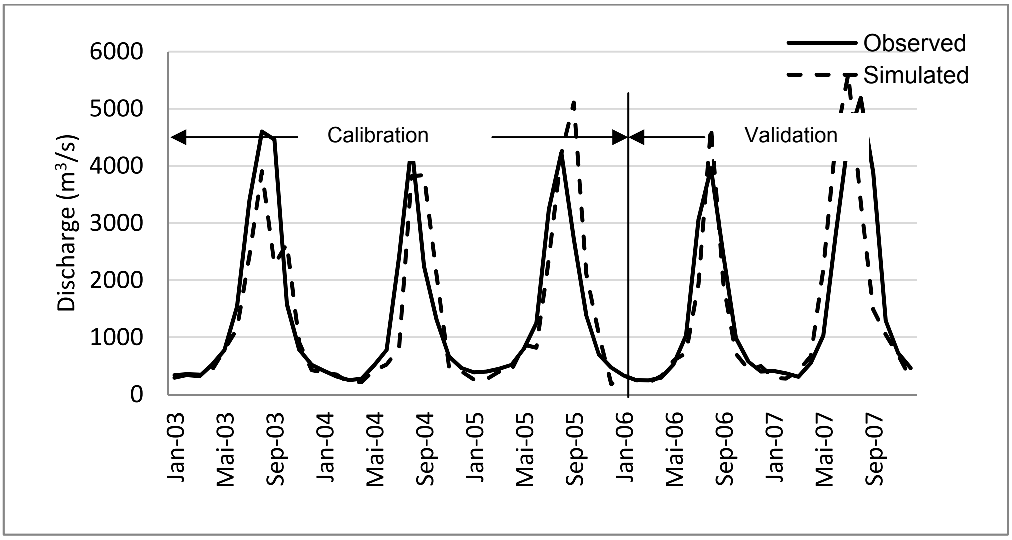

Figure A-9: Observed and simulated discharge at station No.280 in the Karnali basin (Source: Author)

APPENDIX 7

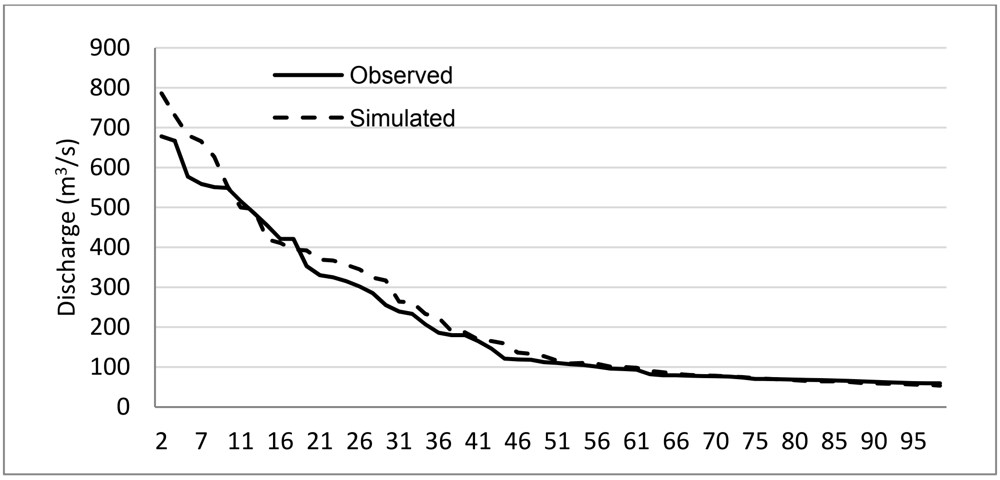

Figure A-10: FDC for observed and simulated flow at station No. 600.1 in the Kosi basin (Source: Author)

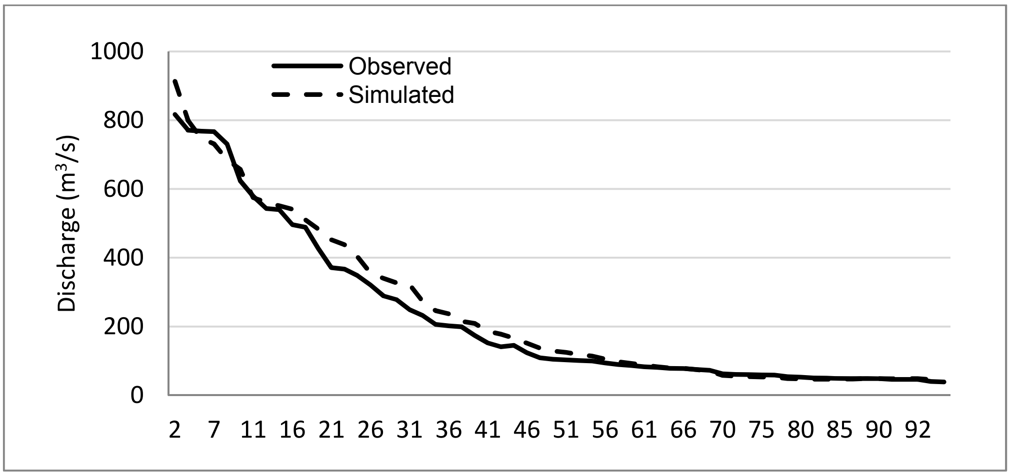

Figure A-11: FDC for observed and simulated flow at station No. 684 in the Kosi basin (Source: Author)

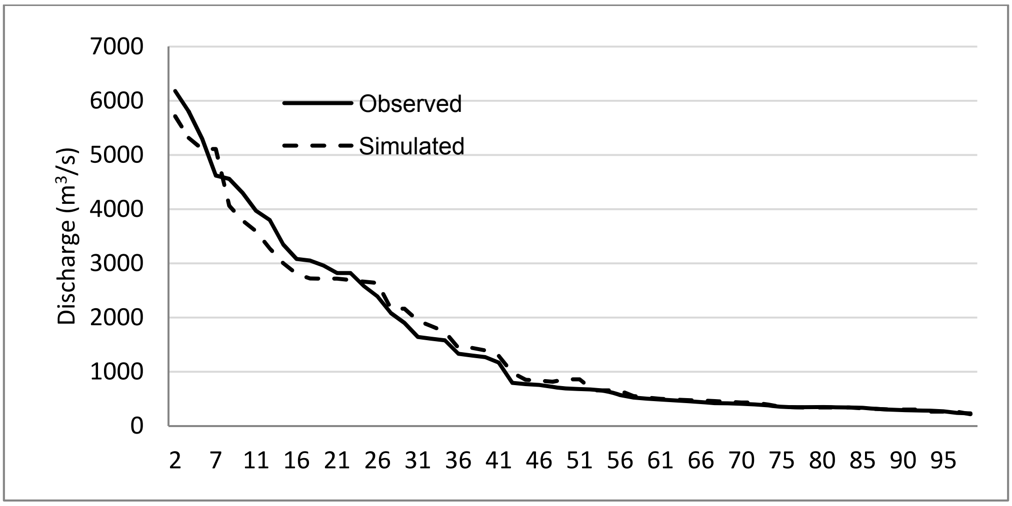

Figure A-12: FDC for observed and simulated flow at station No. 695 in the Koshi basin (Source: Author)

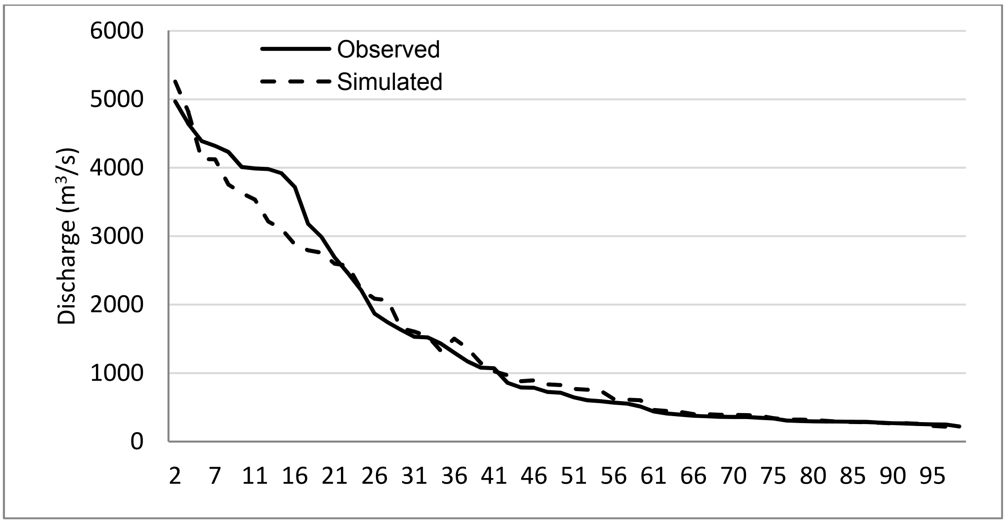

Figure A-13: FDC for observed and simulated flow at station No. 450 in the Narayani basin (Source: Author)

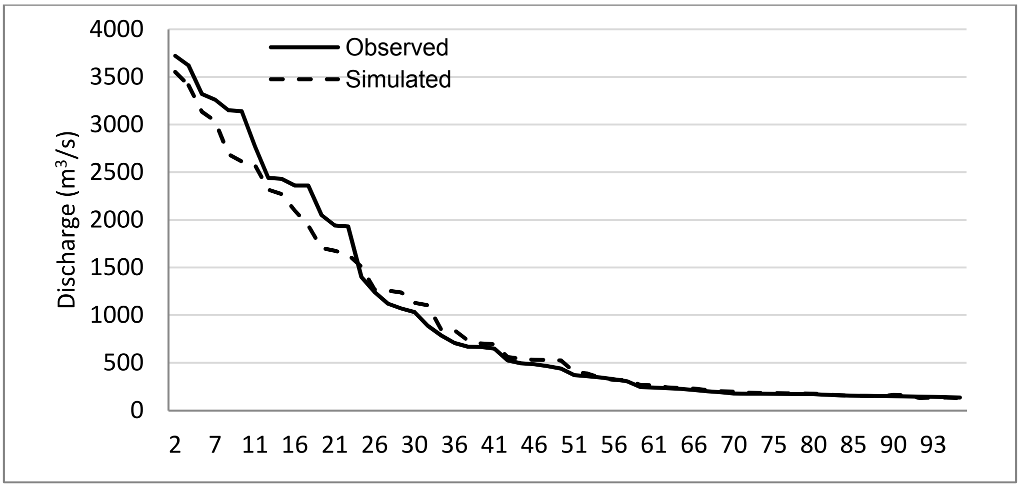

Figure A-14: FDC for observed and simulated flow at station No. 449.1 in the Narayani basin (Source: Author)

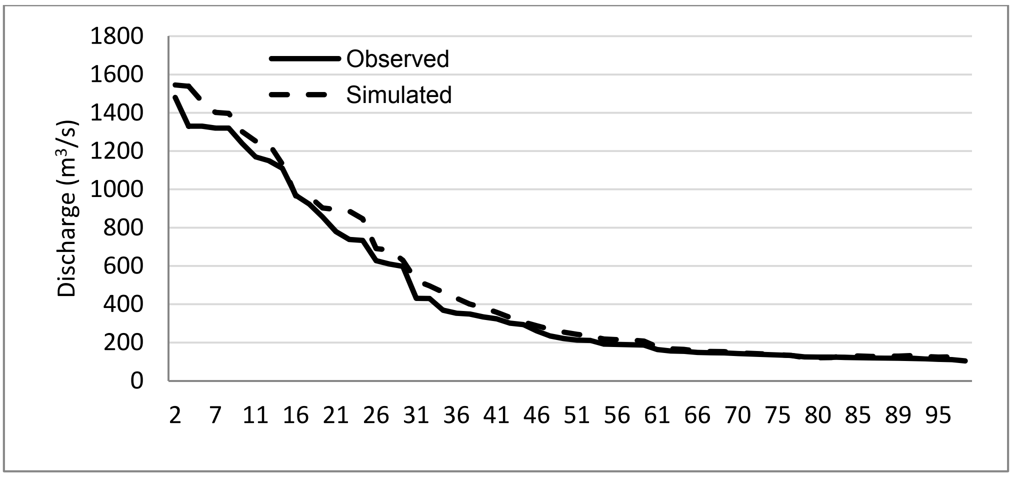

Figure A-15: Flow duration curve for observed and simulated flow at station No. 240 in the Karnali basin (Source: Author)

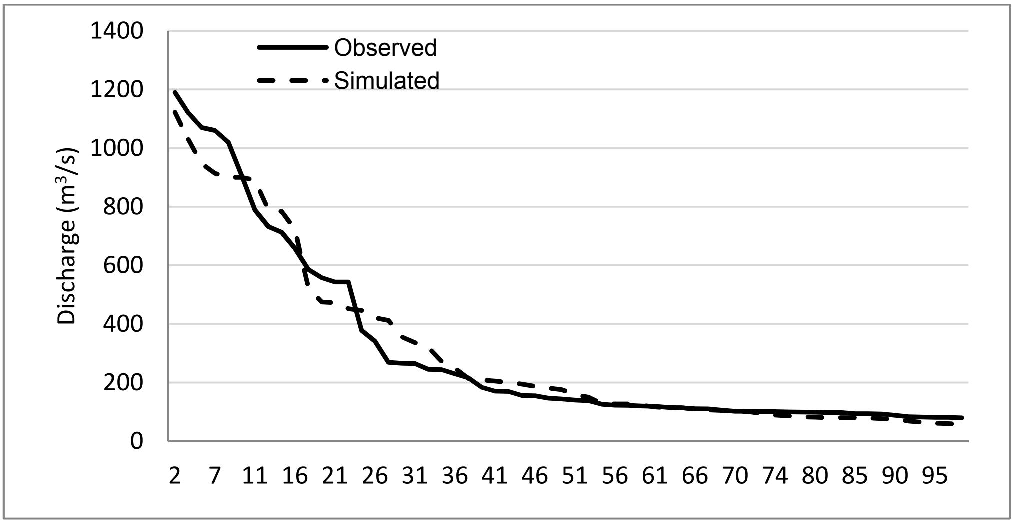

Figure A-16: FDC for observed and simulated flow at station No. 269.5 in the Karnali basin (Source: Author)

APPENDIX 8

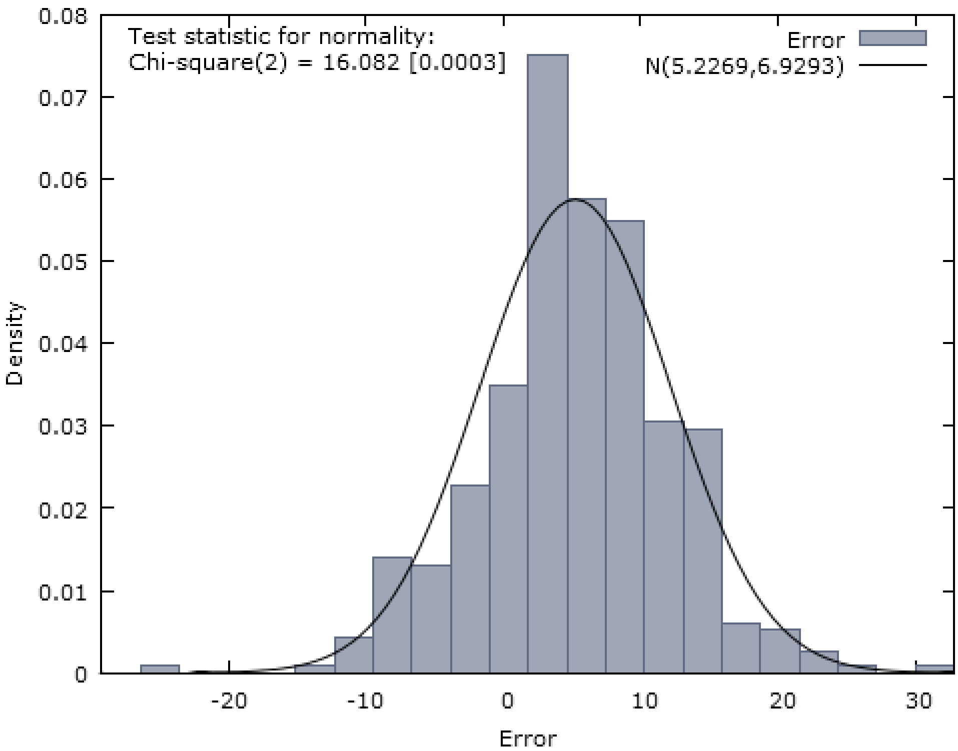

Figure A-17: Error histogram of the flow variation between observed and simulated flow for the flow exceedance ≥ 30% in FDC (Source: Author)

Table A-4: Statistical analysis of variation of flow between observed and simulated flow for the flow exceedance ≥ 30 % in FDC (Source: Author)

Frequency distribution for Error, obs 1-406
number of bins = 21, mean = 5.22692, sd = 6.92926

interval	midpt	frequency	rel.	cum.	
< -23.590	-25.000	1	0.25%	0.25%	
-23.590 - -20.770	-22.180	0	0.00%	0.25%	
-20.770 - -17.950	-19.360	0	0.00%	0.25%	
-17.950 - -15.130	-16.540	0	0.00%	0.25%	
-15.130 - -12.310	-13.720	1	0.25%	0.49%	
-12.310 - -9.4900	-10.900	5	1.23%	1.72%	
-9.4900 - -6.6700	-8.0800	16	3.94%	5.67%	*
-6.6700 - -3.8500	-5.2600	15	3.69%	9.36%	*
-3.8500 - -1.0300	-2.4400	26	6.40%	15.76%	**
-1.0300 - 1.7900	0.38000	40	9.85%	25.62%	***
1.7900 - 4.6100	3.2000	86	21.18%	46.80%	*******
4.6100 - 7.4300	6.0200	66	16.26%	63.05%	*****
7.4300 - 10.250	8.8400	63	15.52%	78.57%	*****
10.250 - 13.070	11.660	35	8.62%	87.19%	***
13.070 - 15.890	14.480	34	8.37%	95.57%	***
15.890 - 18.710	17.300	7	1.72%	97.29%	
18.710 - 21.530	20.120	6	1.48%	98.77%	
21.530 - 24.350	22.940	3	0.74%	99.51%	
24.350 - 27.170	25.760	1	0.25%	99.75%	
27.170 - 29.990	28.580	0	0.00%	99.75%	
>= 29.990	31.400	1	0.25%	100.00%	

Test for null hypothesis of normal distribution:
Chi-square(2) = 16.082 with p-value 0.00032

APPENDIX 9

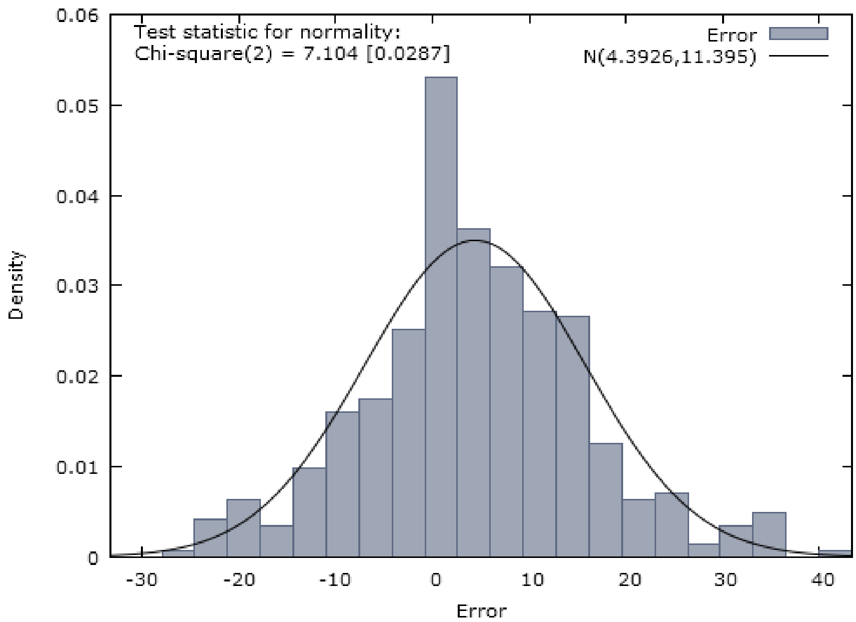

Figure A-18: Error histogram of the flow variation between observed and simulated flow for the entire FDC (Source: Author)

Table A-5: Statistical analysis of variation of flow between observed and simulated flow for the entire FDC (Source: Author)

Frequency distribution for Error, obs 1-422
number of bins = 21, mean = 4.39258, sd = 11.3945

interval	midpt	frequency	rel.	cum.	
< -24.572	-26.270	1	0.24%	0.24%	
-24.572 - -21.176	-22.874	6	1.42%	1.66%	
-21.176 - -17.780	-19.478	9	2.13%	3.79%	
-17.780 - -14.384	-16.082	5	1.18%	4.98%	
-14.384 - -10.988	-12.686	14	3.32%	8.29%	*
-10.988 - -7.5920	-9.2900	23	5.45%	13.74%	*
-7.5920 - -4.1960	-5.8940	25	5.92%	19.67%	**
-4.1960 - -0.80000	-2.4980	36	8.53%	28.20%	***
-0.80000 - 2.5960	0.89800	76	18.01%	46.21%	******
2.5960 - 5.9920	4.2940	52	12.32%	58.53%	****
5.9920 - 9.3880	7.6900	46	10.90%	69.43%	***
9.3880 - 12.784	11.086	39	9.24%	78.67%	***
12.784 - 16.180	14.482	38	9.00%	87.68%	***
16.180 - 19.576	17.878	18	4.27%	91.94%	*
19.576 - 22.972	21.274	9	2.13%	94.08%	
22.972 - 26.368	24.670	10	2.37%	96.45%	
26.368 - 29.764	28.066	2	0.47%	96.92%	
29.764 - 33.160	31.462	5	1.18%	98.10%	
33.160 - 36.556	34.858	7	1.66%	99.76%	
36.556 - 39.952	38.254	0	0.00%	99.76%	
>= 39.952	41.650	1	0.24%	100.00%	

Test for null hypothesis of normal distribution:
Chi-square(2) = 7.104 with p-value 0.02866

APPENDIX 10

The error free power potential is estimated by using following equation:

$$P = \rho g Q H \qquad \text{(A-1)}$$

Where,

P = Estimated power potential (W)

Q = Estimated discharge (m^3/s)

H = Estimated head drop (m)

Let us also assume that ΔP is error in the estimated power potential, ΔQ is the error in the estimated discharge and ΔH is the error in the estimated head drop. Therefore, the total estimated potential will be as follows:

$$(P + \Delta P) = \rho g (Q + \Delta Q)(H + \Delta H) \qquad \text{(A-2)}$$

By expanding equation (2),

$$\rho g Q H + \Delta P = \rho g (Q + \Delta Q)(H + \Delta H)$$

or, $\rho gQH + \Delta P = \rho g(QH + Q\Delta H + H\Delta Q + \Delta Q\Delta H)$

or, $\rho gQH + \Delta P = \rho gQH + \rho g(Q\Delta H + H\Delta Q + \Delta Q\Delta H)$

or, $\Delta P = \rho g(Q\Delta H + H\Delta Q + \Delta Q\Delta H)$

Dividing both sides by P

$$\frac{\Delta P}{P} = \frac{\rho g(Q\Delta H + H\Delta Q + \Delta Q\Delta H)}{P}$$

Substituting the value of P = ρgQH, we get following equation

$$\frac{\Delta P}{P} = \frac{\Delta H}{H} + \frac{\Delta Q}{Q} + \left(\frac{\Delta Q}{Q}\right)\left(\frac{\Delta H}{H}\right)$$

Above equation can be written as follows:

$$P_{error} = H_{error} + Q_{error} + H_{error} \times Q_{error} \tag{A-3}$$

APPENDIX 11

Table A-6: INPS Grid connected hydropower plants in Nepal in 2014 [20]

S.N.	Name of Plants	Capacity (MW)	Longitude			Latitude			River
1	Khimti -I	60	27	28	28	86	15	0	Khimti
2	Devighat	14.1	27	53	7	85	8	45	Trishuli
3	Gandak	15	27	25	21	83	56	25	Narayani
4	Kulekhani -I	60	27	32	6	85	10	50	Kulekhani
5	Kulekhani-II	32	27	30	6	85	8	21	Kulekhani
6	Marsyangdi	69	27	52	25	84	32	42	Marsyangdi
7	Panauti	2.4	27	33	0	85	32	35	Roshi
8	Seti	1.5	28	13	50	83	59	34	Seti
9	Sunkosi	10.05	27	45	0	85	52	30	Sunkosi
10	Tatopani	2	28	31	31	83	40	7	Tatopani
11	Tinau	1.024	27	43	0	83	28	0	Tinau
12	Trishuli	24	27	55	9	85	11	11	Trishuli
13	Andhi Khola	9.4	27	55	34	83	41	6	Andhi Khola
14	Jhimruk Khola	12.5	28	4	2	82	49	7	Jhimruk
15	Puwa	6.2	26	52	28	87	55	52	Puwa
16	Modi Khola	14.8	28	15	42	83	45	45	Modi
17	Kali Gandaki A	144	27	55	0	83	37	20	Kali Gandaki
18	Upper Bhotekoshi	45	27	54	40	85	56	55	Bhotekosi
19	Chilime	22	28	9	15	85	20	28	Chilime
20	Indrawati -III	7.5	27	51	38	85	37	12	Indrawati
21	Madhya Marsyangdi	70	28	8	20	84	26	51	Marsyangdi
22	Piluwa Khola	3	27	12	0	87	20	55	Piluwa

23	Sunkosi Small	2.6	27	46	0	85	56	0	Sunkosi
24	Chaku Khola	3	27	52	0	85	56	0	Chaku
25	Khudi Khola	4	28	16	30	84	21	30	Khudi
26	Thoppal Khola	1.65	27	49	0	84	53	30	Thoppal
27	Mardi Khola	4.8	28	19	10	83	53	30	Mardi
28	Ridi Khola	2.4	27	55	30	83	26	30	Ridi
29	Mai Khola	4.5	26	52	36	87	55	47	Mai
30	Hewa Khola	4.455	27	18	54	87	20	44	Hewa
31	Sipring Khola	10	27	48	38	86	15	18	Sipring
32	Lower Modi-1	10	28	13	15	83	43	0	Modi
33	Siuri Khola	5	28	20	24	84	29	23	Siuri
34	Ankhu Khola-1	7	28	0	0	84	55	55	Ankhu
35	Baramchi Khola HPP	4.2	27	50	11	85	48	15	Baramchi
36	Bijayapur -1	4.5	28	10	37	84	2	26	Bijayapur
37	Middle Chaku Khola	1.8	27	52	20	85	56	0	Chaku
38	Tadi Khola (Thaprek)	5	27	55	0	85	21	8	Tadi
	Total Capacity	700.379							

APPENDIX 12

Table A-7: List of under-construction hydropower plants in Nepal [20]

S.N.	Name of Plants	Capacity (MW)	Latitude			Longitude			River
1	Andhikhola (Upgradation)	4.3	27	57	2	83	41	6	Andhi Khola
2	Ankhu Khola-I	8.4	28	4	0	84	58	35	Ankhu
3	Badi Gad	6.6	28	19	13	83	11	30	Dadigad
4	Belkhu	0.518							
5	Bhairab Kunda	3	27	55	52	85	56	28	Bhairab Kund
6	Chake Khola	2.83	27	37	15	86	21	42	Chake
7	Chaku Khola (Upgradation)	1.5	27	52	0	85	56	0	Chaku
8	Chameliya Khola	30	29	41	0	80	45	0	Chameliya
9	Gelun	3.2	27	49	30	85	49	15	Gelen
10	Hewa Khola	14.9	27	10	9	87	50	58	Hewa
11	Jhyari Khola	2	27	44	30	85	41	2	Jhyari
12	Jiri Khola	2.2	27	35	6	86	14	0	Jiri
13	Khani Khola -1	40	27	47	48	86	22	0	Khani
14	Kulekhani -III	14	27	27	30	85	3	30	Kulekhani
15	Lower Chaku Khola	1.765	27	52	33	85	55	29	Chaku
16	Lower Indrawati Khola	4.5	27	50	0	85	34	46	Indrawati
17	Madhya Bhotekoshi	102	27	49	8	85	54	43	Bhotekoshi
18	Mai Khola	22	26	47	21	87	55	0	Mai
19	Mailung Khola	5	28	4	3	85	11	26	Mailung
20	Phawa Khola	4.95	26	54	50	87	55	0	Phawa

21	Pikhuwa Khola	2.475	27	8	38	87	2	3	Pikhuwa
22	Radhi Small	4.4	28	23	48	84	24	34	Radhi
23	Rahughat	32	28	22	21	83	34	15	Rahughat
24	Rasuwagadhi	111	28	14	5	85	21	22	Bhotekoshi
25	Sanjen	42.5	28	11	0	85	18	15	Sanjen
26	Tanahu HEP (Storage)	140							
27	Upper Madi	19.008	28	15	37	84	7	0	Madi
28	Upper Mai Khola	9.98	27	1	22	87	58	0	Mai
29	Upper Marsyangdi A	50	28	17	7	84	24	10	Marsyangdi
30	Upper Modi	42	28	15	37	84	7	0	
31	Upper Puwa Khola -1	3	26	59	47	87	54	10	Puwa
32	Upper Sanjen	14.8	28	13	0	85	18	15	Sanjen
33	Upper Tamakosi	456	27	49	0	86	10	0	Tamakosi
34	Upper Trishuli 3A	60	28	1	21	85	12	38	Trishuli
	Total Capacity	1256.526							

Curriculum Vitae

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