Assessment of Hydropower Potential of Astore River Basin Using HEC-HMS Model and GIS Based Workflows

By

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DEDICATION

Dedicated to my beloved family and parents.

ACKNOWLEDGEMENTS

All praise be to ALLAH the Almighty the Exalted, the Lord of all the worlds and gratitude to the last Prophet MUHAMMAD **(**P.B.U.H**)**.

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Abdul Waheed

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LIST OF ABBREVIATIONS

Abbreviation	**Explanation**
ROR	Run of River
GIS	Geographical Information System
EROI	Excellent Return on Investment
PMD	Pakistan Meteorological Department
WAPDA	Water and Power Development Authority
HEC-HMS	Hydrological Engineering Center’s Hydrological Modeling System
SCS	Soil Conservation Science
CN	Curve Number
FDC	Flow Duration Curve
USA	United States of America
SWAT	Soil and Water Assessment Tool
RHAM	Rapid Hydropower Assessment Model
VIC	Variable Infiltration Capacity

ABSTRACT

The aim of this study was to investigate the hydrological response by using Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS), subsequently, the assessment of run of the river hydropower potential. For this study the Astore River Basin located in Upper Indus Basin (UIB), northern Pakistan, was selected. The daily data of climatic variables (e.g. precipitation and temperature) at three (3) stations and stream flows at Doian station were obtained from Water and Power Development Authority (WAPDA). Further the global digital elevation model (GDEM) at 30×30 m spatial resolution was used to extract the physical parameters such as slope, imperviousness (%), catchment area, stream network etc. The HEC-HMS was calibrated and validated during 1999-2003 (5 years) and 2004-2007 (4 years), respectively. Further, the hydropower potential was estimated by using flow duration curve (FDC) at 30% of flow exceedance. The FDC was developed for the simulated stream flows which further utilized in power equation for the power potential estimation analysis. The HEC-HMS was found efficient with Nash-Sutcliffe (NS) coefficient value of 0.66 and 0.64 for calibration and validation period, respectively. Moreover, the total theoretical hydropower potential at twenty five (25) identified sites was found 1593 MW. The results of the study would be helpful in awareness of exploiting the hydropower potential of the region and also help in building confidence and investment in hydropower sector by private partners.

Chapter 1

INTRODUCTION

There is no means for economic development other than energy. There are numerous studies that have analyzed the strength of correlation between the economic development and energy consumption of a nation (Pirlogea et al., 2012). It is very essential for a country to have viable and clean energy supply for sustainable economic development. In the modern world the most prominent source of energy is fossil fuel it would be fulfilling the energy needs of the world for next 25 years that is up to 2040. However, there is a great risk associated with large scale use of fossil fuels as it is the primary source of global greenhouse gas emissions. Greenhouse gases from fossil fuel that is CO_2 have a share of 56% of overall word's greenhouse gas emissions. Enormous amount of greenhouse gas emissions from the fossil fuels have adversely affected the world climate as link between greenhouse gas emissions and global warming has been recognized. There have been number of strategies that are proposed for reducing the amount of greenhouse gas emissions (EIA, 2013). The only possible solution for this problem is the use of renewable energy sources. One of the abundant renewable power sources is hydropower. Hydropower is one of the major contributors to renewable energy and has significantly contributed in reduction of greenhouse gas emissions (OECD/IEA, 2014).

The electricity demand has been increasing very rapidly in the developing countries and progressively growing in the developed world. This increasing demand for electricity is projected to be doubled in 2030 with an annual increasing rate of 2.4 % (Birol, 2010). To meet such a high rate of demand the production of electricity while complying with environmental regulations is a great challenge. It has been estimated that hydropower is fulfilling 16% of the world's power demand and almost four-fifth of global renewable electricity.

Hydropower offers the best renewable energy conversion efficiency and excellent return on investment as compared to all other renewable energy sources (OECD/IEA, 2014). It is very important for a country to deploy its assets for assessment of its hydropower potential.

Hydropower is generated from natural gradient which can be provided either by building water storage dams or by making use of the kinetic energy of the flowing or falling water in a mountainous topography. The energy from the flowing or falling water for driving turbines generates hydropower (Kurse et al., 2010).

An increase in large scale hydropower production has been observed as there is a progressive technological maturity in the hydropower industry. However, despite in such a technologically advance era the hydropower produced has not been equivalent to the potentiality. There is a huge gap between the production and available hydropower potential. The overall energy mix of the hydropower is quite low. From recently calculated statistics it is evident that the hydropower is only 6.15 % of the total world energy mix. So, the estimated hydropower harnessed so far is only quarter of the total economically viable potential (BEE, 2007)

1.1 Hydropower in Pakistan

In Pakistan, the hydel resources are mainly in the north. The hydropower potential of Pakistan can be divided into six regions Punjab, KPK, Azad Jammu Kashmir, Gilgit Baltistan, Sindh and Balochistan. Allah has bestowed Pakistan with a hydropower potential of approximately 41722 MW, most of which lies in the KPK, Northern Areas, Punjab and Kashmir. However, an abundant hydropower potential is still not harnessed. Capacity of the total installed hydropower is around 6600 MW, out of which 3700 MW is in KPK, 1700 MW in Punjab, 1040 MW in AJK and 100 MW in the Gilgit Baltistan. (PPIB, 2009)

Hydropower is the product of head and flow rate at a given location. So, it is evident that the hydropower requires assessment of water resources. The accurate hydropower assessment is dependent upon the accurate water resource assessment. The biggest constraint or hurdle in the way hydropower development is the lack of accurate water resource assessment and it is specifically true for under developed countries. Under developed countries have poor water resource management and have no reliable historical data for available water resources (Kurse et al., 2009). The northern areas of Pakistan particularly the Himalayan region contributing to the Indus River is a hydropower resource rich but low growth area.

1.2 Challenges Involved in Hydropower Development

Traditional hydropower assessment methods consider historic data of discharge for estimation of power resource. Mostly the availability of past time records are location specific. The location specific historical water resource records are not enough for assessment because of the complexities related to hydrological phenomenon, so the water resource assessment based on the historic location specific records may have uncertainties regarding accuracy of the assessment which may led to underestimation, secondly collection of observed data from large number of observatories would be costly and quite time taking. Another problem is that the data collection from a fixed location might miss some potentially significant events occurring at other locations that might result in wrong planning (Kulkarni et al., 2009).

1.3 Role of Remote Sensing and GIS in Hydropower

GIS (Geographical Information System) and Remote Sensing can play a significant role in estimation of hydropower potential and identification of run of river hydropower generation sites. With the help of GIS and Remote Sensing based hydrological models simulation of actual situation of terrain, climate and complexity of hydrological phenomenon is possible. Computerized simulation models have made it possible to simulate the spatial and temporal availability of the water.

GIS based hydrological models have provided the opportunity for the hydrologists and water resource engineers to integrate all possible physical processes and events that are involved in hydrological modeling for better hydrological simulation. Hydrological models are able to provide information about quantity of water discharge for three different flows that are surface flow, subsurface flow and channel flows (Coskun et al., 2010). Use of hydrological models has been increased due to their advantages over tradition water resource assessment techniques (OECD/IEA, 2014). For futuristic planning of water resources hydrological models have proven to be useful tool for quantification of climatic change impact on water resources (IRENA, 2014)

1.4 Run of River Hydropower

Run of river hydropower plants are constructed along the river flow and there is no water storing mechanism for hydropower generation. Run of river power plants have very little control over the natural flow of water along the river. If flow in the river reduces, power production from the power plant also decreases. Run of river hydropower plants are designed to utilize the river flow during the dry season. The installed capacity of run of river hydropower plants is based upon the dependable flow of the river that sustains throughout the year. The run of river power plants are generally designed at 30 % dependable flow. The major components of a run of river power plant are a barrage, a forebay tank or a small pond structure for keeping constant flow, a penstock pipe to deliver pressurized water to turbine connected to power generator. The power generator is connected to the main grid to deliver generated power.

1.5 Objectives

Following were the main objectives of the study:

a) Characterization of Astore watershed using HEC-HMS model and calibrating the model parameters for the period 1999-2003 (5 years) and validating for the period 2004-2007 (4 years).

b) Development of flow duration curves from simulated discharge and estimating theoretical hydropower potential at 30% time probability flow exceedence.

c) Identification of feasible run of river hydropower generation sites based upon discharge and head.

Chapter 2

LITERATURE REVIEW

Forecasting stream flows is extremely essential while investigating hydrology and optimizing water resources. Hydrological modeling being part of hydrological analysis is important for understanding the potential issues related to water supply for domestic, hydropower, agriculture and other uses. Hydrological modeling requires the use of most suitable hydrological model for a particular study which depends upon the characteristics of the watershed, required accuracy, availability of data, system on hand and objectives of the study (Abraham et al., 2007). Accuracy of hydrological prediction of high elevation regions using hydrological models is commonly not satisfactory due to contribution of snow melt. So, it is quite challenging to assess the hydrology in high altitude and limitedly gauged watersheds. Studies have been carried out by the scientific community in past few decades to overcome these challenges. Numerous researchers have used observed and remotely sensed meteorological data in integration with modern hydrological models to predict the discharge in poorly gauged and relatively high altitude regions. Kurse et al, 2009 successfully predicted the hydrology of Kopoli river basin by using observed meteorological data in conjunction with the SWAT hydrological model. Numerous methodologies have been proposed for hydrological assessment. Kulkarni et al, 2002 derived a temperature index based methodology by using remote sensing data of spatial extents for assessing long term average stream runoff in Himalayan region. The derived methodology was proved useful for assessing hydropower potential of the snow and streams fed from glaciers of the Himalayan region where data availability of stream flow is a big constraint. Hydrological prediction is directly connected to the hydropower generation. Change in quantity and timing of runoff directly effects the hydropower production. This study is aimed at predicting the hydrology of the Astore watershed in addition to investigating the theoretical hydropower and identification of potential run of river hydropower generation sites. A number of studies have been conducted in the past using various methods for investigating hydrology and hydropower prediction. Monk et al, 2009 conducted a GIS based hydropower assessment study for identifying small run of river hydro power sites using Rapid Hydropower Assessment Model (RHAM). Chalise et al, 2003 used water balance principle and hydrological response grids to estimate low flows for assessing small hydropower potential in the Hindukush region of Himalayas. Ramachandra et al, 2004 developed a spatial decision support system for assessing micro mini and small hydro power project in Karnataka, India. Integrated information from water resource assessment methods and GIS were used for decision support system. Carroll et al, 2004 configured GIS tools to identify potential small hydropower sites in USA. Rasanen et al, 2013 studied existing and planned reservoirs for irrigation and their effects on the production of hydropower. He used the approach of hydrological and hydropower modeling of multipurpose reservoirs on catchment scale. Fay et al, 2013 used globally available satellite data and local rainfall data to assess the hydropower potential of rivers in island of Saint Lucia. Runoff modeling was done using a hydrological model by considering climatic conditions of the region. Ouarda et al, 1997 estimated the project dependable hydropower capacity using the Indexed Sequential Hydrological Modeling (ISHM) for federally owned projects in the Colorado River basin. Coskun et al, 2010 developed a regression equations based hydrological model and used remote sensing data to derive the artificial drainage network and estimated hydropower potential. Cuya et al, 2013 used GIS based procedures to assess the hydropower potential in the La Plata basin. Rojanomom et al, 2009 identified run of river hydropower projects in Thailand using GIS, economic and environmental criteria.

Azmat et al. 2015 estimated the water resource availability of Mangla watershed and assessed its impact on mini hydropower production at Upper Jhelum Canal. They characterize the Mangla watershed with HEC-HMS using satellite and other available data. The result of the study suggested that HEC-HMS can efficiently reproduce daily stream flows in snow fed glaciated catchments. GIS and remote sensing have been used in recent times in combination with hydrological modeling systems for many water resource applications. However there are some limitations associated with such advance technologies, the biggest limitations is the enormous amount of data required and secondly expensive GIS software and temporal resolution of data.

Hydropower is the product of river discharge and head drop (Monk et al., 2010). Head drop is estimated manually from the topographic map or by using GIS software that uses the DEM to determine the head drop along the stream automatically (Kulkarni et al., 2002). Discharge of river is another component of hydropower assessment. Some of the major processes that contribute to the river flow are surface runoff generated by precipitation, ground water flow, snow and glacial melt (Kurse et al., 2009). Data of river discharge is normally acquired at specific locations along the river or at junctions with its major tributaries and therefore the observed discharge is normally not available at location of interest. So, river discharge estimation is essentially required upstream and downstream of observed location and also for ungagged river basin (Chalise et al., 2003)

Chapter 3

MATERIALS AND METHODS

3.1 Study Area

Astore River catchment selected for this study is located at 75°06′36.9″ longitude and 35°02′20.3″N latitude. Astore Valley has an estimated area of 5092 km^2 and has an average altitude of 2600 m. The climate of Astore is moderate during summer while winters are quite a bit harsh and the snowfall can reach up to 15 cm in the main valley and up to 1 m in the mountains. Mirmalik is one of the prominent peaks of the region and it receives snowfall up to 2 m in the month of February (Tahir et al., 2015). According to Pakistan Meteorological Department (PMD) the average annual temperature of Astore is 9 ºC that varies between -4.5 ºC in January and 20 ºC during month of July. Astore receives 427 mm of annual rainfall. Highest rainfall occurs during the month of April with average 72 mm and lowest 10 mm during November. The Astore Valley is homes prominent glaciers of the region that include the Chungphar glacier, Chongra glacier, Bazhin glacier and Tashin glacier. Entrance of Astore basin is located about 60 km southeast of Gilgit district. Astore Valley has few working hydropower plants that are installed at torrents and river tributaries that are contributing for fulfilling power needs of the local population (Hasil et al., 2015). Some well-known mountain peaks of the Astore are Nanga Parbat, Rupal, Shaigiri, Mazeno and Laila. Some famous villages of the valley are Gudai, Shekong, Dass Kariam, Chongra, Tari Shing, Rattu, Kamri,and Minimerg. Astore Valley has been divided into five sub-basins for this study the names of these sub-basins are Rattu, Pershing Gah, Nanga, Harcho and Gorikot. These sub-basins were delineated based upon the major tributaries of Astore River. Figure 3.1 shows the Astore watershed in detail.

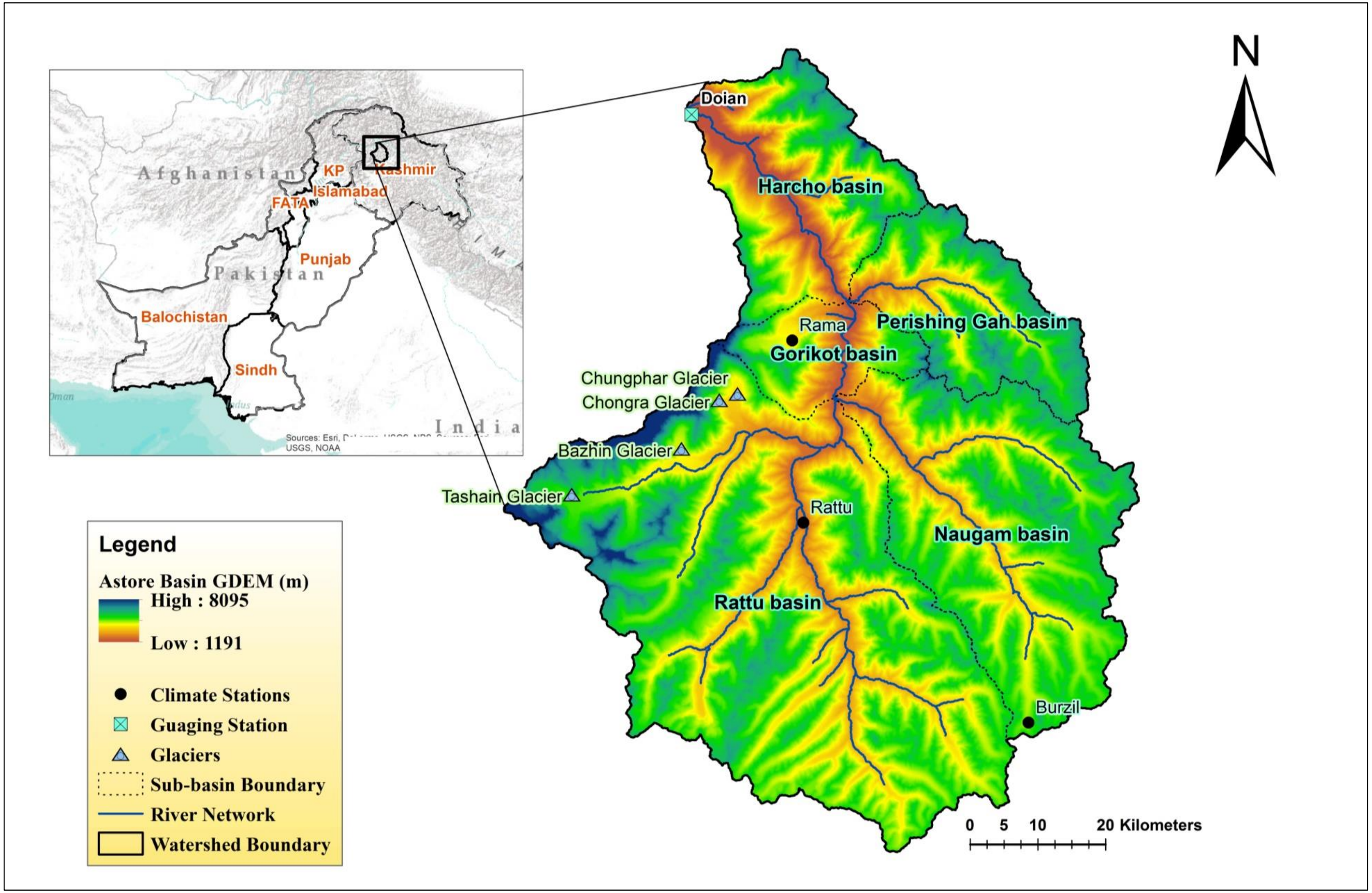


Figure 3.1. Map of Astore River basin.

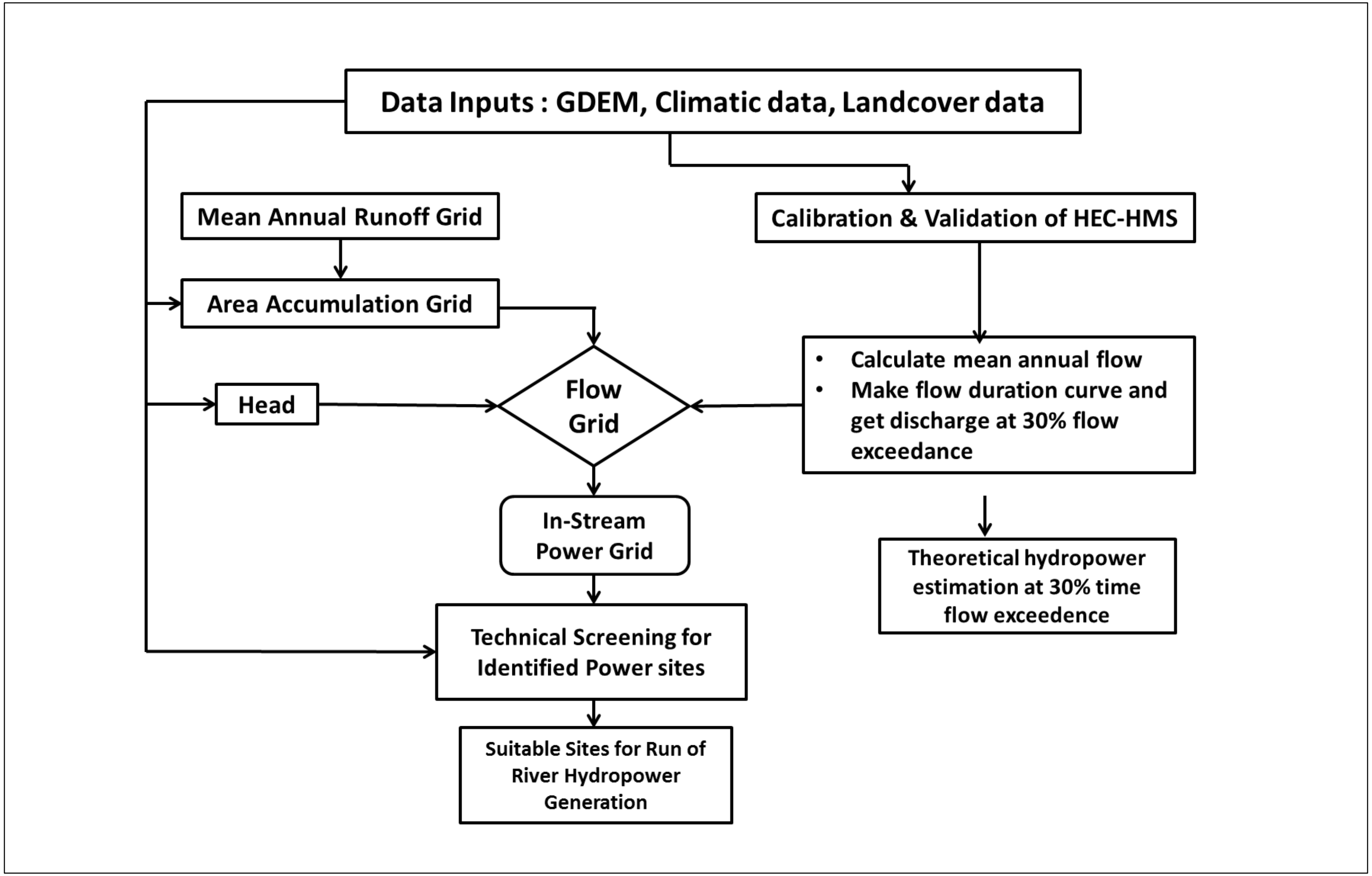


Figure 3.2. Research methodology flow chart.

3.2 Data Acquisition and Processing

HEC-HMS model required a range of data for hydrological modeling. These data included the basin model that was derived from DEM (Digital Elevation Model). The basin model was processed and developed in HEC-Geo-HMS plugin of Arc GIS software. Basin model prepared in HEC-Geo-HMS was exported in HEC-HMS. Hydrological modeling in HEC-HMS requires data related to landcover, climatic variables in the form of daily precipitation and average temperature records. These data were processed to meet the model requirements. Following were the data used and processed for HEC-HMS model simulation.

3.2.1 DEM (Digital Elevation Model)

DEM is a digital three dimensional cartographic dataset of elevation (USGS, 2012). DEM is used in numerous studies such as landscape studies, wild life, forestry, geology hydrological characterization and GIS and climate impact studies (Sulebak, 2000). Two digital elevation datasets accessible were Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER Global DEM) and Shuttle Radar Topography Mission (SRTM) DEM. ASTER Global DEM is better with 30 m resolution compared to 90 m resolution of SRTM DEM and was better for high altitude mountainous regions than SRTM (Isioye et al., 2013). Therefore, ASTER GDEM was selected for this study. Figure 3.3 shows the DEM for the Astore watershed.

3.2.2 Land Cover Map

Land cover map was downloaded from Global Land Cover 2000 for the study area. The required portion of map was extracted with the help of Astore River basin watershed boundary. The grid data was then projected at WGS 1984/UTM zone 44N coordinate system. The land use map provided the spatial information regarding the use of land for agriculture, human settlement, forests and water bodies. Figure 3.4 shows the landcover map for Astore

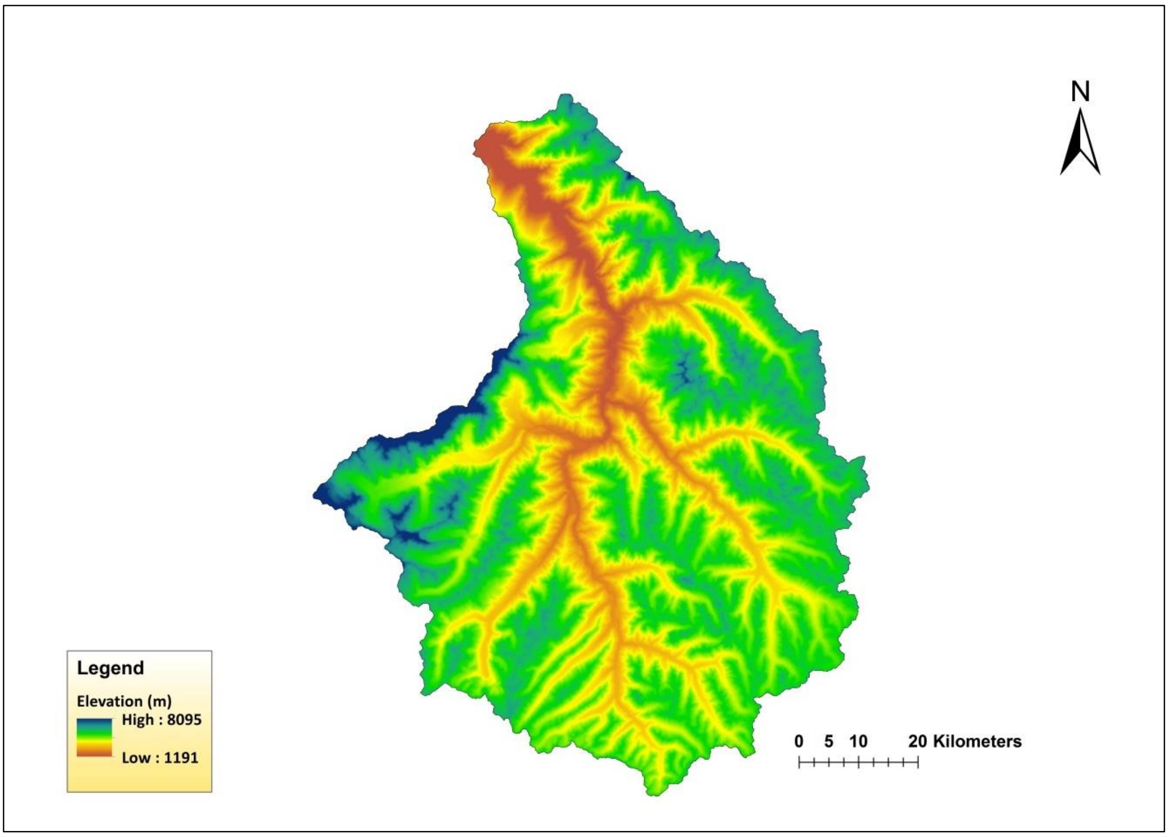


Figure 1.3. DEM (Digital Elevation Model) for Astore River basin.

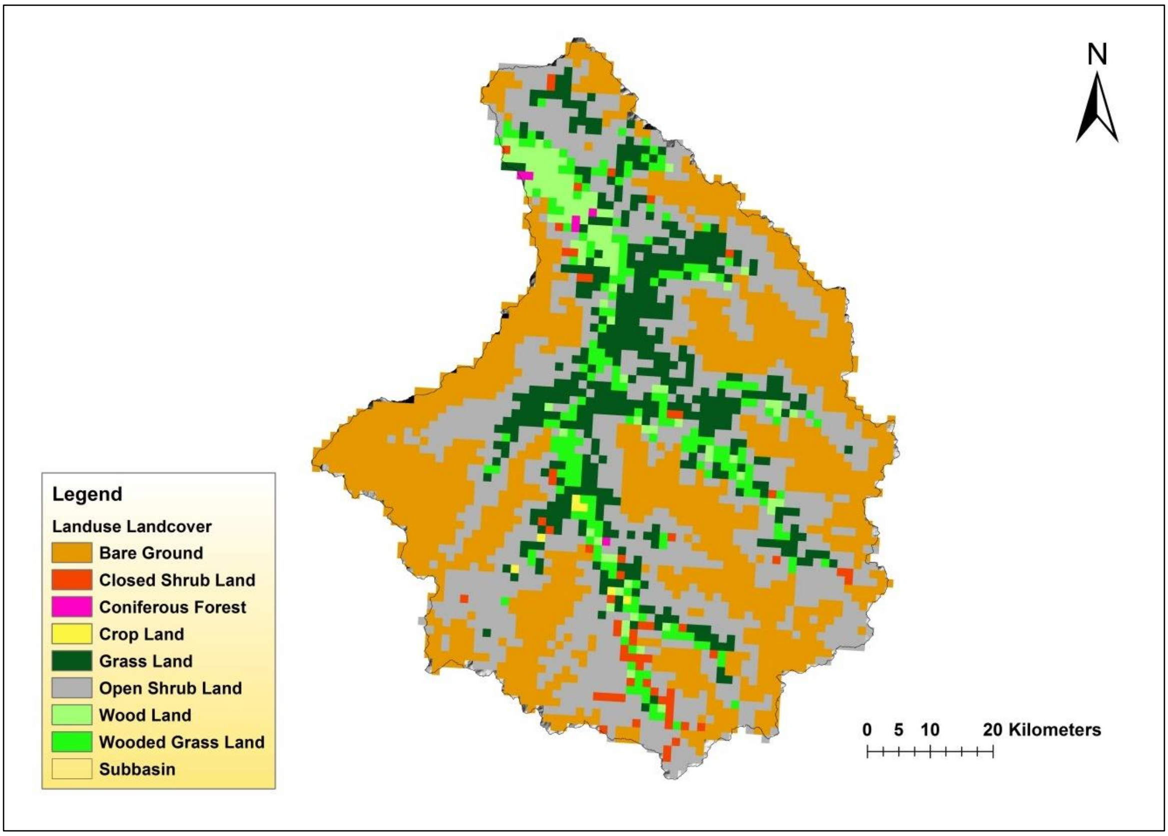


Figure 3.4. Landcover map for Astore River basin (1 km resolution).

watershed. The landcover map was able to provide the necessary data regarding the landcover features that are forest areas, crop land etc.

3.2.3 Climate Data

For Astore basin, the daily precipitation data was collected from 3 meteorological stations for the period 1999 to 2007 (8 years) from Pakistan Meteorological Department (PMD). The data was checked and missing data was interpolated. The daily minimum and maximum air temperature data was also collected from PMD. The temperature data was required for the hydrological model to compute snow melt, precipitation type and potential evapotranspiration. The daily discharge data was collected from Water and Power Development Authority (WAPDA) for the period 1999-2007 for Doian Station at the outlet. The data from 1999 to 2003 (5 years) were used for model calibration and from 2004-2007 (4 years) for validation.

3.2.4 Runoff Grid

Runoff in the form of grid was obtained from Noah model data outputs available online. Mean monthly global data was available. The required data was downloaded, extracted for the study area and was annually averaged. Same procedure was adopted for all the years. From annual average raster data average annual runoff grid was developed at 30 m resolution. The available data was having coarse resolution not suitable to be used with Aster 30 m DEM to simulate the flow. So, spatial smoothing tools were used to bring the data resolution to 30 m. The spatial smoothing was performed using the spline interpolation method. Spline estimates the values using a mathematical function that minimizes surface curvature resulting in smooth surface. The average annual runoff grid was then transformed into average annual flow using GIS tools. The average annual flow was then validated with observed flow at the outlet point.

3.3 Hydrological Modeling

In the first step hydrological modeling was performed to get the simulated discharge for the ungauged sub-basins. In this process the calibrated model was run for the specified time period and validated with the unchanged model parameters for another period. In the next step accuracy of the model was evaluated. From simulated daily discharge the flow duration curves were developed and theoretical hydropower was estimated for all sub-basins at 30 % probability flow exceedence. Potential run of river hydropower generation sites were identified using validated runoff grid data and GDEM. Feasibility analysis was conducted by considering slope, inter-sites distance and minimum power output.

A number of methodologies have been devised to estimate the river discharge. One of the simplest methods for river discharge estimation is the use of regression equations. Regression equations utilize data regarding drainage area, land use land cover, climatic variables and geomorphology as independent parameters to simulate stream flow of a given watershed. Another conventional and simple method for estimating river discharge is to use the drainage area ratio method. In this study hydrological modeling method is used.

Hydrological modeling can be defined as simplified conceptual representation of a hydrological cycle. The purpose of using hydrological models is to predict hydrology and for understanding the hydrological processes. Hydrological models use mathematical and statistical concepts to link data inputs such as rainfall, temperature and terrain characteristics etc. for modeling outputs such as runoff. There are three different types of hydrological models generally applied. One of the basic types of hydrological models is lumped model. Lumped models are simple and require less data inputs and are only applicable or useful for basins with similar basin characteristics. Another type of model used is the semi distributed hydrological model. This type of model allows the input parameters to vary among the sub-basins. This type of model requires more detailed data and parameter estimation as compared to the lumped model. Amongst all three types of hydrological models the most complex hydrological model and that has most realistic representation of hydrological processes occurring in a river basin is the distributed hydrological model. Distributed hydrological model requires input data in grid form. There are a number of factors that are important to be considered before selecting any hydrological model one of them is the availability of the data, data is very essential to be made available for a particular model to be simulated. Other important factors are desired accuracy and cost of the software, cost of data acquisition, processing speed and user support etc. Accessibility of the models was performed based upon the data requirement, cost of the tools, user support and processing power of the system available. HEC-HMS model was selected for this study based upon the above mentioned constraints. HEC-HMS is a semi distributed model. The details of HEC-HMS model are mentioned below (Arlen, 2000).

3.3.1 HEC-HMS Model

The Hydrologic Engineering Center’s Hydrological Modeling System (HEC-HMS) is designed to simulate the complete hydrological processes of watershed systems. The software includes various hydrological analysis procedures including infiltration, hydrographs, and hydrologic routing. HEC-HMS also includes procedures for continuous simulation including evapotranspiration and snowmelt. There are also capabilities provided for gridded runoff simulation using the linear quasi-distributed runoff transformation method. HEC-HMS modeling system is unique as it uses separate components that work in combination as a complete hydrological model. HEC-HMS components include a model for computing runoff volume, a model for direct runoff calculation, a base flow model, a model for channel flow (Arlen, 2000). For computing runoff volume, HEC-HMS possess loss models that include initial and constant rate, SCS curve number, Gridded SCS CN, Green and Ampt, Deficit and

Constant Rate, Soil Moisture Accounting Model and Gridded SMA. In this study for computing runoff volumes Deficit and Constant rate was selected. For computing direct runoff Clark UH method was adopted. There are other direct runoff models also provided in HEC-HMS. These methods include User Specified Unit Hydrograph, Snyder's UH, SCS UH and ModClark. There are a number of baseflow models included in HEC-HMS model. For current study the monthly baseflow method was used. In constant monthly method the observed data of a bigger time period is required. Monthly base flow is computed by considering minimal flow for all months individually of a given number of years and then averaging minimal flow for every month of all years. HEC-HMS gives a number of options for routing. Kinematic Wave model was used in this study. Other models provided in HEC-HMS are Lag Model, Modified plus Model, Muskingum Wave Model, Muskingum-Cunge Standard Section, Confluence and Bifurcation (Arlen, 2000).

3.4 HEC HMS Model Setup

Setting up HEC-HMS model involves a few steps. First is the creation of basin model in HEC-Geo-HMS and writing the basin geometrical parameters. Next step is exporting the basin model in HEC-HMS and defining the parameters for all sub-basins related to loss, runoff, base flow and routing methods. In the third step meteorological model is setup by defining the meteorological stations and tabulating the daily meteorological data for defined time period. In the last step observed discharge data is fed in the model for evaluation of results.

3.4.1 Creation of Basin Model

For this study HEC-Geo-HMS tool for ArcGIS was used to build basin model. HEC-Geo-HMS is a plugin for data preparation for HEC-HMS model that runs on ArcGIS software. After installing ArcGIS, HEC-Geo-HMS can be installed as a plugin. HEC-Geo-

HMS prepared the necessary basin model for Astore River basin. HEC-Geo-HMS used DEM to develop stream network, sub-basins and also estimated some basic required watershed properties that are area, slope, flow, length, stream network density, River Slope, Basin Slope, Longest Flow path, Basin Centroid, Centroid Elevation and Centroidal Flow path. This data was stored as separate files in the basin model and was then exported to HEC-HMS.

3.4.2 Creation of Meteorological Model

In this step the meteorological model was developed in HEC-HMS software along with the basin model imported from HEC-Geo-HMS. Meteorological data to respected stations was assigned in the watershed. The meteorological data included daily precipitation, temperature records and some other basin characteristics parameters.

3.4.3 HEC-HMS Model Run

Before running the model, canopy method, surface method, loss method, routing method, base flow method for basin model were selected in addition to snowmelt and evapotranspiration methods for meteorological model simulation.

3.4.4 Calibration and Validation of Model

After running model with specific inputs it was calibrated by tuning the model parameters within the recommended ranges to match the simulated output with the observed data. Validated model was used to get the daily discharge data of selected sub-basins. Calibration involved the comparison of model results with the recorded runoff data at selected outlet. 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 In this study, the model calibration period was 1999-2003 (5 years) and validation period was 2004-2007 (4 years).

3.5 Flow Duration Curve

Flow duration curve is a form of cumulative frequency graph that represents the percent of the time flow in a stream is likely to equal or exceed some specified value. Flow duration curves are used in solving numerous hydrological problems related to hydropower, river or reservoir sedimentation, and water quality assessment**.** Flow duration curves are also developed to explore the flow characteristics of streams and for comparing one basin to another (Castellarin et al., 2004). Hydrological and geological characteristics of a watershed determine shape or slope of a flow duration curve. Flow duration curve is also used to determine the hydrological response of a watershed to different forms of and intensity of precipitations. Upper part of a flow duration curve determines the type of flood system and the slope of lower end predicts the ability of basin to sustain low flows during dry season. Flow duration curves can be prepared for the daily, weekly or monthly stream flow data. Following are the steps for preparing flow duration curves (Rojanamon et al., 2009)

1. Sorting the average daily/monthly discharges in descending order for the period of record from the greatest observed value to the smallest.
2. Assigning rank M, starting with 1 for the largest discharge value.
3. Calculating the exceedance probability as in equation 1

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

Prb = Probability that a given flow will be equaled or exceeded (% time)

M = Ranked position.

n_e = Number of events.

3.6 Accuracy Assessment of the Model

The accuracy assessment of model was performed in order to assess how close the simulated values were with the observed. There are several statistical techniques for evaluating the performance of a model such as coefficient of determination (R^2), Pearson's correlation coefficient (r), Nash Sutcliffe coefficient (E) etc. (Feyereisen et al., 2007). In this study, the performance of the model was evaluated by using the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E). Arnold et al. 2012 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 value of E is greater than 0.5 and R^2 is greater than 0.6 and acceptable if E is between 0.5 and 0.75 and very good if value of E and R^2 is greater than 0.75. The coefficient of determination (R^2) is explained as the strength of a liner relationship between observed and simulated data. It is calculated using equation 2.

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

Where *Oi* is the *ith* observed value, O_{av} is the mean of observed value, *Si* is the *ith* 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 (Feyereisen et al., 2007). Nash-Sutcliffe efficiency (E) is a normalized statistics that determines the relative magnitude of the residual variance. (E) Indicates how well the plot of observed versus simulated data fits (Arnold, 2012). It is computed by the equation 3.

$$E_{NS} = \left\{ 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - O_{av})^2} \right\} \quad (3)$$

Where O_i is the *ith* observed value, O_{av} is the observed values' mean, S_i is the *ith* simulated value and *n* is the number of data. The value of E varies from 0 to 1 with 1 is the perfect and greater than 0.5 is regarded as satisfactory.

3.7 Estimation of Hydropower

For this study hydropower was estimated as theoretical hydropower potential for all sub-basins and also for the identified potential run of river hydropower generation sites. As discussed before hydropower is the product of head and flow. Estimation of hydropower potential involves following steps mentioned in detail below.

3.7.1 Hydropower Potential Calculation

Hydropower potential is a function of head drop and discharge. The hydropower potential is calculated using equation (4).

$$P = \rho g Q H \tag{4}$$

Where,

P = Power generated in Watt (W)
ρ = Mass density of water (kg/m^3)
g = Gravitational Acceleration (m/s^2)
Q = Discharge/Flow (m^3/s)
H = Head drop (m)

The mass density of water is taken as 1000 kg/m^3 and acceleration due to gravity as 9.81 m/s^2. Head is the elevation difference. Theoretical hydropower is the sum of the hydropower potential estimated from all sub-basins. In this study there were five sub-basins identified for calculation of theoretical hydropower potential (Monk et al., 2010). As mentioned above the hydropower potential estimation requires the estimation of its components that are head drop H and discharge of river Q.

3.7.2 Theoretical Hydropower Estimation

Theoretical hydropower assessment required the flow or river discharge for all the sub-basins. Determining the flow for theoretical hydropower potential estimation involved the flow duration curve analysis. At 30% time exceedence flow for all sub-basins was determined from the flow duration curves developed for all sub-basins. The next step was to obtain the head. The head for theoretical hydropower assessment was determined by overlaying the DEM, stream network and sub-basins. The elevation values were determined for each sub-basin by taking one elevation value at the outlet of a sub-basin and the other value at the start of stream of every sub-basin. The difference of the two elevation values provided the head. As discussed before theoretical hydropower potential is calculated by combining the head drop with the river discharge or in stream flow So, by combining the head with respective flow or river discharge, theoretical hydropower potential was calculated for all sub-basins. There were 5 sub-basins and hydropower potential for every sub-basin was calculated separately. The total theoretical hydropower potential of the watershed was calculated by adding up hydropower potential of all sub-basins.

3.7.3 In-stream Hydropower Estimation

For identification of run of river hydropower generation sites it is required to determine the in-stream flow at every point along the river. To estimate the in-stream flow runoff data was required in the form of grid. Runoff grid data as mentioned before was obtained from Noah hydrological model outputs. The data was processed to get the mean annual runoff grid having 30 m resolution to be used with available DEM. The runoff data was transformed into river flow using GIS hydrological tools. The flow data was able to provide the river discharge at every point of the stream network. The other data set required to get the power grid was the head. Head was estimated by using spatial statistics tools that are provided in ArcGIS. The search was conducted in 10 iterations at 200 m increments, from 200 m to 2,000 m (Monk et al., 2010). These functions were configured to search around a point and provide the minimum elevation, which was assigned back to the search location. The in-stream power grid was converted to vector data or points. The vector data was able to store the data related to flow head and corresponding power. Given large number of vector data providing power at every 30 meter increment along the river was then filtered, explained in section 3.8. In section below detail about the in-stream power estimation is given.

3.8 Identification of Run of River Hydropower Generation Sites

Head was multiplied with flow and fluid weight to get in-stream power. ArcGIS was used to multiply the head and flow raster and producing in-stream power grid. The power grid was then converted to vector dataset of points representing potential power project locations. The vector dataset was provided with information at each location, related to head, flow and stream power. After getting point data containing all the information including flow, head and equivalent power feasible sites were identified based upon specific given criteria of slope, minimum power generation limit and distance between the consecutive potential run of river power generation sites (Rojanamon et al., 2010)

RESULTS AND DISCUSSION

4.1 Calibration and Validation

Tuning the model parameters within recommended ranges to match the simulated output with the observed data termed as calibration. Calibration involved the comparison of model results with the recorded runoff data at selected outlets. In this process, the model parameters were adjusted in such a way that the simulated results were matched to the recorded flow pattern within some accepted criteria. The calibration was done by trial and error manually or by automatic trial and optimization. After the calibration of the model, validation was done. Comparison of model output with an independent observed dataset not used in the calibration without further adjustment of model parameters termed as validation.

In this study, the model calibration and validation periods were 1999-2003 (5 years) and 2004-2007 (4 years), respectively. HEC-HMS model comes with a number of sub models for hydrological simulation. For calculation of runoff depth, deficit constant loss model was used. Clark unit hydrograph was used for routing and Snyder Unit hydrograph method was adopted to compute stream flow hydrograph. The constant monthly base flow method was used to account for the base flows. The parameters used in the model, their recommended ranges are given in Table 4.1. Adjusted parametric values for all sub-basins are given in table 4.2. Peak discharge and runoff volumes were found to be most sensitive to rate of infiltration for the five sub-basins. Percentage Imperviousness was varied by 10% to 25%. Impervious area percentage was the most sensitive parameter. The Snyder’s peaking coefficient parameter and rate of infiltration were the second most sensitive parameters. Catchment models have been reported to be very sensitive to infiltration parameter (IEA, 2012).

Table 4.1. Range of parameter values for application of HEC-HMS in Astore basin.

ID	**Model Parameters**	**Parametric Values Range**	**Source**
1	Initial Deficit (mm)	10 to 15	HEC-HMS help
2	Maximum Deficit (mm)	30 to 40	HEC-HMS trail optimization
3	Constant Rate (mm/hr)	1.5 to 3	HEC-HMS trail optimization
4	Impervious %	15 to 25	HEC-HMS trail optimization
5	Time of Concentration (HR)	2 to 4	HEC-HMS trail optimization
6	Storage Coefficient (HR)	3- 4.5	HEC-HMS trail optimization
7	Lapse Rate (Deg. ˚C/1000 m)	-3.5 to -6.5	By using observed temperature data
8	Base Temperature ˚C	0	HEC-HMS help (constant for all basins)
9	*Px* Temperature ˚C	2.5-3.5	HEC-HMS help (constant for all basins)
10	Degree Day factor (mm/˚C-day)	4 to 5.9	Extracted from previous studies
11	ATI melt rate coefficient	0.98	HEC-HMS help (trial and error method)
12	Cold Limit (mm/day)	1	HEC-HMS help (trial and error method)
13	Water Capacity (%)	3	Extracted from previous studies
14	Wet melt rate (mm/˚C-day)	4.9	Extracted from previous studies
15	ATI cold rate coefficient	0.7	HEC-HMS help (trial and error method)
16	Rain Rate Limit (mm/day)	0.5	Extracted from previous studies
17	Ground melt (mm/day)	0	HEC-HMS help (trial and error method)

Table 4.2. Calibrated values used for hydrological simulation in HEC-HMS for Astore basin.

ID	**Adjusted Model Parameters**	**Parametric Values Range**	**Sub-basins**				
			Pershing Gah	**Gorikot**	**Naugam**	**Rattu**	**Harcho**
1	Initial Deficit (mm)	10 to 15	10	15	11	12	14
2	Maximum Deficit (mm)	30 to 40	30	34	32	33	40
3	Constant Rate (mm/hr)	1.5 to 3	3	4	3	3	5
4	Impervious %	15 to 25	15	25	17	20	25
5	Lag Time (hr)	2 to 4	2	2	3	4	2
6	Storage Coefficient (hr)	3- 4.5	3	3	3.5	4.5	3
7	Lapse Rate (˚C/1000 m)	-3.5 to -6.5	-5.5	-4.5	-6	-6.5	-3.5

The average simulated flow values match reasonably well with the measured flow. The monthly stream flow patterns depict an overestimation of flow in June and July. In figure 4.1 the calibrated period model results are given. Peak discharge occurred annually during the monsoon season. Discharge starts decreasing during the subsequent time period after the monsoon season and reaches minimum before the start of monsoon season again. The snowmelt increases during the late summer season and during the monsoon period and gradually decreases with the onset of winter season again. The computed or simulated hydrograph had peak flow in the year 2003 during onset of monsoon season as shown in figure 4.1. In figure 4.2 the simulated and observed hydrographs are given for the validation period. The peak discharge occurred during the year 2005 just before the monsoon season**.**

4.2 Model Accuracy Assessment

In this study, the performance of HEC-HMS was evaluated by using the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E). A model is considered satisfactory and can be used for further application if E is greater than 0.5 and R^2 is greater than 0.6, good if E between 0.5 and 0.75 and very good if E and R^2 is greater than 0.75. In this study the value of coefficient of determination for the calibration period was found to be R^2= 0.68 and for the validation period was R^2= 0.66. Figure 4.3 and figure 4.4 show the regression analysis of the simulated results. During the calibration period the simulated results were under estimated during calibration period while during the validation period the simulated results from the model show significant under estimation during low and high flows. This could be the result of the glacial ice melt which is not covered in this study as HEC-HMS only models the snow melt using Temperature Index method. Nash-Sutcliffe efficiency (E) estimates the relative residual. The Nash-Sutcliffe coefficient value for the calibration period was found to be E = 0.66 and for the validation period was E = 0.64 and values of determination coefficient were

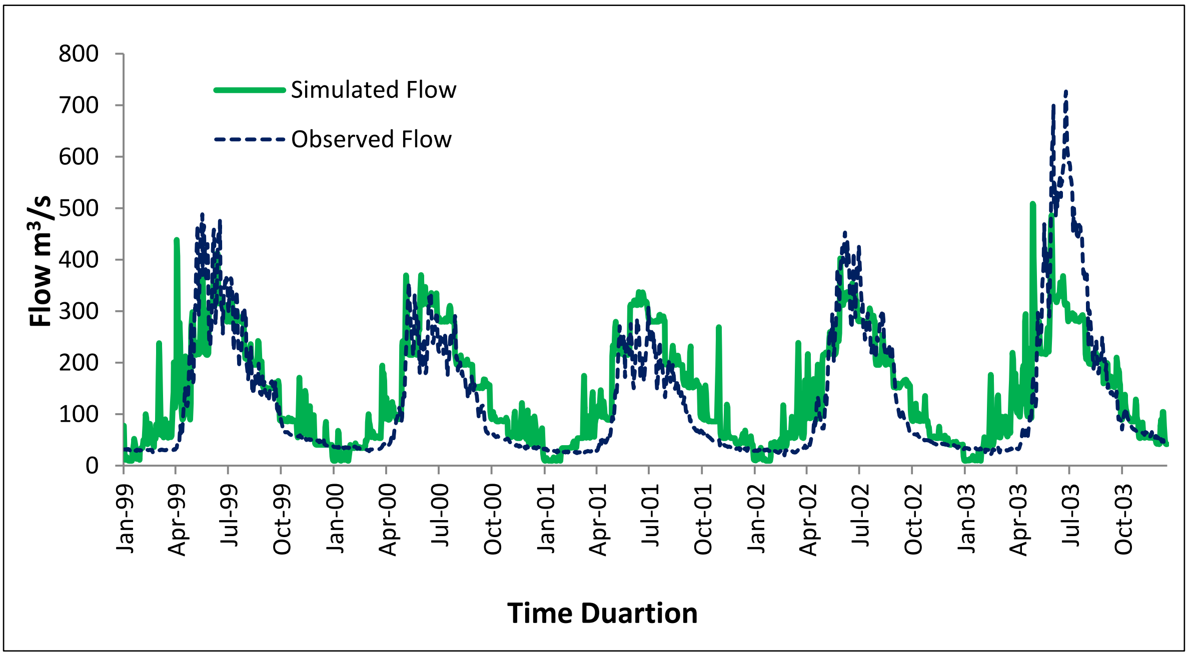


Figure 4.1. Hydrograph for the calibration period (1999-2003).

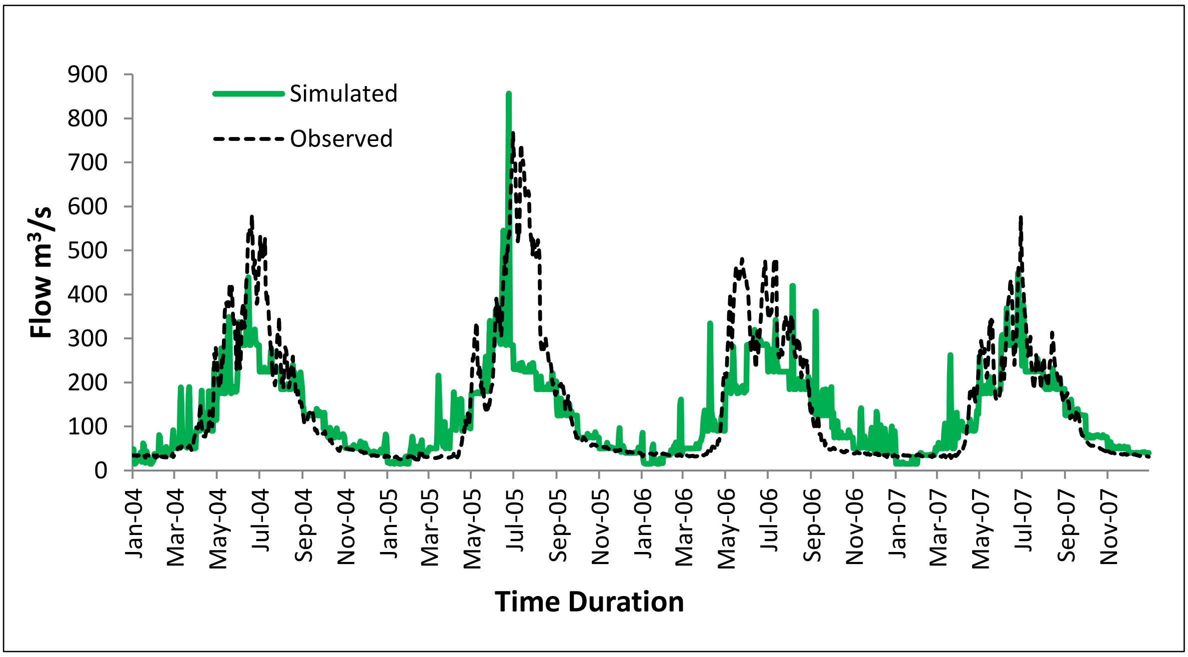


Figure 4.2. Hydrograph for validation period (2004-2007).

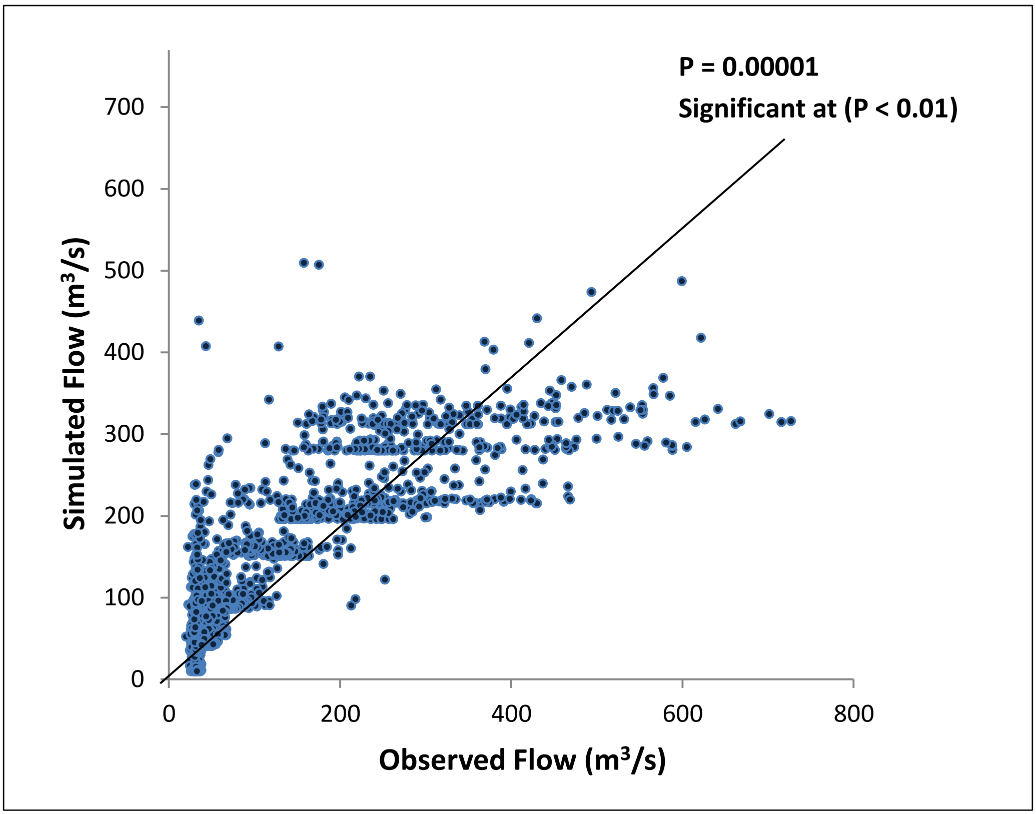


Figure 4.3. Regression analysis for calibration period (1999-2003).

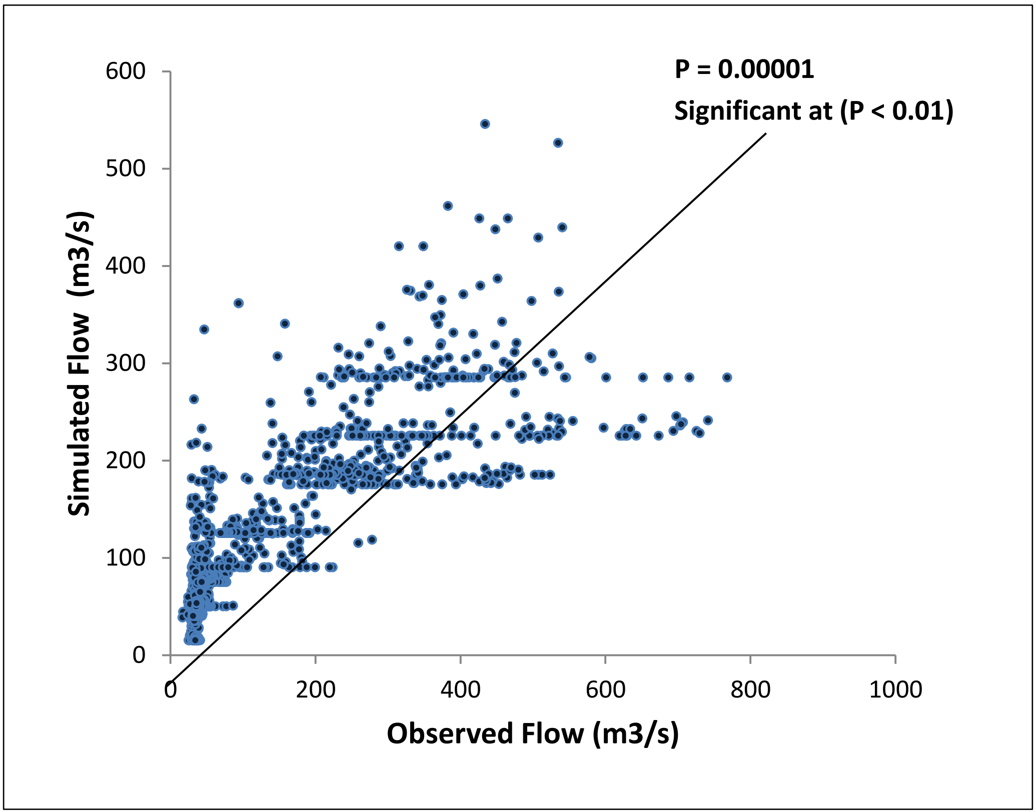


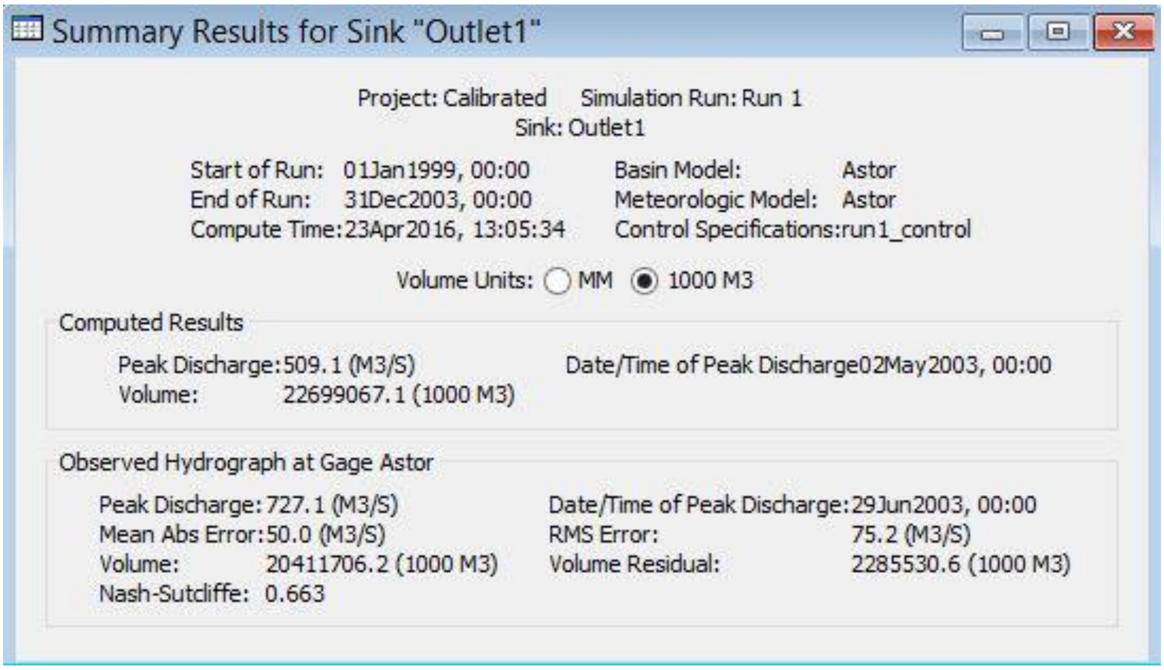
Figure 4.4. Regression analysis for validation period (2004-2007).

0.68 for calibration period and 0.67 for validation period. P value was calculated as 0.0001 and was significant at ($P < 0.01$).The simulated results from the model show peak discharge and runoff volumes were found to be most sensitive to rate of infiltration for the five sub-basins**.** Percentage imperviousness was found to vary between 15% and 25%, respectively. Percentage of impervious area was estimated the second most sensitive parameter. The Snyder's peaking coefficient parameter and rate of infiltration were the second most sensitive parameters. The peak values of the simulated flow match reasonably well with the peak values of measured flow. However, the model under-predicts most peak flows for the sub-basins. The monthly stream flow patterns depict an overestimation of flow in June and July. Peak discharge is occurred annually during the monsoon season. For peak discharge the observed value was 727 m^3/s and the computed was 509 m^3/s. The RMS error was found to be 75 m^3/s. Discharge starts decreasing during the subsequent time period after the monsoon season and reaches minimum before the start of monsoon season again generally the snowmelt increases during the late summer season and during the monsoon period and gradually decreases with the onset of winter season again. The computed or simulated hydrograph has got peak flow in the year 2003 during onset of monsoon. The peak discharge was occurred on 2, May 2003 for the simulation and on 29, June 2013 for the observed. The percentage error volume was found to be -11.2 % and percentage error in simulated peak was found to be 29.9%.

The performance of the model was good and results were acceptable in terms of Nash-Sutcliffe efficiency (E) values were 0.66 during calibration phase and between 0.64 during the validation phase. As expected Nash-Sutcliffe model efficiency values were better for monthly predictions rather than those obtained for daily periods. Estimated mean flow and standard deviation (SD) was found to be in close agreement with the corresponding observed value. The discrepancy of 37% in standard deviation have been found to be slightly higher than the acceptable levels of ±20% accuracy of hydrological simulations. Thus the results indicate that overall estimation of discharge by HEC-HMS model during the calibration period was satisfactory and therefore may be accepted for further analysis. The calibrated model was then used to estimate the daily discharge for the years 2004-2007. The model under predicts most peak flows. The monthly stream flow patterns depict an over estimation during the June and July months during validation period. The performance measures that are percentage error volume were found 13% and percentage error for simulated peak was found to be -11%. The percentage error volume and percentage error for simulated peak were found to lie in the recommended range of ±20%. For validation period the Nash Sutcliffe Coefficient value was found to be 0.64 and R^2 value was found to be 0.67. Figure 4.5 and 4.6 show the model summary results for calibration and validation periods. The (E) value as mentioned above was found to be better for the monthly periods as compared to daily flows. Estimated values for mean and standard deviation were found to be 10% and 34% respectively. Thus the results indicate that the model could predict the discharge for the study basin with marginal deviation as discussed above for the study years.

4.3 Flow Duration Curve

Flow duration curve is the basic tool for run of river hydropower study**.** Flow duration curve is also used to determine the hydrological response of a watershed to different types and intensity of precipitations. Flow duration curve shape is helpful in determining various characteristics of stream and basin. The upper part of the flow duration curve determines the type of flood system and the slope of lower end flow duration curves indicates the ability of basin to sustain low flows during dry season. Flow duration curves can be prepared for the daily, weekly or monthly stream flow data. Figure 4.7 (a) shows the comparison of observed and simulated flow-duration curve at outlet and shows a close match between the observed and simulated flow at the lower end of the curve, but high flows are little underestimated by



```
Summary Results for Sink "Outlet1"

                 Project: Calibrated     Simulation Run: Run 1
                               Sink: Outlet1

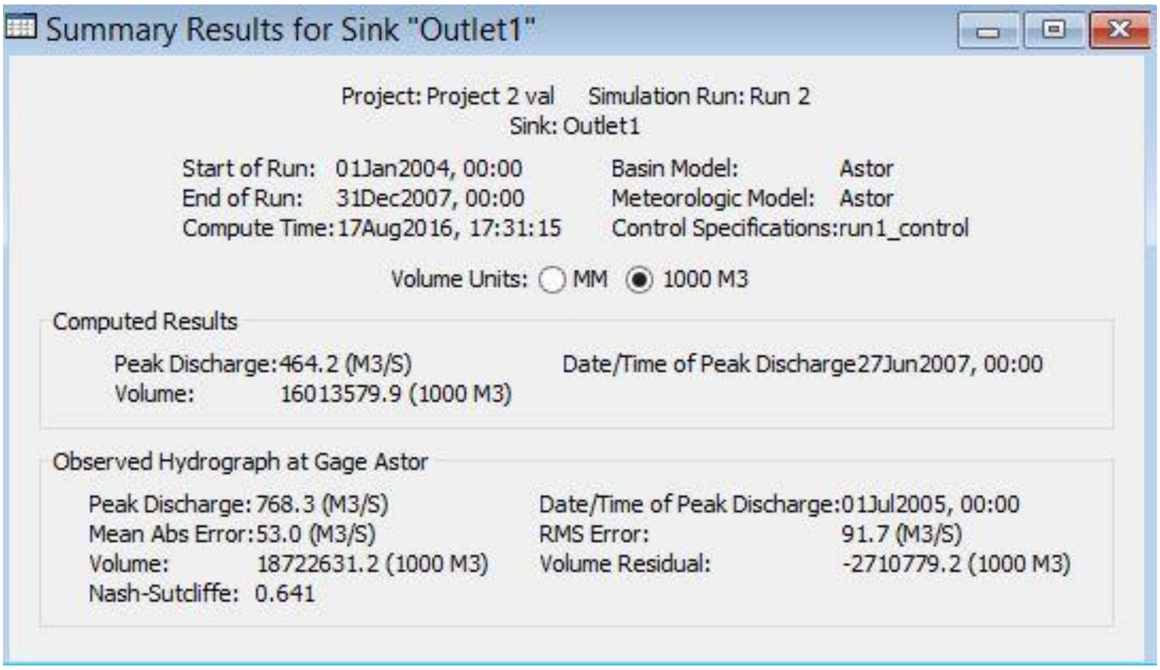
        Start of Run:   01Jan1999, 00:00       Basin Model:            Astor
        End of Run:     31Dec2003, 00:00       Meteorologic Model:     Astor
        Compute Time:23Apr2016, 13:05:34       Control Specifications:run1_control

                    Volume Units: ○ MM  ● 1000 M3

  Computed Results
      Peak Discharge:509.1 (M3/S)          Date/Time of Peak Discharge02May2003, 00:00
      Volume:         22699067.1 (1000 M3)

  Observed Hydrograph at Gage Astor
     Peak Discharge: 727.1 (M3/S)         Date/Time of Peak Discharge:29Jun2003, 00:00
     Mean Abs Error:50.0 (M3/S)           RMS Error:                  75.2 (M3/S)
     Volume:         20411706.2 (1000 M3) Volume Residual:            2285530.6 (1000 M3)
     Nash-Sutcliffe:  0.663
```

Figure 4.5. Model results with Nash Sutcliffe coefficient value for calibration period.



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Summary Results for Sink "Outlet1"

                 Project: Project 2 val     Simulation Run: Run 2
                               Sink: Outlet1

        Start of Run:   01Jan2004, 00:00       Basin Model:            Astor
        End of Run:     31Dec2007, 00:00       Meteorologic Model:     Astor
        Compute Time:17Aug2016, 17:31:15       Control Specifications:run1_control

                    Volume Units: ○ MM  ● 1000 M3

  Computed Results
      Peak Discharge:464.2 (M3/S)          Date/Time of Peak Discharge27Jun2007, 00:00
      Volume:         16013579.9 (1000 M3)

  Observed Hydrograph at Gage Astor
     Peak Discharge: 768.3 (M3/S)         Date/Time of Peak Discharge:01Jul2005, 00:00
     Mean Abs Error:53.0 (M3/S)           RMS Error:                  91.7 (M3/S)
     Volume:         18722631.2 (1000 M3) Volume Residual:            -2710779.2 (1000 M3)
     Nash-Sutcliffe:  0.641
```

Figure 4.6. Model results with Nash Sutcliffe Coefficient value for validation period.

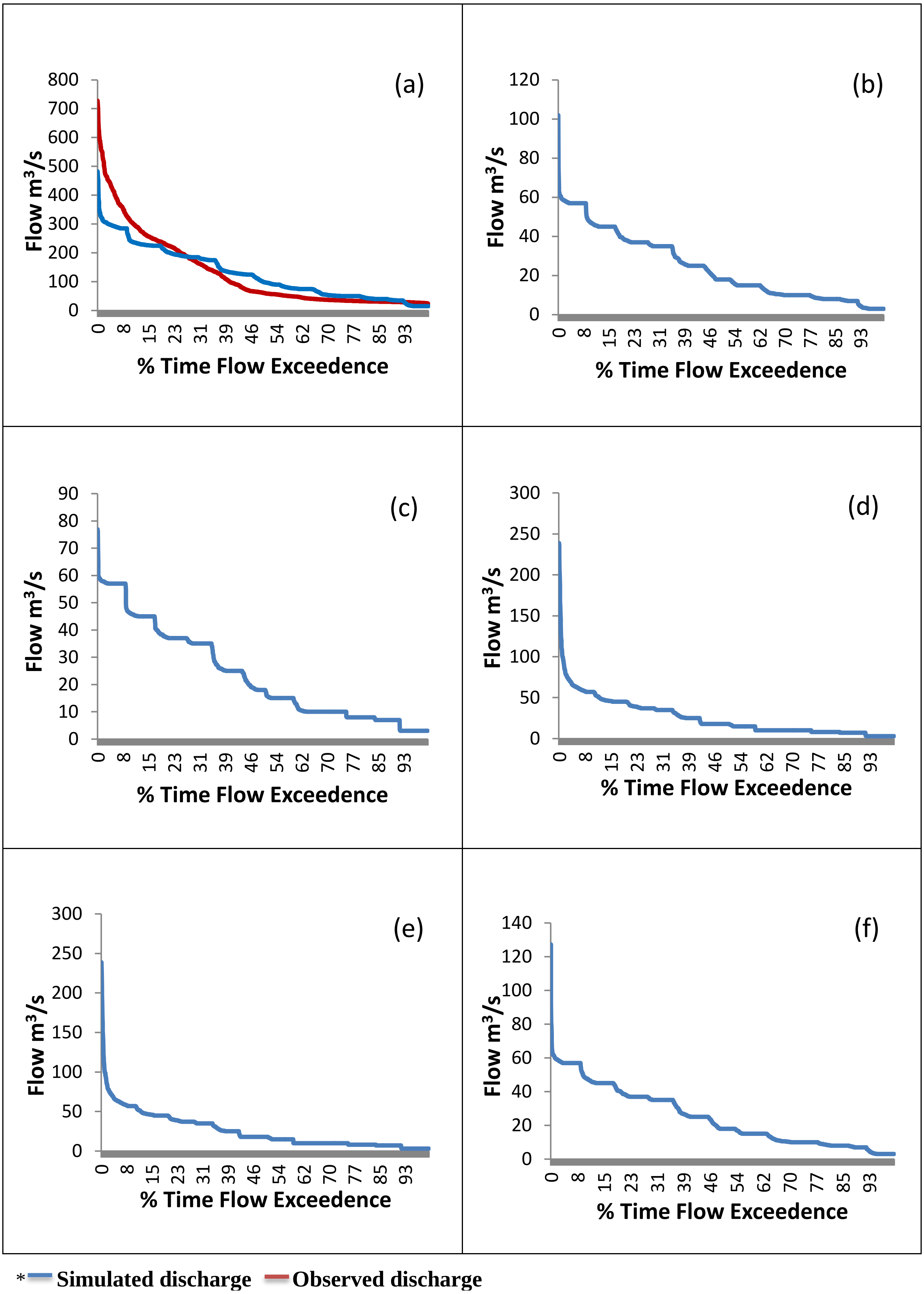

Figure 4.7. (a) Flow Duration Curve (FDC) for Astore watershed with observed and simulated curves (b) FDC for Pershing Gah sub-basin (c) FDC for Gorikot sub-basin (d) FDC for Naugam sub-basin (e) FDC for Rattu sub-basin (f) FDC for Harcho sub-basin.

the model. 30% probability flow exceedence was selected during the estimation of theoretical hydropower potential for all sub-basins. Observed discharge data was only available for outlet point of the basin. So the flow duration curves for the sub-basins only present the simulated flow. From flow duration curves it was determined that the flow of the basin was varied between 38m^3/s to 183m^3/s. These flow values as discussed above were estimated at 30% probability flow exceedence. This flow was later used as mean annual discharge for theoretical hydropower estimation.

4.4 Theoretical Hydropower Potential Estimation

Theoretical hydropower estimation of Astore basin involves the determination of head drop for all the delineated sub-basins. The head was determined using the DEM and overlaying it with stream network and the sub-basins. The head was then combined with the flow. Flows at the ungauged locations that are the outlet points of all the sub-basins were taken from the simulated discharge of HEC-HMS model. The flow data was plotted for flow duration curves. At 30% time exceedence the flow of all the sub-basins of Astore watershed was determined. This flow data was then combined with the head drop estimated in the previous step to get the power output. This power output for every sub-basin is added up to get the theoretical hydropower potential of the Astore watershed. For Astore watershed the total theoretical hydropower potential was estimated as 3198 MW. The head drop, river discharge or flow and power output of all the sub-basins of Astore watershed are given in Table 4.4

4.5 Identification of Power Generation Sites

In the power equation, head was multiplied with flow and fluid weight to harvest in-stream power. ArcGIS software was used to combine the head and flow grids, thereby developing a grid of in-stream power. The power grid was then converted to vector format in the form of points representing potential power project locations. The vector dataset stored all the information at each location regarding head, flow and stream power. After getting point data containing all the information including flow, head and equivalent power, feasible sites were identified based upon specific feasible criteria of slope, minimum power generation limit and distance between the consecutive power generation sites. Flow was estimated using GIS tools, and was independent of any existing stream network mapping. The algorithm that estimated head drop was run in 10 iterations at 200 meters increments, from 200 meters to 2,000 meters. To prevent the search from identifying a minimum elevation in another sub-basin, the algorithm was calibrated to get the lowest value that falls within the same sub-basin and in-stream power was assumed to be proportional to mean annual discharge (Monk et al., 2010).

4.6 Technical Screening Criteria

Once the power output is obtained in the form of large number of points along the stream, the next step was to identify feasible run of river hydropower generation sites. Penstock was optimized by dividing the change in power and change in length for every 200 m increment. The optimized penstock distance for all points was the search radius that returned the maximum power per length. Table 4.3 describes the characteristics that are slope and power output as screening criteria. Table 4.5 presents the final output as the identified power generation sites. There were total of 25 run of river hydropower generation sites identified as feasible with a total power output of 1593 MW. Table 4.7 shows for each identified locations of the identified power generation sites.

4.7 Hydropower Potential and Identified Sites

Simulated discharge data for the ungauged sub-basins of Astore watershed was used to draw the flow duration curves. Flow duration curves plots the discharge against the % time

Table 4.3. Feasibility criteria for run of river hydropower generation sites identification.

Parameter	Valid Range
Slope	>4%
In-Stream Power	>1000 KW
Inter Sites Distance	> 2000 m

Table 4.4. Sub-basin wise theoretical hydropower potential.

Sub-basin	Head (m)	Flow (m^3/s)	γ	Power (MW)
Rattu	978	38	10	364
Gorikot	176	75	10	129
Naugam	1006	40	10	394
Peshing Gah	1639	36	10	578
Harcho	951	185	10	1724
Total Power				3189

Table 4.5. Identified hydropower generation sites with available head, flow and power

ID	Locality Name	Longitude	Latitude	Head (m)	Flow (m^3/s)	Power (MW)
1	Doian	74.667	35.573	98	164	161
2	Near Doian	74.703	35.547	173	164	283
3	Near Doian	74.727	35.539	40	161	64
4	Near Harcho	74.754	35.508	98	159	156
5	Near Harcho	74.782	35.484	67	154	103
6	Harcho	74.804	35.449	70	152	106
7	Near Harcho	74.823	35.424	46	149	68
8	Near Harcho	74.838	35.404	54	148	80
9	Perishing Gah	74.918	35.390	215	13	29
10	Near Perishing Gah	74.878	35.379	221	15	34
11	Near Astore Village	74.859	35.372	38	131	50
12	Astore Village	74.864	35.347	43	128	55
13	Near Eid Gah	74.860	35.327	50	126	63
14	Bulan Pine	74.854	35.296	54	125	67
15	Gorikot	74.840	35.270	19	123	23
16	Naugam Village	74.874	35.259	93	38	36
17	Near Naugam	74.903	35.240	61	37	22
18	Gudai	74.937	35.201	54	35	19
19	Mankial	74.842	35.247	33	83	27
20	Near Mankial	74.833	35.217	54	80	43
21	Near Denyor	74.779	35.224	76	23	18
22	Denyor	74.734	35.230	111	22	25
23	Near Rattu	74.809	35.205	43	55	24
24	Near Rattu	74.785	35.187	38	55	21
25	Rattu	74.793	35.157	31	53	16
Total Power						1593

For theoretical hydropower potential estimation 30 % probability flow exceedence was utilized. Flow duration curves were generated for all sub-basins. The flow data obtained from flow duration curves was used to predict the theoretical hydropower potential of the ungauged sub-basins of Astore River. Using GIS based algorithm head drop was estimated along the stream and using the feasible criteria for hydropower sites identification, twenty five potential run of river hydropower generation sites were identified. The total expected power generation from all sites was found to be 1593 MW. Figure 4.8 shows the geographical locations of identified run of river hydropower generation sites with their respective power outputs.

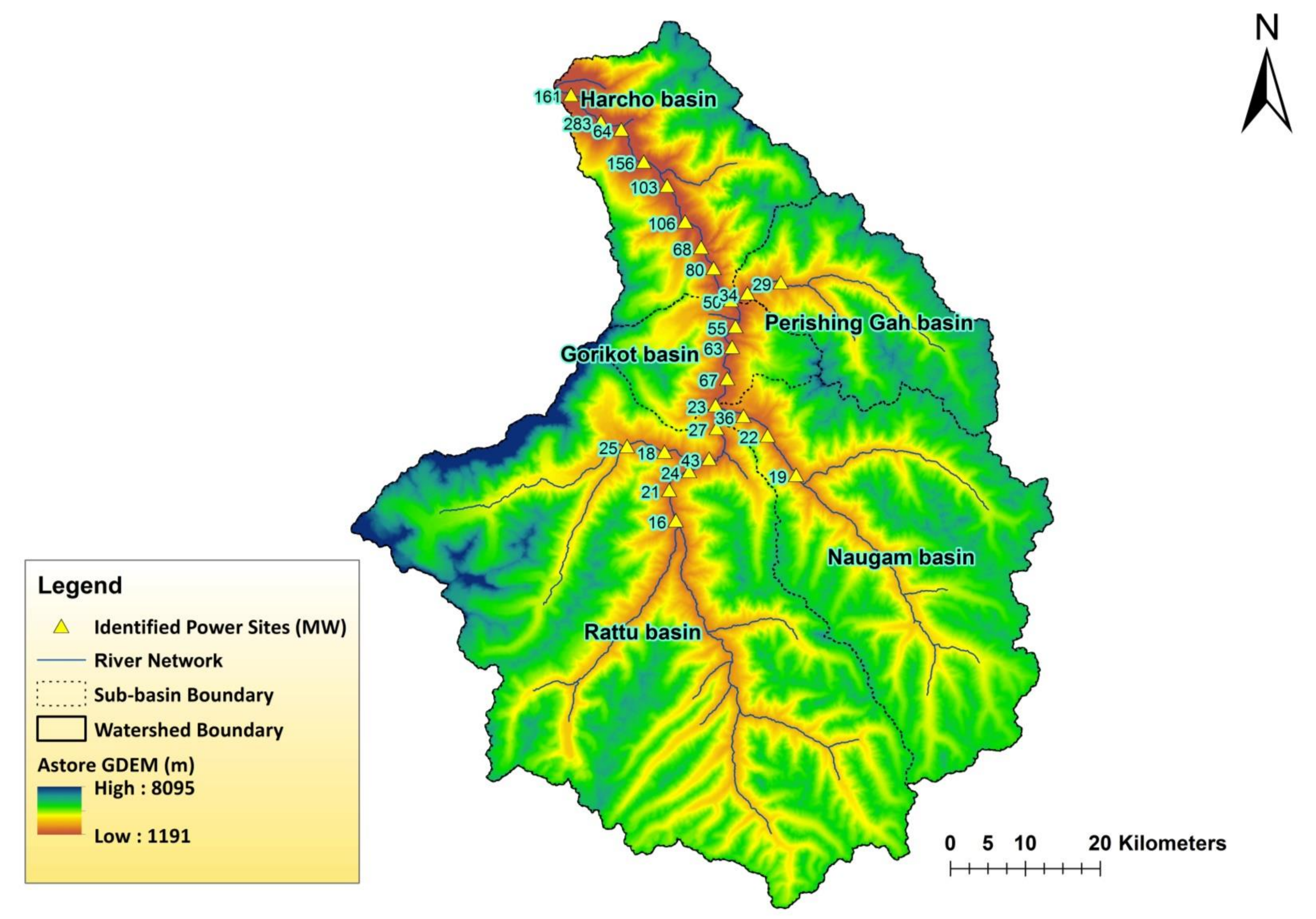

Figure 4.8. Identified potential hydropower generation sites with generation capacity in MW (Mega Watts).

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study, GIS-based spatial tools were utilized for estimating hydro power potential. Hydrological modeling of the study area was done using the HEC-HMS model. The vales Nash Sutcliffe Efficiency and Coefficient of Determination were found to be 0.66 and 0.68 for calibration period while 0.64 and 0.67 for validation period respectively. The cumulative hydropower potential from identified twenty five (25) hydropower generation sites was 1593 Megawatts. Using the validated runoff grid data the in stream flow data was calculated and by estimating head using DEM feasible run of river hydropower generation sites were identified. Findings of this research provide valuable insights. The estimated theoretical hydro potential in this study has provided the new potential figure for the Astore River and its sub-basins. This study has proved the usefulness of GIS based hydrological models and their power to simulate the complex spatially distributed hydrological processes and also the power of GIS & Remote Sensing based procedures to remotely identify the potential run of river hydropower generation sites. This will provide the fundamental information to the government and concerned stakeholders to formulate plans and policies to develop hydropower in the country.

5.2 Limitations

All models including HEC-HMS are simplified representation of the reality. Therefore, model output reflects uncertainties. The model output is compared to observed data to determine the performance of the model. The performance of the model will be the perfect when the value of Nash-Sutcliffe efficiency (E) and Coefficient of determination (R^2) is 1. However, due to various reasons the model fails to achieve this perfect value and always vary and the best could be closer to but not exactly 1. Some of the basic reasons for this inaccuracy 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. Uncertainty in precipitation and discharge data also result in poor calibration and validation of results. The error in land use data used in the model or the parameters derived from them can affect the model outputs. Accuracy and cell size of DEM may also affect the accuracy of the delineated watershed which in turn affects the model outputs. Insufficient calibration may also lead to model output error. So, the hydropower potential calculated from simulated discharge for ungauged water sources wouldn't be an ultimate approach for hydropower assessment. Similarly GIS based procedures used to identify the potential run of river hydropower generation sites had to be verified on the ground due to limited accuracy of the available DEM.

5.3 Recommendations

In this study, only theoretical run of river hydro potential has been calculated using the flow duration curves and potential run of river hydropower generation sites have been identified using GIS procedures. The information about the technical and economical perspective is very important to be considered for development of hydropower in the country. So, the study can be extended to estimate the technical and economic potential of hydropower in the future. The present work can be extended to estimate the storage potential as well. In this study the identified hydropower generation sites using GIS techniques are yet to be verified on ground. While identifying the potential run of river hydropower generation sites the environmental impact has not been considered. Methodology used in this can be applied in other Himalayan regions for hydropower assessment by using more accurate high resolution elevation data.

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