Screening of Potential Sites for Run of The River Hydropower Estimation Using GIS and Hydrological Model in Swat River Basin, Pakistan

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DEDICATION

This work is dedicated

To

My parents

ACKNOWLEDGEMENTS

I am thankful to Almighty Allah, Who is the Creator of all and is the Master of Day of Judgment. No words of thanks can be appropriate for His immense blessings.

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Mishkat Ul Saba

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Abstract

Most of the world's energy demand is fulfilled from non-renewable energy resources, but these resources are depleting because of the increasing demand for energy due to population growth and climate change. Global installed hydropower capacity has been growing in recent years by an average of 24.2 GW/year. Hydropower seems to be more reliable and cleaner among all renewable energy sources due to less greenhouse gas emissions. This study's objective was to select potential sites for the Run of the River (RoR) projects and determine their theoretical potential using the SWAT model. The Swat River basin's sub-basins theoretical power potential has been estimated using the power formula and regional flow duration curve. Flow at 40th and 60th percentiles have been considered in the study. GIS-based tools and hydrological model SWAT have been implemented to select the sites to pinpoint weir, powerhouse, head acre, and penstock. The results reveal that the Swat River basin has enormous hydropower potential. Total 62 sites have been identified in the basin. The power ranges from 52KW to 7025KW at the 40th percentile, while power ranges from 200KW to 27471KW at the 60th percentile. Those basins have greater potential that has a higher elevation and are located on the greater stream order i.e. 4,5 and 6. if fully utilized the power potential of Pakistan, such as Swat river, only solve the energy crisis of Pakistan but also reliance on non-renewable energy.

INTRODUCTION

1.1 Climate Change A Global Issue

Climate change is among the global environmental issues and gain much concern since last few decades (Aslam et al., 2018; Bhatti et al., 2018) as it is going under substantial changes due to elevated greenhouse emissions. The existing changing climate condition is contributed mainly by anthropogenic activities in the industrial world followed by increasing demands of the growing population. (Ali et al., 2019). Due to the low level of adaptation strategies, developing countries are severely affected by the negative impacts of climate change (Abid et al., 2015).

Hydrological systems are experiencing alterations worldwide due to changes in precipitation patterns and glacier thawing, gaining the attention of policymakers towards climate variability (Khan & Geology, 2019). Elevated concentration of Greenhouse gases in the atmosphere is the leading cause of temperature rise and changes in precipitation patterns around the globe, temperature and precipitation being major indicators of climate change have led to the variation in the flood and drought patterns, availability of water for agriculture purpose and the utilization in the other renewable resources such as hydropower development (Padhiary, Das, Patra, Sahoo, & Singh, 2018). Anthropogenic activities such as the burning of fossil fuels, biomass, industrialization, and deforestation are the contributing factors in global warming and in return, global energy budget imbalance as the global average temperature has been risen by 0.75-0.18 since 1906-2005, and it is projected that it will continue in the future at the rate of 0.3-0.8 under the Representative concentration pathways. The effects of global warming will probably continue to rise in the future and disturb the global hydrological cycle (R. Mahmood & Jia, 2016).Its components include water availability in river flows, glaciers retreat, and uncertain precipitation patterns in liquid and solid form. As mentioned earlier, burring of fossils fuels for domestic and industrial use contributes to the elevated concentration of GHG's in the atmosphere and they are depleting rapidly so to mitigate the detrimental effects of global warming and climate change, there must be a shift from non-renewable energy resources to renewable energy resources (Avtar et al., 2019) but to changing climatic condition, they are also at risk as most of the worlds renewable energy source come from hydropower. The accessibility of this resource is highly dependent on local climatic conditions, which interns fluctuate with global climate changes on water resources. (de Oliveira Tiezzi, Vieira, & Simões, 2018)

1.2 Role of Hydropower in mitigating Climate Change

Energy is a key indicator considered for a country's social and economic growth (Zafar, Shahbaz, Hou, & Sinha, 2019). In the global context, most of the world's energy demand is fulfilled by non-renewable energy sources such as petroleum, natural gas and coal, consequently boosts up carbon dioxide in the atmosphere, which is considered as the primary driving force behind climate change and ultimately triggering environmental degradation together with serious global social and political pressure to drop down emissions (Inglesi-Lotz & Dogan, 2018). Non-renewable energy resources are responsible for 61% of the emissions into the atmosphere that can lead to potential climate change (Zafar et al., 2019). According to a special report on renewable energy and mitigation of climate change by IPCC 2011, renewable energy sources have a potential to contribute towards social and economic development, safe energy supply to all and also ensuring environmental and health safety if fully implemented.

From renewable energy resources hydropower seems to be most efficient and green energy resource and its use will be significantly rise in the future to due to low level of emissions, because its functionality only depends upon water flow and a turbine to convert kinetic energy into electricity (Kusre, Baruah, Bordoloi, & Patra, 2010), having high efficiencies as compared to other power plants such as natural gas power plant (Tarroja, Forrest, Chiang, AghaKouchak, & Samuelsen, 2019).Currently the total installed capacity of hydropower is increasing at average rate of 24.3 GW per year and it is estimated that it will double in the future by 2050 (IEA., 2012; Sakulphan & Bohez, 2018) 20% of the world's energy demand is fulfilled by renewable energy resources out of which 70% comes from hydropower plants (World Bank 2014b),(Wang, Wang, Wei, Li, & reviews, 2018). To meet the needs of growing population and for sustainable economic development of a country hydropower growth plays strategic role in meeting the energy demand (Zhou, Hanasaki, Fujimori, Masaki, & Hijioka, 2018) along with efficiently mitigating climate change by reducing greenhouse emissions in terms of shifting from non-renewable energy resources towards renewables resources. It can also help developed countries to lower their GHG's emissions according to the Paris protocol to drop down the CO2 level to pre-industrial era by increasing the share from RE to their energy nexus (dogan 2016), (Kahia, Aïssa, Lanouar, & Reviews, 2017) and meeting the 7th sustainable developing goal to ensure access to affordable, reliable and sustainable energy to all by 2030 (Romanelli, Silva, Horta, & Picoli, 2018). In climate change mitigation policies small hydroelectric power is encouraged at national level.

Although it contributed only 2% of the total hydropower potential, but due to easy applicability, globally it has the 75GW installed capacity and 173GW still needs to be developed only concerted in the hilly terrain (Kelly-Richards, Silber-Coats, Crootof, Tecklin, & Bauer, 2017). Small hydropower is considered as efficient source of energy for the electrification of rural areas which lacks access to power grid, but also to combat climate change without posing much environmental degradation such as social displacement, biodiversity loss and not need complex infrastructure like large storage dams (Winemiller et al., 2016). Run of the River SHP are small diversion systems, without storage requirements are capable of producing low cost and stable electricity source alternate to burning of fossil fuels. (Hennig & Harlan, 2018).

1.3 Need for Hydropower development in Pakistan

Energy is a basic requirement for the economic and social well-being of the country. Pakistan being a developing country whose economy was initially agrarian but now it's a mix of agriculture and industrialization, has become the major contributor to the country's GDP Hence, in such a situation, the economy would greatly benefit from sufficient reasonable priced energy. (Sadiqa, Gulagi, & Breyer, 2018). Moving towards industrialisation, agriculture is still an important pillar of Pakistan's economy and development, comprising of the country's 21% GDP and accounting for 78% of its exports (Bank, 2017) . Most of the energy demand is fulfilled by non-renewable energy sources such as coal, gas, oil out of which major source is natural gas, around 65% of the demand is met by fossil fuels, whereas 30% comes from hydropower and 5% from nuclear power (Ali & Imtiaz, 2019). The use of natural resources could not only fulfil the energy demand of any nation as they are limited, not sustainable, and are on their way of depletion; it is estimated that the reserves in Pakistan will remain up to 30% in 2027-28. (Shabbir et al., 2020). In the current scenario, Pakistan is facing an acute shortage in electricity demand and current hydropower resources, along with other resources, are not enough to cope up with the shortfall between the demand side and supply. The energy crisis will continue to enhance with the growth in population and economic production (Ali, Behera, & Reviews, 2016). The extensive use of non-renewable energy resources is not vanishing but also damaging to the environment, which is evident in the form of global warming and ultimately climate change (Tahir et al., 2019). Like other countries such as China and India, Pakistan's contribution to greenhouse is considerably less due to economic production and fossil fuel burning to meet national demand, but due to geographical location and by having the massive treasure of glaciers, Pakistan is among the most vulnerable country to climate change. (S. Shah, Zhou, Walasai, & Mohsin, 2019). The occurrence of extreme events will intensify in the future (IPCC 2007; IPCC 2013). Precipitation and temperature trends are altering, the temperature has been risen by 0.1 degrees Celsius per decade since 1960 (Khan, Shahid, bin Ismail, & Wang, 2018) and precipitation become unpredictable (Ahmed et al.,2018). The trend of precipitation in monsoon has increase in most of the monsoon regions in the country and decreasing precipitation in winter in the arid region has been observed (Z. Ahmad, Hafeez, Ahmad, & assessment, 2012). Moreover, the excessive use of non-renewable resources to fulfil requirements will alter the climate and further weaken the fragile economy. In such a delinquent situation, in which there is urged to keep the balance between energy requirements and mitigate the negative consequences of climate change, (S. A. A. Shah, Solangi, & Research, 2019).The only way to get out of this is to formulate the policies and harness the renewable energy resources comprised of hydel, solar, wind, and biomass (Ghafoor et al., 2016). The geographical location of Pakistan is very reliable for the mining of hydropower resources due to the natural flows of rivers and terrain. In 2010 the total installed capacity of hydropower resources was 6720MW, KPK the largest producer due to Terbela Dam with 3849MW, which is around 80% of the total supply, Punjab is on the second with the capacity of 1699MW. Traditional hydropower projects are not enough to meet the energy needs. In addition to large storage dams, run of the river type projects can combat the energy crisis in the country. In Pakistan, many agencies related to renewable energy have installed RoR projects in the country's various regions, particularly in the mountainous regions to light up many villages that are off-grid to the national grid stations.

1.4 Application of Hydrological Modelling and GIS in RoR

The traditional way of surveying for the site selection was a time-consuming and difficult task with lots of economic expenses. However, with the advent of novel tools and technology within the interface of Geographic information systems, along with the applicability of hydrological modelling and remote sensing data, it has become easier to pre-plan the selection of potential sites for small hydropower on the complex stream network and terrain. In the of penstock and then powerhouse to compute generation capacity. GIS tools and remote sensing data can be used to generate the stream network grid map from digital elevation model that can be further utilized in pinpointing the sites for SHP and assessing potential by applying hydrological modelling (Ibrahim, Imam, & Ghanem, 2019).

In Herman, authors developed a visual basic computer program within the interface of Microsoft excel to select the site for run of the river hydropower based on head and power criteria then to find the discharge at that sites, HEC-HMS and WMS hydrological modelling was applied. Gene expression programming was utilized to generate flow duration curves (Al-Juboori & Guven, 2016). Hydrological modelling (SWAT) along with GIS tools has been explored by (Kusre et al., 2010) and (Pandey, Lalrempuia, & Jain, 2015) for the evaluation of hydropower potential in Hassam India. Sites for hydropower was selected using DEM, river network within GIS environment while discharge (Q) at potential sites was simulated using SWAT modelling and concluded that Indian basin has potential has up to 132.67MW. (Nistoran, Abdelal, Ionescu, Opriş, & Costinaş, 2017) in Romania assesses the theoretical power potential of the sites using mean and annual river flows, GIS and open-source satellite data, HEC-GeoHM to generate stream network and then the stream network was overlaid on DEM to determine head drop. Linear theoretical power potential was calculated and compared with already operating 17 plants in the basin. Sammartano et al.,2019 also make use of SWAT and GIS technology to identify location for RoR and then to estimate power potential in Umber leigh river basin. By using different power thresholds, many sites have been identified, but by applying various filters, only those locations were selected that were environmentally and economically feasible to maximize profit with the least environmental degradation across the basin. Some of the researchers have used multi-decision criteria analysis along with the use of hydrological models for the optimal point for the installation of the hydropower plant. (Fuentes-Bargues & Ferrer-Gisbert, 2015) used AHP to select suitable sites based on technical, environmental, and economic criteria. The study reveals that AHP and GIS use can be effectively utilized where there is a need to choose between various alternatives and multicriteria to carry out decision. (Goyal, Singh, & Meena, 2015) also used the multicriteria method to select the potential sites for run of the river hydropower in rainfed basin in India by utilizing raster-based grid layers and weighted some overlay. SWAT model was used for 17 years of hydrological data to parametrize the basin climatology and then used them as criteria along with some other parameters such as soil, LULC, for selecting potential sites for hydropower projects.

1.5 Working principle of Run of River hydropower plant

The working principle of the run of the river hydropower plant is simple (Figure 1.1):

- ✓ It composes of a take-off point, penstock, and a turbine.
- ✓ The take-off point is located at a higher elevation, from where water is diverted via penstock toward the turbine.
- ✓ Where turbine converts the potential energy to rotational energy and then water is released back to the river, or it can be utilized for other purposes such as irrigation or the domestic purpose (Jawahar, Michael, & Reviews, 2017)

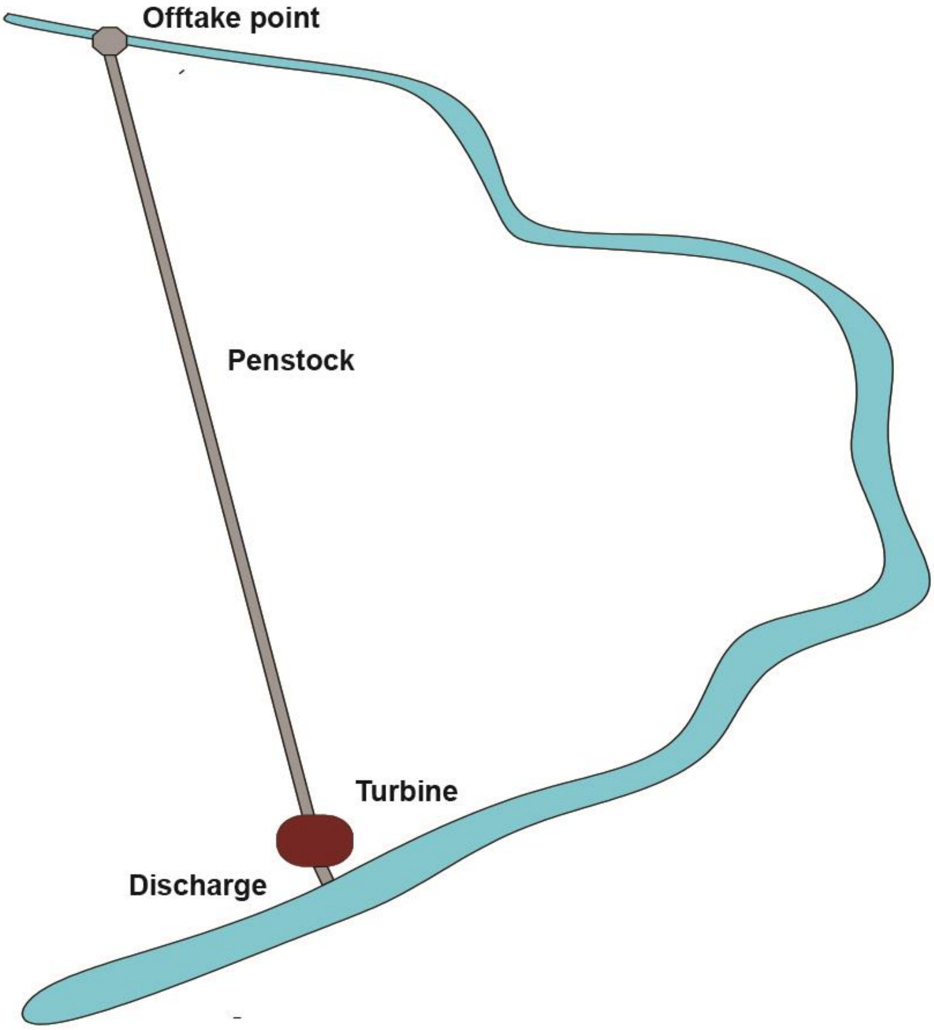

Figure 1.1. Working Principle of Run of the River hydropower.

1.6 Climate change Impact on Swat River Basin

Naveed et al., 2019 studies the impact of climate change on the Swat River Basin, which is the westerlies, subtropical basin of Hindukush ranges, due increasing demand for Irrigation and ongoing hydropower development. Changes in flow regimes are the consequence of variation in precipitation and temperature, so to study hydro-climatological conditions of the basin, data from six Global Circulation Models (GCM) from two RCP's 4.5 and 8.5 up the end of the 21st century were feed into the calibrated SWAT model and lead the following results

- There would be an increase in average annual temperature by comparing to baseline situation, ranging from 2.2C to 4.18C under RCP 4.5 and 4.63C to 8.49C under RCP 8.5.
- Unlike temperature, precipitation shows the variable trend in different GCM models by comparing to baseline situation, output from four models shows an increase in precipitation ranging from 1.51% to 22.52% under RCP 4.5 and 1.05 to 35.98% under RCP 8.5, while two models show a decrease in precipitation, -9.74 to -2.99 under RCP 4.5 and -13.72 to -3.24 under RCP 8.5.
- Climate change has a prominent effect on river flow regimes of the Swat River basin under both concentration pathways of all GCM's used in the study. There would be a significant increase in average annual flows, an increase in high and low flows of the river throughout the year, and there would be also intensification in peak flows (from June to September).

The results indicate that projected climate change has a profound impact on the seasonal variation of the Swat River Basin flow regimes. It is important to consider this impact in the management of freshwater resources, sustainable growth in the management of hydropower resources, and irrigation activities in the future.

1.7 Objectives

- To select potential Sites for the Run of the River project Sites
- Determine the theoretical potential of the Swat River basin by integrating semi-distributed hydrological model SWAT.

CHAPTER 2

MATERIALS AND METHODS

2.1 Study area

Geographically Swat River basin tracks the boundary of Swat basin, lies between latitude 34° 34′ to 35° 55′ north and longitude 72° 08′ to 72° 50′ east. The starting point of the swat river is the natural lake and Gorbela glaciers which falls through local streams Gol and Khor in the Ushu and Utror valleys and then join in the extreme north of Swat Valley known as Kalam. The river moves into the central part of Hindu Kash Mountains (S. Mahmood & Rahman, 2019) to the Swat district, flourish the Lower Dir district, followed by Malakand and with the elevation ranges from 360m to 4500m south to north glaciers are located at the elevation above 4000 meters while vegetation and other land use and landcover at an elevation between 1800m to 3000m. The Basin receives average annual precipitation of about 375mm, which is further distributed into two seasons: winters due to westerlies circulation (January to March) and summer, mainly in monsoon month that starts in July and ends in late September (Anjum, Ding, Shangguan, Ijaz, & Zhang, 2016). Swat river has economic significance as it holds three hydroelectric power plants with a capacity of 123 MW, contribute to national grid stations, and the Munda headwork, which drains up to 1400 km2 area (Bahadar, Shafique, Khan, Tabassum, & Ali, 2015). Muhmad Dam, a multipurpose dam is also planned on river swat at about 5km upstream to Munda headwork with an estimated capacity of 740 MW will irrigate up to 15100 acres of agricultural land and will also protect downstream districts such as Charsadda, Nowshera, Mardan from flash floods (I. Ahmad, Tang, Wang, Wang, & Wagan, 2015).

2.2 Datasets

ASTER Global Digital Elevation model was acquired from NASA Earth explorer with 30 m resolution, which was utilized to divide the entire catchment into sub sub-catchments based on elevation and generate stream network and head calculation at potential sites. Soil Data and LULC will be acquired from Food and Agriculture Organization (FAO) and the European Space agency (ESA).

There are many meteorological stations in swat river basin located at different elevations within the catchment. Climate data includes daily precipitation, daily T_{max} and T_{min}, was acquired from Pakistan Meteorological department for last 12 years (2007-2018) for three stations. Daily discharge data would also be collected from irrigation department KPK. Climatic data will be utilized in generation of input files for SWAT model, while observed flow data will be used to analyse flood frequency and hence for model calibration and validation.

2.3 Methodological framework for hydropower site selection

The research focuses on the methodical framework for site selection of run of the river (RoR) type hydropower site selection which is essential in planning before implementation and theoretical power potential of sub-basins. The Swat river basin has been estimated using power formula under present and future scenario. The working principle of RoR comprises a penstock or a weir used to divert the river flow into the turbine and then water is returned to the river, there is no storage reservoir required, which makes its application easy (figure). The availability of flow and its magnitude, elevation difference(head), and the length of penstock are some of the

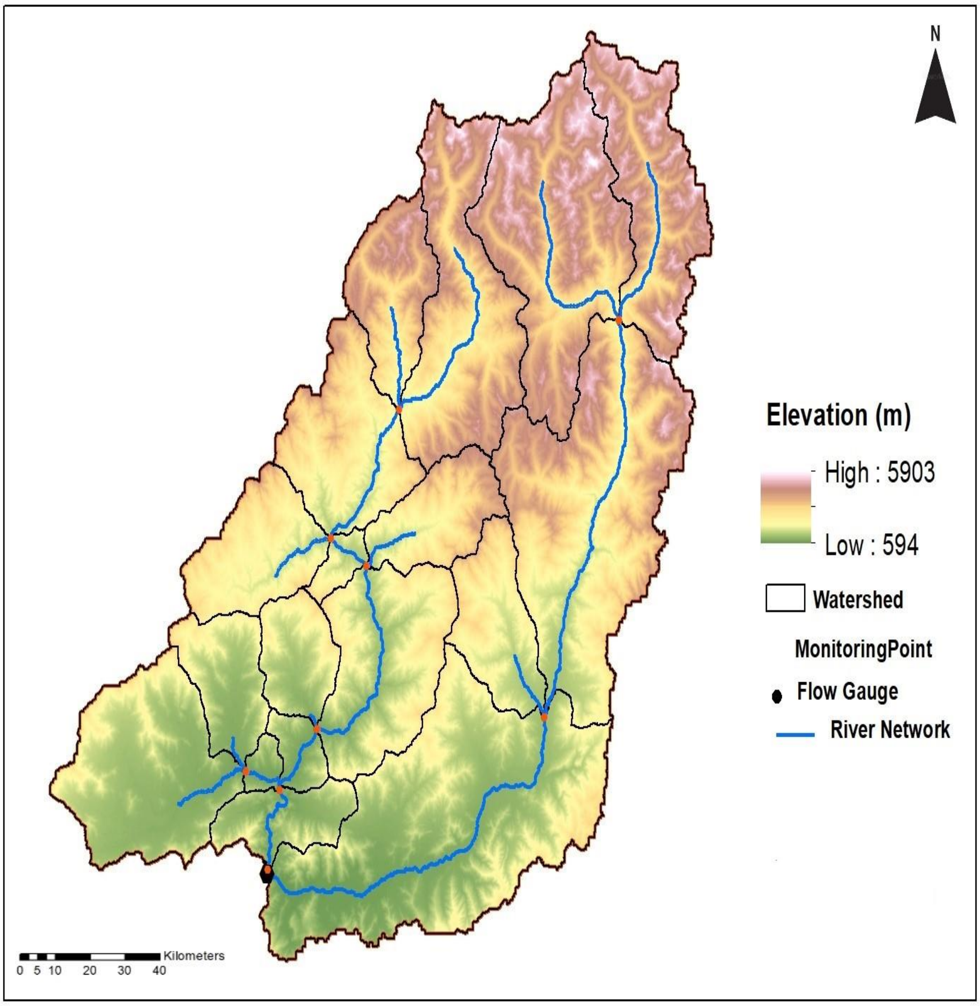

Figure 2.1. Map showing study area.

Essential factors in identifying the power potential of sites. GIS-based tools and hydrological model SWAT has been implemented to select the sites to pinpoint weir, powerhouse, head acre, and penstock and then stimulate discharge at the selected potential sites by developing regional flow duration curve at the sites (Rojanamon, Chaisomphob, Bureekul, & Reviews, 2009)

The mathematical formula for theoretical power potential of proposed can be estimated as:

$$P = \gamma * \eta * Q * h \text{……………………..(2.1)}$$

$$\gamma = \rho g \text{……………………(2.2)}$$

Where, P is the power (W)

$\Upsilon = \rho g$ = Specific weight of water (N/m^3

g = Acceleration due to gravity (m/s^2)

ρ = Density of Water = (1000 kg/m^3)

Q = Discharge (m^3/sec)

H = Head (m)

Ƞ = overall efficiency = 1 in this case

Head and Discharge are the two basic requirements for the power potential, head is calculated using DEM and other GIS tools, discharge is estimated by applying rainfall-runoff modelling. Efficiency depends upon type of turbine, distribution of head and availability of flow rates. Pelton and Turgo turbines are suitable for a high head (>50m) but require relatively low flow rates, Crossflow and Francis are suitable for a low head (<50m) but variable flow rates and some turbines such as Kaplan can be operated on the head lower than 10m but requires very high flow rates. Framework for the methodology is shown in figure 2.2.

2.4 Hydropower Site Selection and Head assessment

For the site selection of hydropower plants, a 30x30m resolution DEM has been utilized to delineate watershed to extract stream network and sub-basin using arc hydrology toolset in ArcMap to generate river-bed slope and to get the elevation that has been generated along the river channels for head assessment. To compute head of the selection of suitable sites, points at the interval of 500m has been generated using construct tool in ArcGIS. Each consecutive point represents a starting point at higher elevation where water is diverted towards plant and an ending point at lower elevation where water is pushed back to river. To assess head, drop along each pair of points, they were overlaid on the digital elevation model. Strahler method has been followed to order the river network along the watershed (Strahler, 1957). For the selection of the potential site for the RoR hydropower projects following criteria have been set:

1. Stream Order greater than three has been selected in order to have enough discharge at that site.
2. Hydraulic head equal or greater than 20 meters has been considered.
3. Minimum distance between two the potential sites must be equal or greater than 500m.

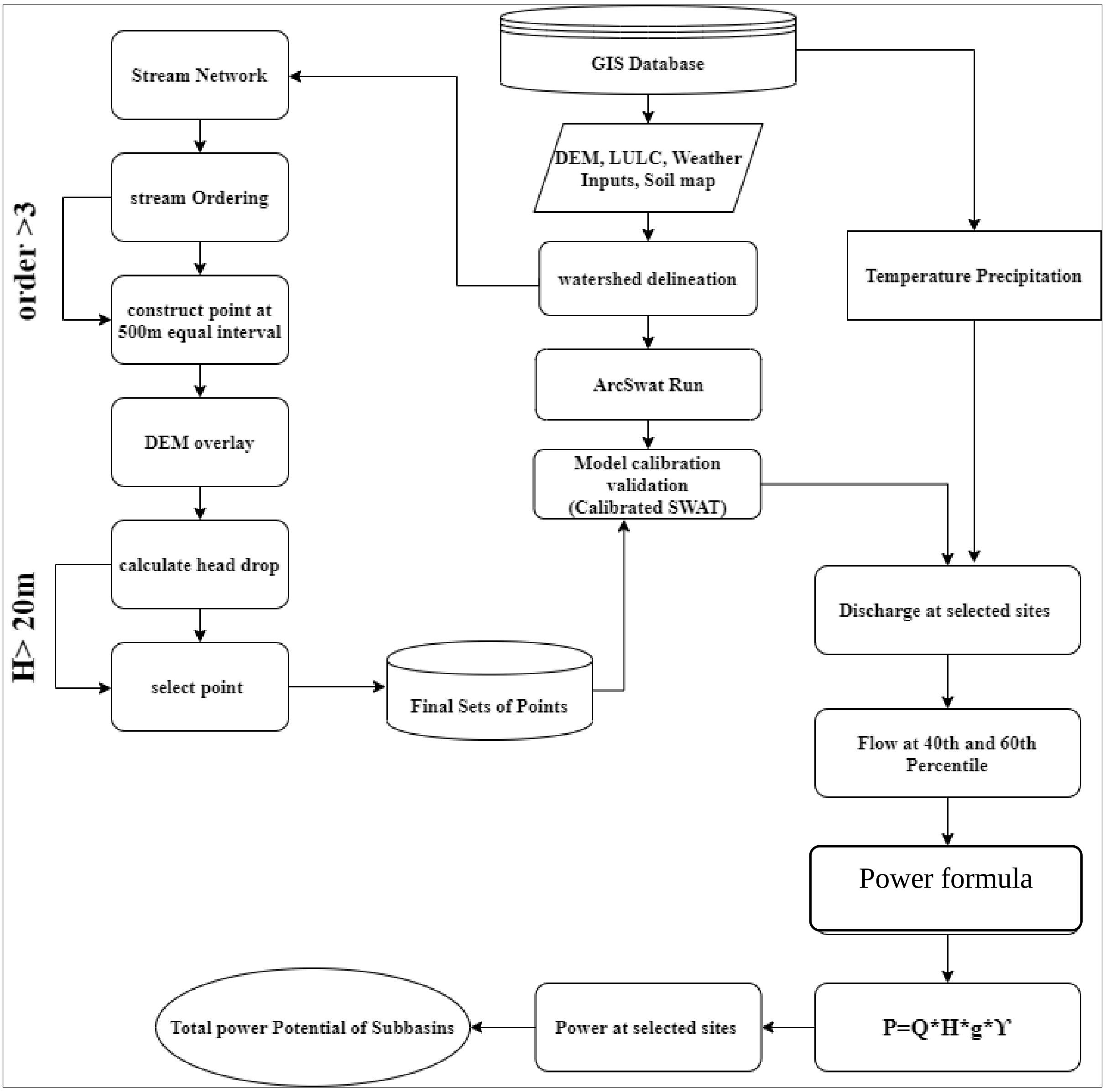

Figure 2.2. Flow chart showing methodology

2.5 Determination of flow rates

For the determination of flow rates, the Soil water Assessment Tool (SWAT) would be used to compute the discharge at the potential site and generate future flows to evaluate climate change effect on power potential. It is a semi-distributed model initially developed for rainfall-runoff modelling, water quality and reliability for implantation in large river basins. SWAT model operates within the interface of ArcGIS and the model divides the catchment into areas of the homogenous unit, so-called hydrological response units (HRU) based on land use, soil, and slope (Muthuwatta et al., 2017). Data inputs required for the SWAT model required for the SWAT model include daily temperature (Tmax & Tmin), precipitation, DEM, LULC map, and Soil and Slope map of the study area. SWAT model operates by following water balance equation to derive hydrological cycle within the basin as:

$$SW_t = SW_o + \sum_{i=1}^{t} (Rday - Qsurf - Ea - wseep - Qgw) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.3)$$

Where t is the time of day i , SW_t and SW_o is the final and initial amount of soil water content (mm). Rday is the amount of precipitation on day i (mm), Qsurf is the amount of runoff on day i (mm), E_a is the amount evapotranspiration on day i (mm), Wseep is the amount of water entering into the vadose zone from soil profile on day i (mm) and Qgw is the amount of return flow on day i (mm) (Goraba et al., 2015). Arcswat version 10.3 was utilized in this study to delineate watershed and generate stream network while calibration and validation.

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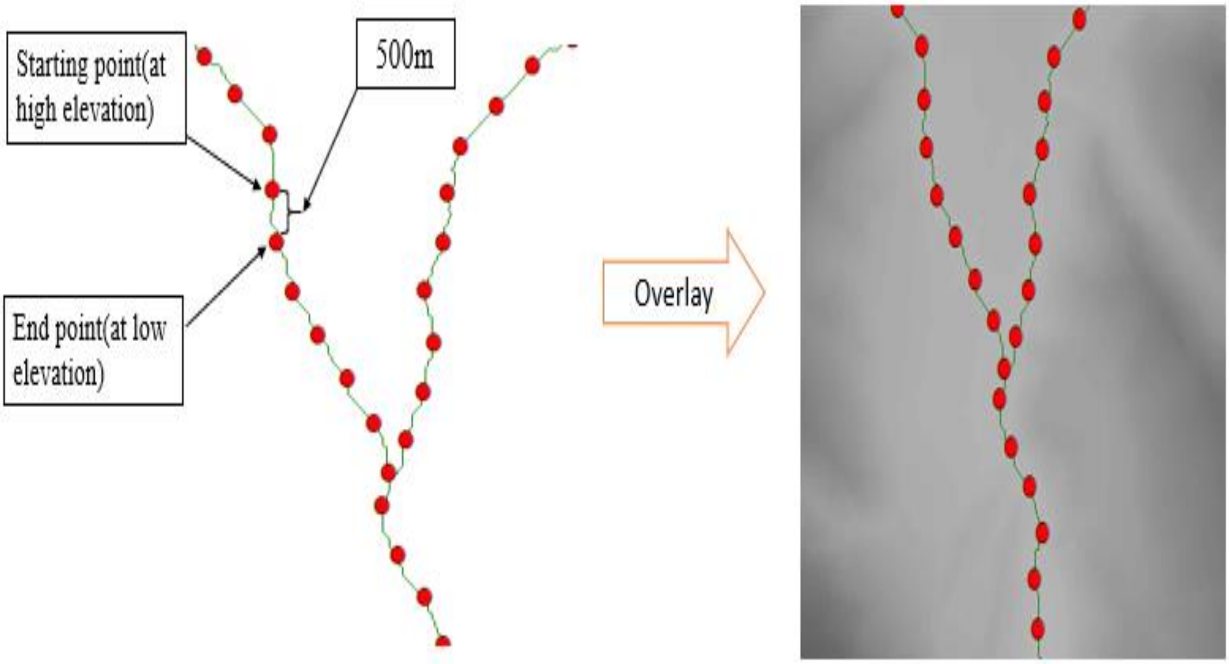

Figure 2.3. Head assessment and hydropower site selection.

procedures SWATCUP software will be used. The setting of the model was done using the protocol provided by Anjum et al., 2019 for the Swat River Basin. The was calibrated on a daily and monthly basis by using the flow data at the basin outlet. Model performance was examined both qualitatively and quantitively. Qualitative via visual inspection and interpretation, timing of the peaks in the graph and quantitative by using objective function such as Nash-Sutcliffe co-efficient of efficiency (NS), Root Mean Squared Error (RMSE), Percent Bias (PBIAS) (Hasan, Wyseure, & Engineering, 2018)

$$NSE = \frac{\sum_{i=1}^{n}(Qi^{obs} - Qi^{sim}\ )2}{\sum_{i=1}^{n} Qi^{obs}\ - Q^{mean})2} \text{ ……………………… (2.4)}$$

$$R^2 = \frac{[\sum_{i=1}^{n}[Qi^{Obs} - Qi^{sim}][Qi^{sim} - Qi^{sim\ mean}]]^2}{\sum_{i=1}^{n}[Qi^{obs} - Qi^{mean}]^2 \sum_{i=1}^{n}[Qi^{obs} - Qi^{mean}]^2} \text{…………..(2.5)}$$

Where Qi^{Obs} and Qi^{Sim} are observed and simulated values, and Q^{mean} and $Q^{simmean}$ are the average values of observed and simulated discharge.

After the getting calibrated SWAT it was then run along the potential sites that have been selecting for RoR projects and flow was generated for different periods.

2.6 Model uncertainty and sensitivity analysis

To check the uncertainty of a hydrological model it is necessary to optimize the model that matches best to the observed condition. It is accomplished by doing sensitivity analysis to pick the more sensitive parameters. Sensitivity analysis is the process by which model performance is checked by changing the input parameters. The parameters that has greater influence on model output are more sensitive. SWAT model has inbuilt two type of sensitivity analysis tools one is global sensitivity analysis in which sensitivity of one parameter is check relative to other parameters. Sensitivity of the parameter is checked by considering t-test score and p-value. Second type of sensitivity analysis is called one at a time sensitivity analysis, in which parameter influence is checked individually. Sensitivity in this case is checked by visual inspection of flow graphs. Twenty different parameters were selected based on literature, out of which only 13 were found sensitive.

2.7 SWAT Calibration and Validation

Model calibration and validation is crucial in any hydrological model to make the simulated flow conditions in line with the observed conditions by changing model parameters under some criteria. In SWAT, there are two types of calibration and validation techniques i.e., manual calibration and auto-calibration. Manual calibration is a lengthy process and time-consuming, and involves changing the parameters, until the modelled flow matches with the observed flow. However, automatic calibration within the interface of SWAT-CUP software, Monticello simulation are used to give the range of parameters. SWAT cup uses a predefined algorithm to carry out model calibration. The research Sufi-2 algorithm is implemented to optimize the model to get the flow rates at ungauged sites.

Table 2.1. Best parameters for the SWAT model input.

	Parameters	**Min value**	**Max value**	**Fitted value**
1.	v__ESCO.hru	0	1	0.689
2.	r__SOL_AWC().sol	0	1	0.064
3.	r__GWQMN.gw	0	500	151.708
4.	r__CN2.mgt	-5	5	-0.299
5.	r__ALPHA_BF.gw	0	1	0.057
6.	r__OV_N.hru	0.02	30	28.143
7.	r__GW_REVAP.gw	0.02	0.2	0.146
8.	v__GW_DELAY.gw	0	1000	94.214
9.	r__HRU_SLP.hru	0	1	0.716
10.	v__SLSUBBSN.hru	10	150	142.098
11.	v__SURLAG.hru	0.05	24	15.511
12.	r__SOL_K().sol	0	200	26.211
13.	v__REVAPMN.gw	0	500	139.640

RESULTS AND DISCUSSION

3.1 Land Use Land Cover (LULC)

There are seven major LULC classes in the swat river basin table 3.1, among which rangeland and forest cover most large landscape type covers 78% of the total area, agricultural land is 16.14%, bare land 3.3% glacier cover is up to 2%. The basin is sustained naturally as it has minimum urbanization and is exposed to a very low level of human interference. Figure 3.1. shows LULC map of Swat River Basin.

3.2 Soil Classification of Swat

The swat river basin is spatially divided into four broader groups of soils Table (), based on FAO soil classification. Major type of soil is called Lithosols covers of 58.64% of total area. Lithosols are formed by weathering of weak rock fragments, and they are usually found on steep slopes. They have more significant potential for grazing lands and forests. Eutric Cambisols second abundant soil type in the region covers 37.19% of the basin. This group of soil belongs to the plains and wide valleys, has plains and wide valleys, has sandy gravel composition, and is suitable for extensive agricultural activities. Glaceris soil type is the soil covered by permanent glaciers 2.26% of Swat basin land comprises permanent glaciers. Hapalic Xerosols (1.28%). Figure 3.2. shows the spatial distribution of soils in the basin.

3.3 Site identification

To identify proposed sites of ROR hydropower plants, stream order, head and discharge were used as the suitability criteria. In the Swat River basin, there are two major streams known as the Panjkora river and other is swat river and they both combine in the lower part of the basin to form one major river that ultimately falls into Kabul River.

3.3.1 Stream Ordering

Streams of swat river basins were classified using Strahler method fig (3.3). In total, sixteen streams were identified, out of which thirteen streams were or order 4, two streams were identified of order five, and one stream was of order 6. Table (3.3) show a detailed classification of streams in the swat river. Greater stream order would have more significant potential for hydropower harnessing.

To compute head-drop across each point, streams were equally divided at the interval of 500m, and then overlaid over DEM to compute elevation drop across each point and then only that point were selected that have head greater than 20m. by keeping this criterion only 62 sites meet the conditions with the head ranges from 20m to 48m. Maximum sites were found in stream order four and then in the main channel with the order 5. The topography of the swat river and complex stream network it is suitable for RoR hydropower sites to meet local electricity demand in the region, as its elevation ranges from 59003m to 594m at the outlet of the basin, and hence there is a considerable elevation difference observed between each proposed site. Maximum sites have head ranges between 20m to 26m which are in the upper part of the basin and in the middle elevation range, 39 sites have head drop ranges from 20m to 26m, 9 sites located with the range of 27m to 31m, 11 sites in the range of 32m to 37m and 2 sites head’s drop vary from 43m to 48m table (3.4).

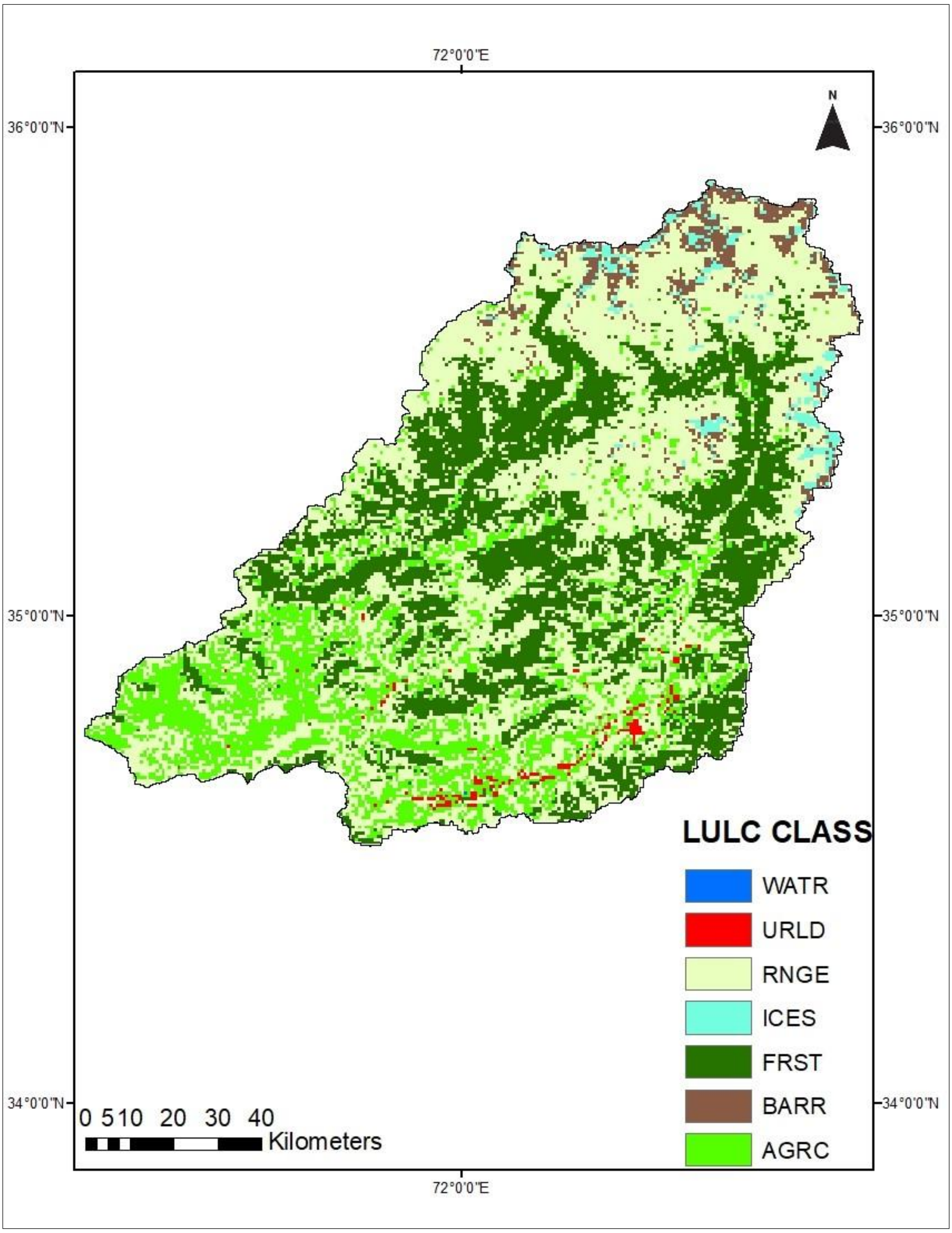

Figure 3.1. Land-use land cover map of Swat River basin.

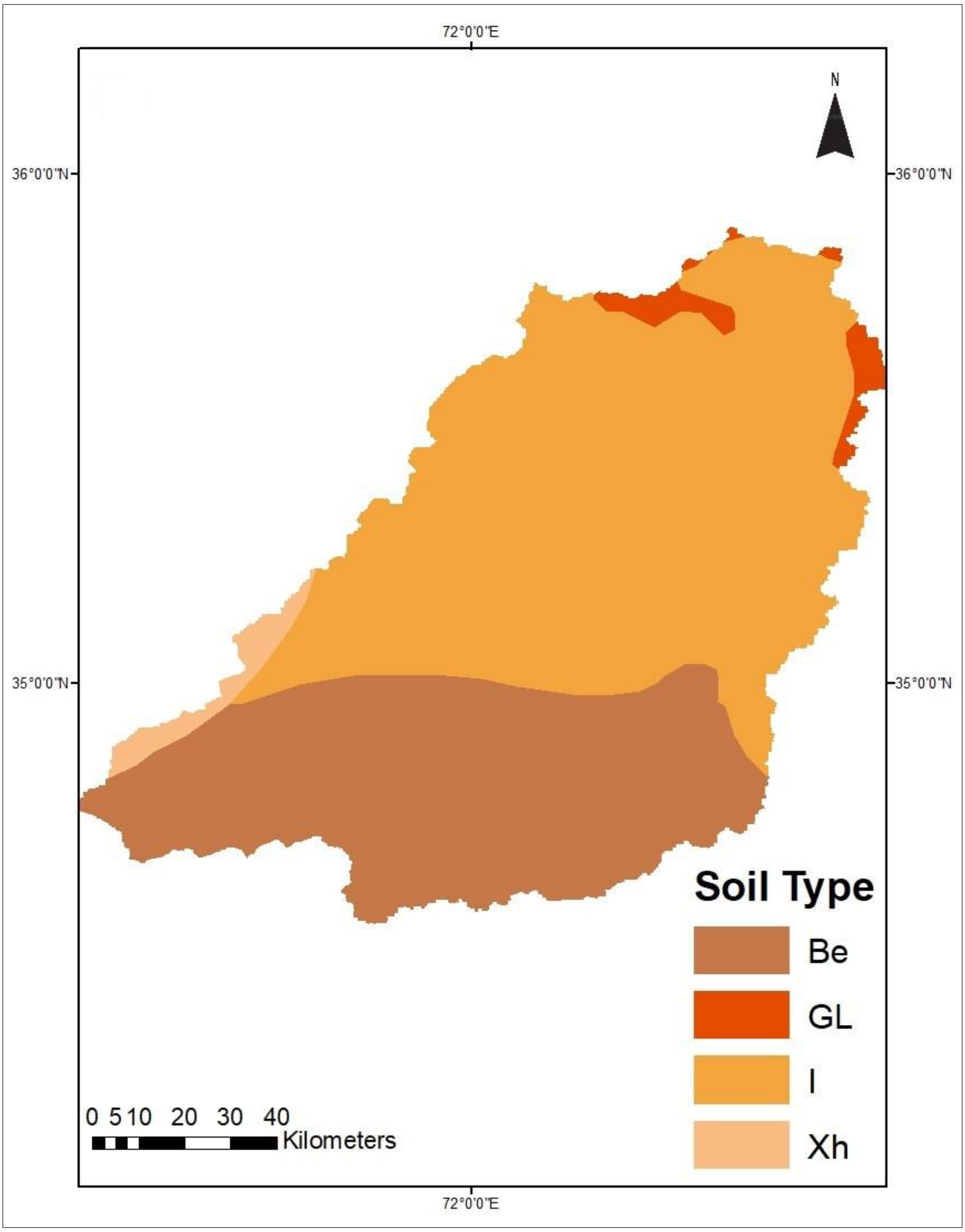

Figure 3.2. Soil classification map of Swat River basin.

Table 3.1. Description of land use land cover in the watershed.

Sr.no	**Class**	**Area (Km^2)**	**LULC %**
1	Water	0.267	0.00
2	Agriculture	1929	16.14
3	Bare land	396.9	3.32
4	Forest Cover	3552	29.72
5	Rangeland	5803	48.55
6	Ice	192.7	1.61
7	Urban	79.57	0.67

Table 3.2. Description of soil type in the watershed.

Sr.no	**Soil Type**	**Percentage (%)**
1	Eutric Cambisols	37.19
2	Glaceris	2.26
3	Haplic Xerosols	1.28
4	Lithosols	58.64

Table 3.3. Stream classification of streams in Swat River.

Stream order	**No.of Streams**
4	13
5	2
6	1

3.4 Application of Hydrological modeling

3.4.1 Sensitivity analysis

Sensitivity analysis of the model was carried out using Global sensitivity analysis and one at a time sensitivity analysis within the interface of SWATCUP. 20 parameters were selected based on literature review, and after analysis it was found that only 13 parameters were found sensitive. Both Global and one at a time sensitivity analysis was done, and parameters were sort based on p-value and t-test score, as well its individual effect on the objective function of the model, smaller p-value and larger t-stat value, then the parameter is more sensitive as portrayed in Fig (3.5). Table () shows the ascending order of sensitive parameters based on p-value.

3.4.2 Calibration and validation

The hydrological model was calibrated to fix the simulated flow according to the observed flow, so a wide range of parameters could be used that best define the hydrological modeling of an area (Wallace, Flanagan, & Engel, 2018). The parameter range that was selected was based on literature (Ha, Bastiaanssen, Van Griensven, Van Dijk, & Senay, 2018) that critically affects snowmelt, groundwater recharge, evapotranspiration, and soil component of the model. 13 parameters were chosen after checking their sensitivity within the interface of SWAT cup, and then these parameters were utilized to carry out calibration and validation of the model at daily and monthly

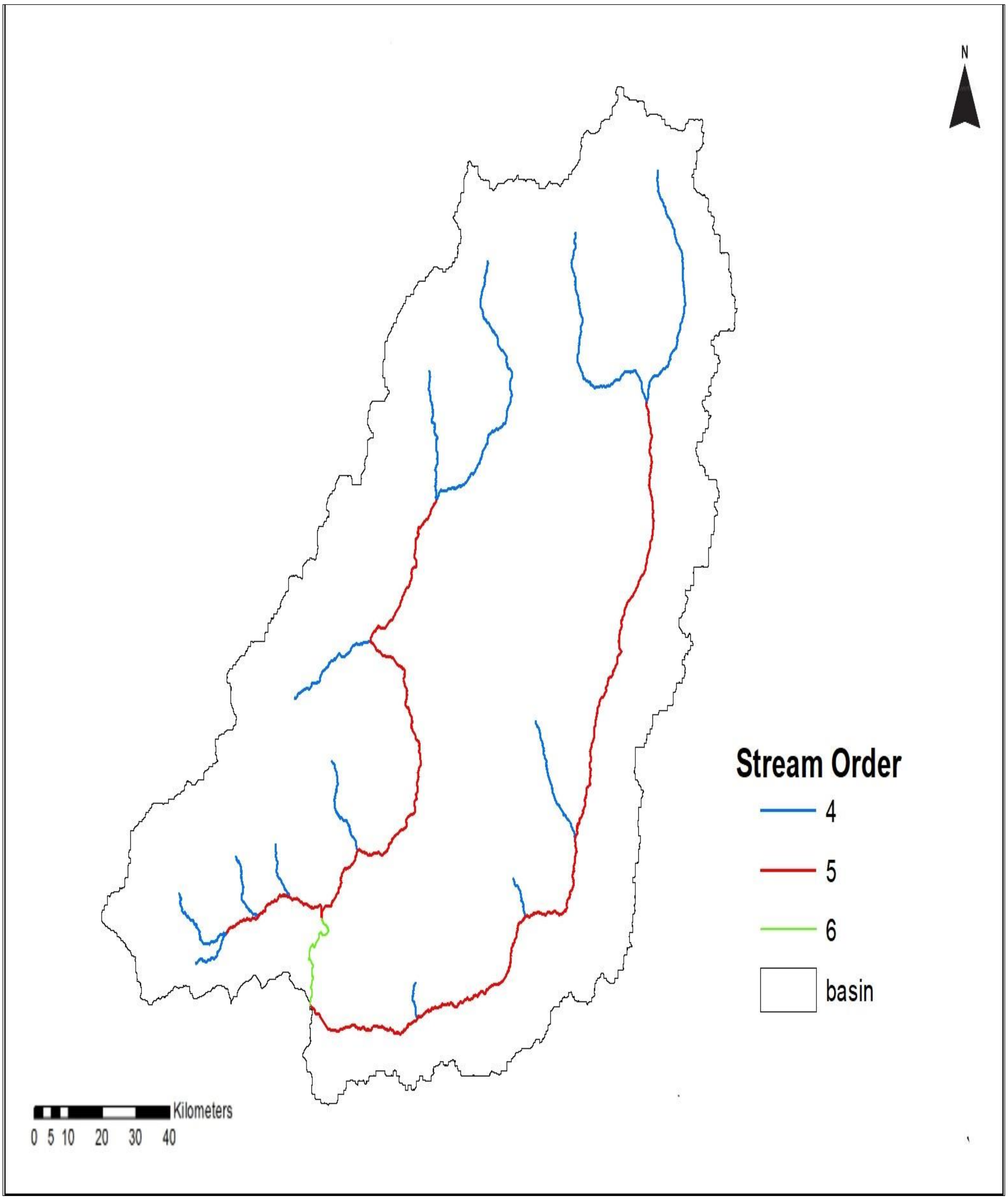

Figure 3.3. Stream ordering in Swat River.

Table 3.4. Head Drop across the selected sites.

Sr.no	**Head (m)**	**No.of sites**
01	20 -26	39
02	27-31	9
03	32-37	11
04	38-42	0
05	43-48	2

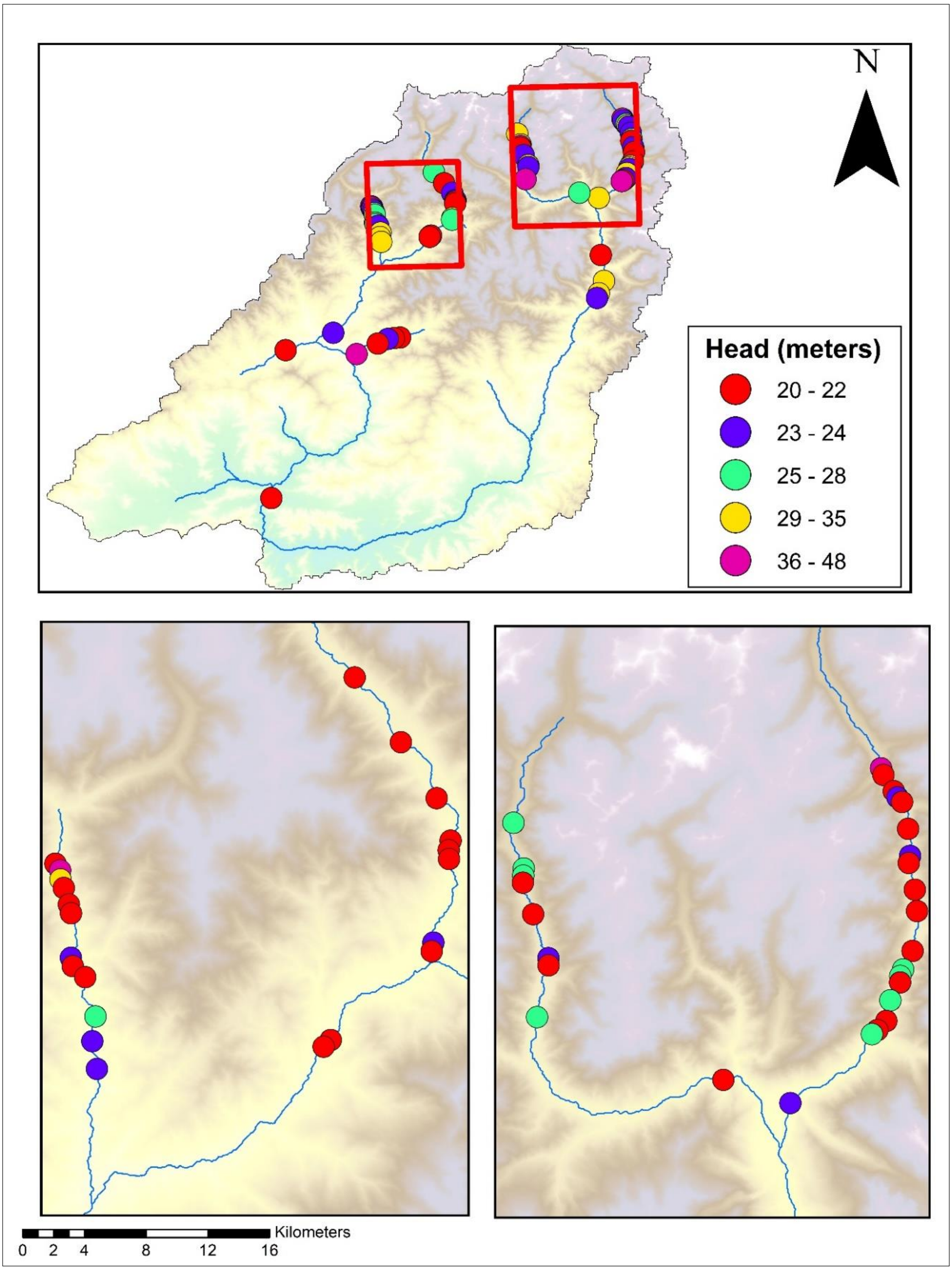

Figure 3.4. Map showing head drop across each point.

scale. The list and range of the sensitive parameters are mentioned in Table (3.5). The discharge data were available for 14 years and it was taken at the outlet of the basin, 4 years were set as warmup period of the model so that the model adjusts itself to the real condition. (Narsimlu, Gosain, Chahar, Singh, & Srivastava, 2015), the time period that was considered for calibration was 8 years 2007-2015, and validation was carried out for the 4 years 2016-2018. After calibration and validation of the model it can be visualized that the modeled flow is in alignment with the observed flow, comparison of the simulated flow and observed flow portrayed in fig (3.6) and from the scattered plot fig (3.7, 3.8) of observed versus simulated flow it can be observed that SWAT model was able to predict the flow satisfactorily. Statistical indicators that were used for model calibration and validation are listed in table (3.6), the value of these indicators shows good agreement between observed flow and simulated flow at the outlet of the basin. For calibration, NSE and R2 values were 0.74 and 0.76, whereas it was relatively lower for validation periods. NSE 0.68 and R2 0.73. The value of PBIAS less than 20% is considered good for model fit hence, in calibration its value was 8.6 and for validation it was 15.7. By observing the peaks flows in the discharge graph, there is some degree of underprediction in both wet and dry seasons, but in hydropower prediction, peaks flows are not of concern. However, the parameters that were used for model calibration and validation were realistic and can be further

utilized in the future climate change analysis and hydropower production under changing climatic conditions.

Table 3.5. Sensitive parameters, respective p-value, and t-stat.

Parameter Name	**t-Stat**	**P-Value**
Snow Parameters		
A__SMTMP.bsn	52.134	0.000
A__SFTMP.bsn	66.500	0.000
A__TIMP.bsn	0.316	0.752
Other parameters		
R__CN2.mgt	-35.805	0.000
R__SOL_K.sol	-20.348	0.000
V__SLSUBBSN.hru	12.225	0.000
R__SOL_AWC.sol	4.030	0.000
R__HRU_SLP.hru	-2.848	0.005
V__GWQMN.gw	2.473	0.014
R__OV_N.hru	1.560	0.119
V__GW_DELAY.gw	-1.381	0.168
R__ALPHA_BF.gw	-0.967	0.334
V__SURLAG.hru	-0.828	0.408
V__REVAPMN.gw	-0.598	0.550
V__ESCO.hru	0.416	0.677
R__GW_REVAP.gw	-0.131	0.896

Table 3.6. Statistical indicators for model calibration and validation.

Sr.no	**Objective Function**	**Calibration**	**Validation**
1	NSE	0.74	0.68
2	R^2	0.76	0.73
3	PBIAS	8.6	15.7

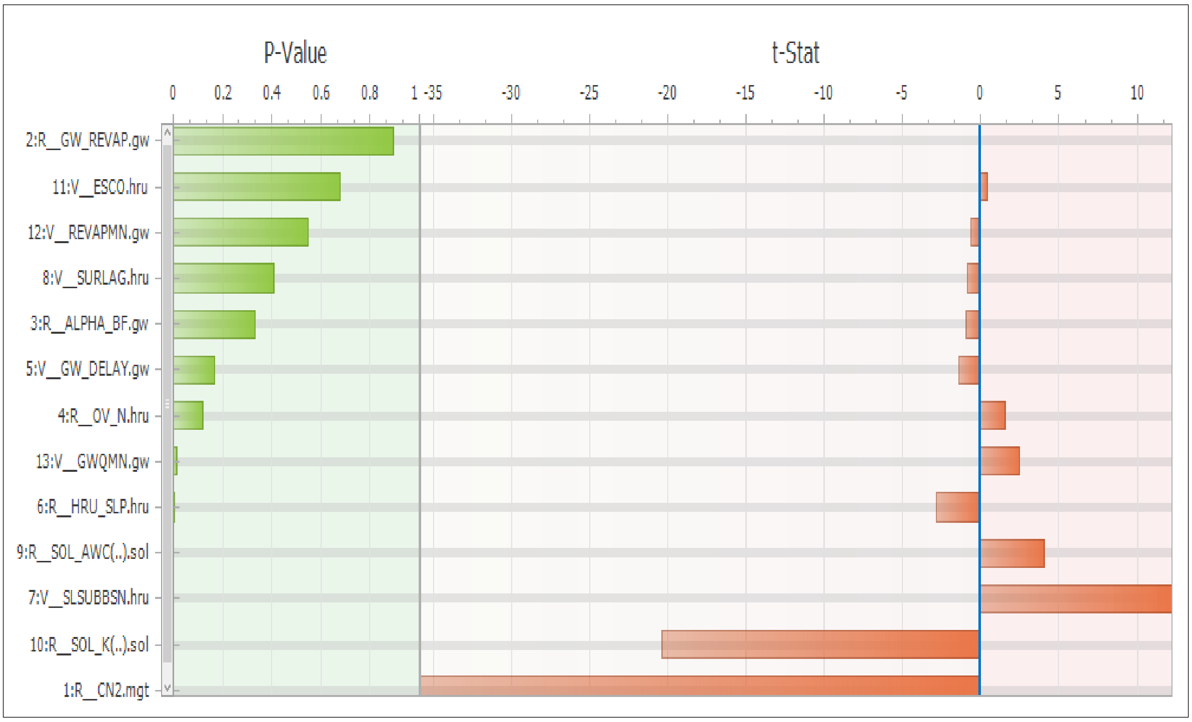

Figure 3.5. Sensitivity analysis and sensitive parameters.

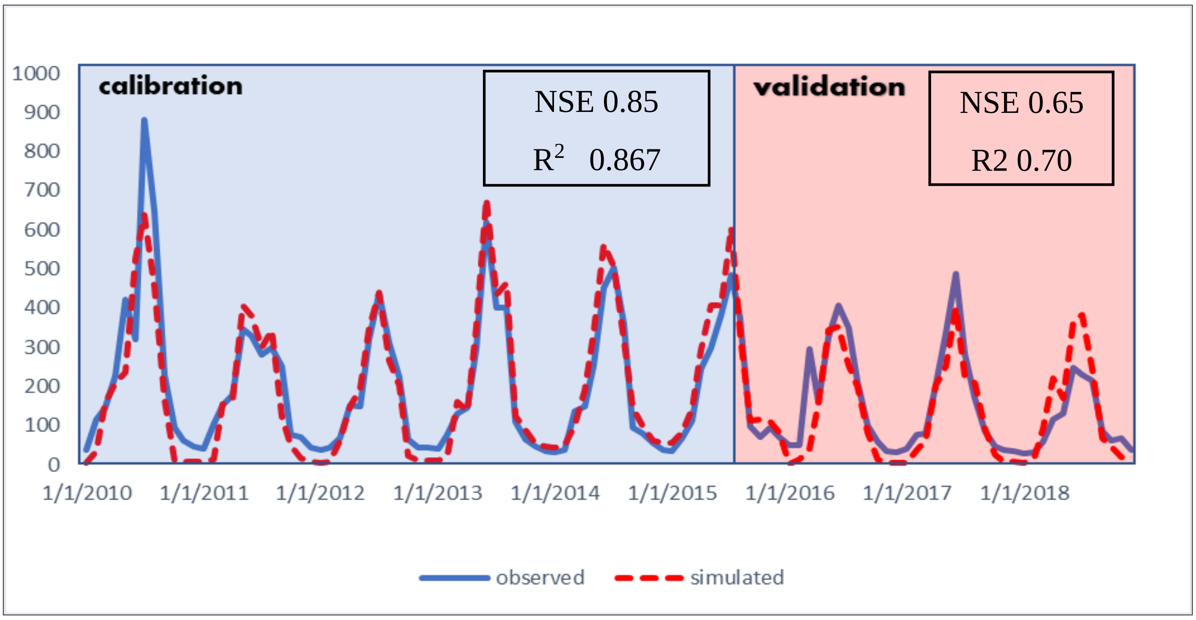

Figure 3.6. Calibration and validation of SWAT model at Swat River basin.

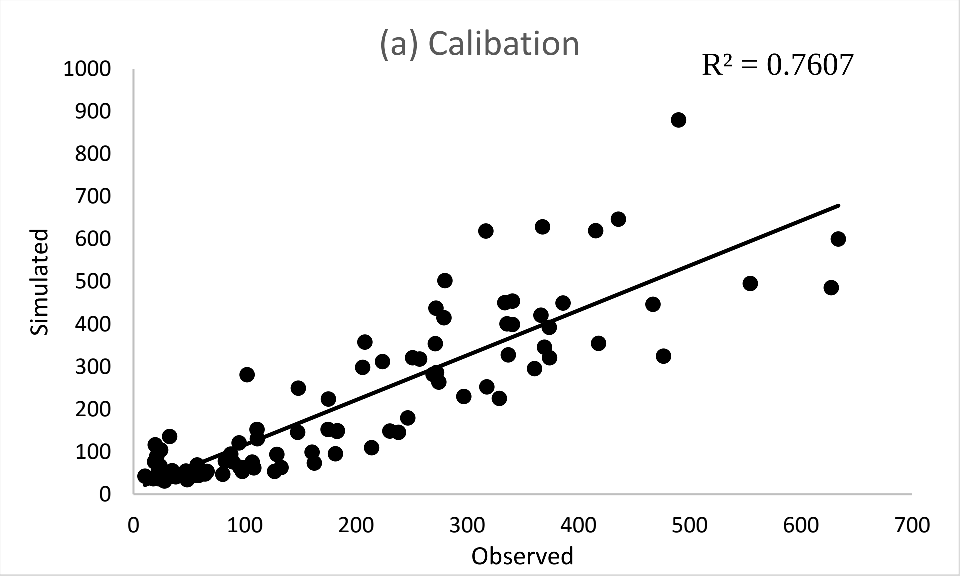

Figure 3.7. Scattered plot of observed Vs simulated for calibration.

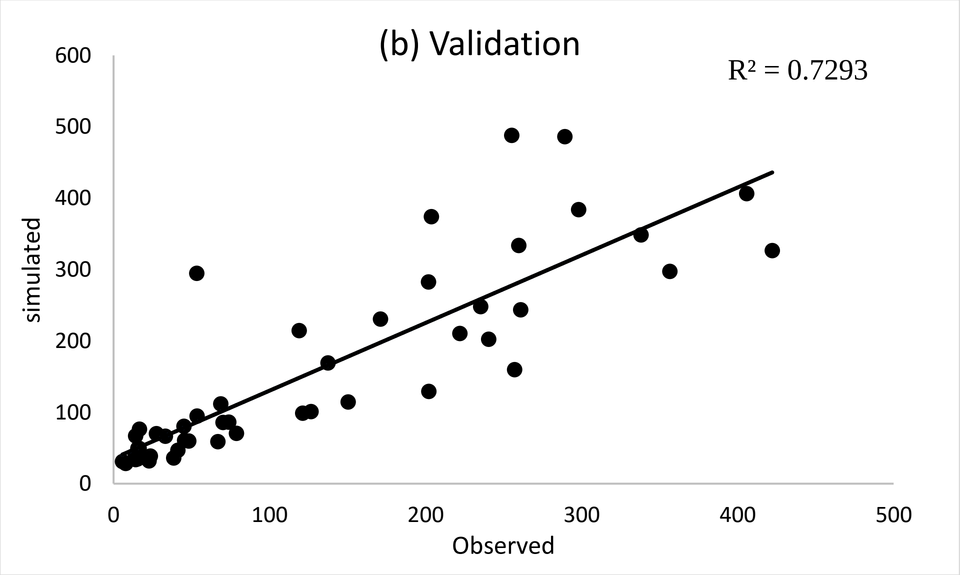

Figure 3.8. Scattered plot of observed Vs simulated for validation.

3.5 Theoretical power Potential Estimation

3.5.1 Flow Duration Curve for theoretical power computation

After calibration and validation of the SWAT model to get the discharge at potential sites, twelve years of run data were used to construct flow duration curves at 63 sites and estimate theoretical hydropower production using power formula. Construction of flow duration curve is essential to get a dependable discharge for the ROR and exceedance of flow availability throughout the year, hence for the Swat River basin, dependable discharge at 60^{th} and 40^{th} percentile was computed for the optimal power production, power at 40^{th} and 60^{th} was considered optimal fig (3.9).

After developing flow duration curve at each potential site, theoretical power potential was estimated at each site, and then it was aggregated to compute the potential of each subbasin of the swat river basin. There are 19 subbasins in the study basin, out of which only 7 basins have the potential for hydropower plant installation and energy production. The power at the 40^{th} percentile ranges from 52.601KW to 7025.93 KW, while at 60^{th} percentile, it ranges from 200.41KW to 26023.49KW. The power potential of suitable sites is divided into five further 5 five classes, details for which are shown in table (3.8). At the 60^{th} percentile, maximum sites have potential ranges from 873 KW to 3627 KW, 18 sites have potential less than 518 KW, they can be considered mini hydropower plants whereas 16 sites have potential within 555 KW to 873 KW, that can be micro hydropower plants. Six sites have potential ranges from 3627 KW to 27471KW that can be classified as mediated size hydropower plants, in the same way,

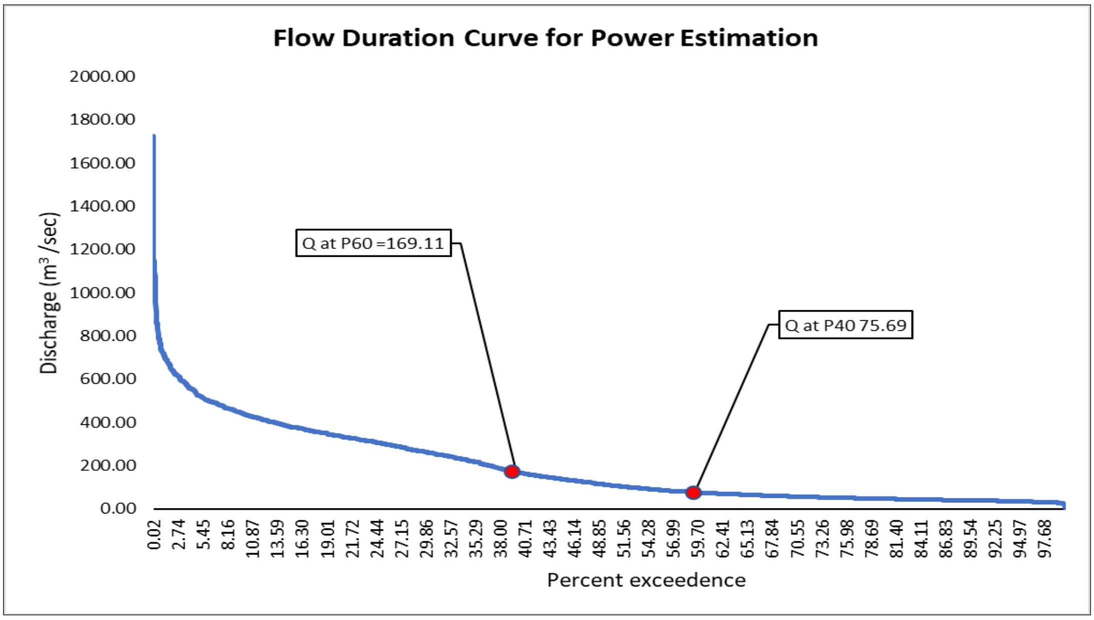

Figure 3.9. Flow duration curve for the estimation of theoretical power potential at the outlet.

Table 3.7. Theoretical power potential at respective sites.

Power KW at 40th Percentile	**No. of sites**	**Power KW at 60th Percentile**	**No. of sites**
52– 140	19	200-518	18
140-152	3	518-555	2
152-240	15	555-873	16
240-971	20	873-3627	20
971-7025	4	3627 -27471	6

at the 40th percentile most of the plants have power potential between 240 KW to 971 KW, 19 sites having potential between 52 KW and 140 KW, 15 sites have power potential ranges from 142 KW to 240 KW, and 4 sites have greater power potential ranges from 971 KW to 7025 KW.

3.5.2 Theoretical power potential of Sub-basins

The theoretical power potential of each sub-basin is calculated by summing the individual sites positioned in that subbasin. There are 19 subbasins in the Swat River basin out of which only 9 have potential, whereas subbasin have no potential for hydropower plants, due to slope and geographic location. In these areas, there is not sufficient head drop between the proposed plants. Fig (3.8, 3.9) highlights the power potential of each subbasin in detail. The basin having variety of slopes could be more suitable and greater number of sites and hence more power could be extracted from it. In case of Swat River basin, the subbasin that are located the higher elevation have more potential as compared to the subbasin that have lower elevation, so subbasin 1 has maximum potential of 19621.5 KW, then next to it is subbasin 10 has potential of 14769 KW, while subbasin 8 has minimum potential of 101.2 KW. All subbasins having the potential in the following order at percentile 40:

Subbasin 1> Subbasin 10> Subbasin 7> Subbasin 2>Subbasin 3>Subbasin 17> Subbasin 4>Subbasin 5> Subbasin 8

At percentile 60, subbasin 10 has a maximum potential of 56944.88 KW, then subbasin 2 has a potential of 16276.16 KW, while subbasin 8 has the least potential 345.1764 KW. Other subbasins have the power potential in the following order:

Subbasin 10> Subbasin 2> Subbasin 7> Subbasin 3>Subbasin 4>Subbasin 17> Subbasin 1>Subbasin 5> Subbasin 8

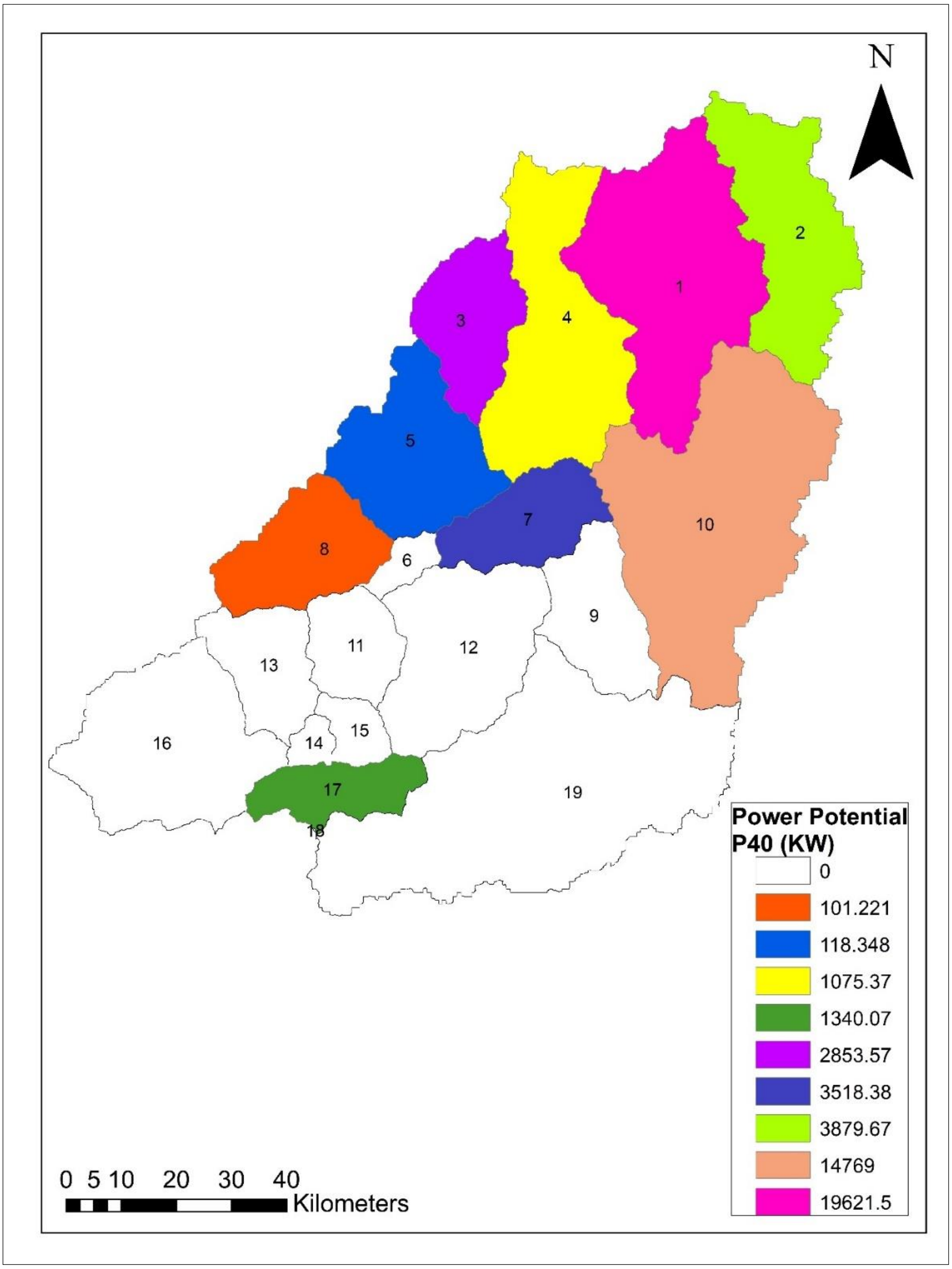

Figure 3.10. The theoretical power potential of Subbasins at percentile 40.

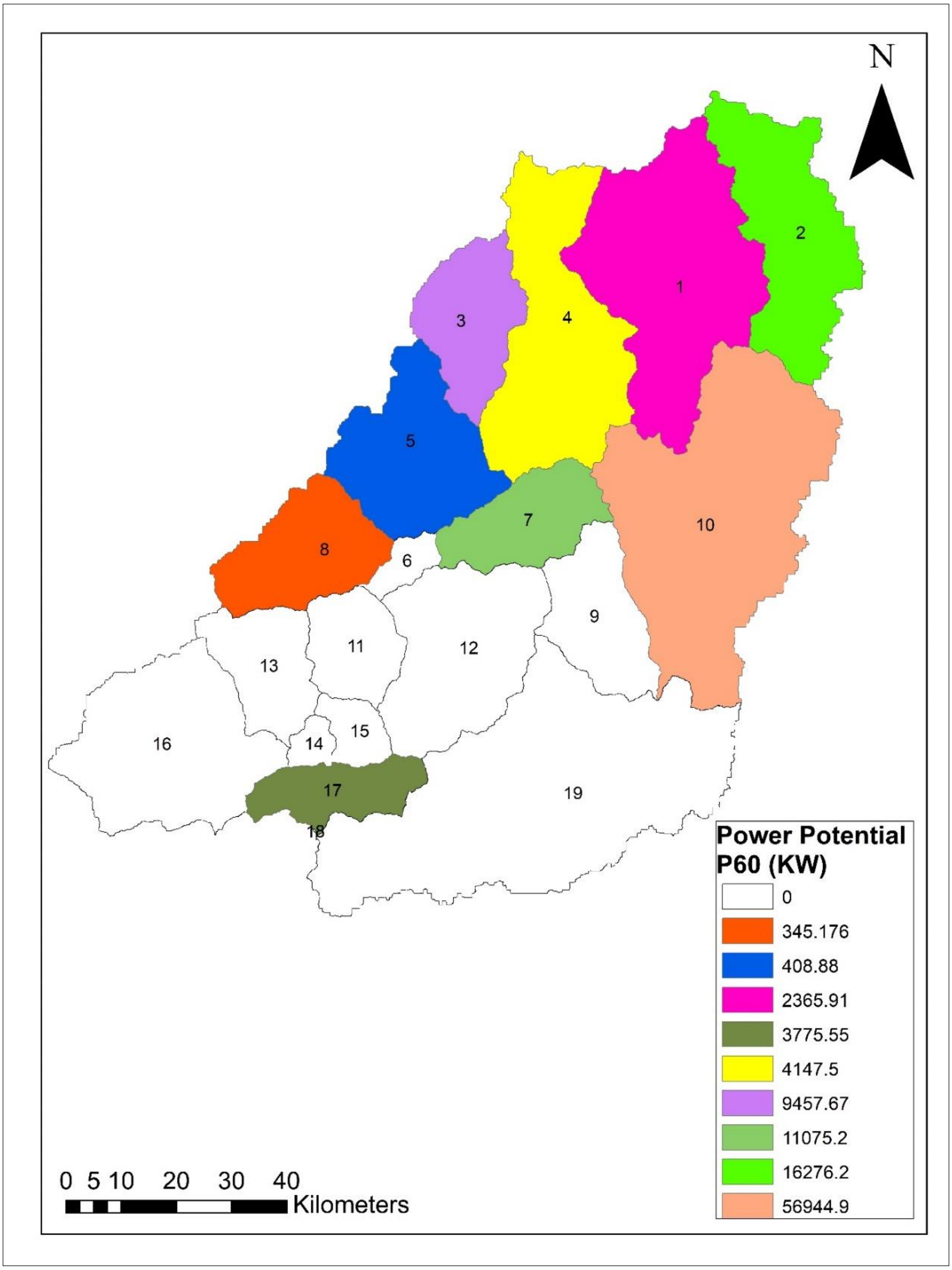

Figure 3.11. Theoretical power potential of subbasins at percentile 60.

CHAPTER 4

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

By keeping in mind, the energy crisis faced by Pakistan elevated prices of hydrocarbons and being 5th most vulnerable country to climate change, hydropower is viable option to come out from all crises, so the research aims to identify the theoretical power potential of swat river basin and pinpoint the suitable locations for the run of the river hydropower project by using SWAT hydrological model and GIS tools. Power potential of swat river was calculated using flows at 40th and 60th percentiles. The results reveal that Swat River basin has enormous hydropower potential that can be extracted by using eco and an economic friendly small run of the river hydropower potential. The potential ranges from 101.221KW to 19621KW at 40th percentile and 345KW to 56944KW at 60th percentile. The result of the study also shows that the flow is highly variable in the period considered hence, it could be predicted that basin is vulnerable to climate change. In the future the flow could ultimately impact hydropower potential in negative sense. Although fully utilized the power potential of Pakistan such as swat river and other rivers flowing in the northern areas of Pakistan can not only solve the energy crisis of Pakistan but also help reduce trade deficit and reliance on non-renewable energy such as oil and natural gas.

4.2 Recommendations

- By keeping the energy crisis faced by Pakistan and elevated prices of hydrocarbons in the global market, hydropower is a viable option to overcome the energy shortfall in the country

- More robust tools such as manual surveys, multipoint SWAT model calibration, and utilization of long-term climatic data can further refine the results of this study as climatic data such as precipitation and temperature data are not frequently available at high elevations.
- Furthermore, incorporating climate change scenarios, such as Global Circulation Models (GCM's) and Regional Circulation Models (RCM), could help analyze the climate change impact on the water resources of Swat River basin specifically on the hydropower potential on the river.

References

1. Shrestha, S., Shrestha, M., & Babel, M. S. (2016). Modelling the potential impacts of climate change on hydrology and water resources in the Indrawati River Basin, Nepal. *Environmental Earth Sciences*, *75*(4), 280.
2. Basheer, A. K., Lu, H., Omer, A., Ali, A. B., & Abdelgader, A. (2016). Impacts of climate change under CMIP5 RCP scenarios on the streamflow in the Dinder River and ecosystem habitats in Dinder National Park, Sudan. *Hydrology and Earth System Sciences*, *20*(4), 1331-1353.
3. Anandhi, A., Frei, A., Pierson, D. C., Schneiderman, E. M., Zion, M. S., Lounsbury, D., & Matonse, A. H. (2011). Examination of change factor methodologies for climate change impact assessment. *Water Resources Research*, *47*(3).
4. Strahler, A. N. (1957). Quantitative analysis of watershed geomorphology. *Eos, Transactions American Geophysical Union*, *38*(6), 913-920.
5. Ahmad, I., Tang, D., Wang, T., Wang, M., & Wagan, B. J. A. i. M. (2015). Precipitation trends over time using Mann-Kendall and spearman’s rho tests in swat river basin, Pakistan. *2015*.
6. Ahmad, Z., Hafeez, M., Ahmad, I. J. E. m., & assessment. (2012). Hydrology of mountainous areas in the upper Indus Basin, Northern Pakistan with the perspective of climate change. *184*(9), 5255-5274.

7. Al-Juboori, A. M., & Guven, A. J. W. r. m. (2016). Hydropower plant site assessment by integrated hydrological modeling, gene expression programming and visual basic programming. *30*(7), 2517-2530.
8. Ali, A., Behera, B. J. R., & Reviews, S. E. (2016). Factors influencing farmers′ adoption of energy-based water pumps and impacts on crop productivity and household income in Pakistan. *54*, 48-57.
9. Ali, A., & Imtiaz, M. J. U. P. (2019). Effects of Pakistan's energy crisis on farm households. *59*, 100930.
10. Anjum, M. N., Ding, Y., Shangguan, D., Ijaz, M. W., & Zhang, S. J. A. i. M. (2016). Evaluation of high-resolution satellite-based real-time and post-real-time precipitation estimates during 2010 extreme flood event in Swat River Basin, Hindukush region. *2016*.
11. Avtar, R., Sahu, N., Aggarwal, A. K., Chakraborty, S., Kharrazi, A., Yunus, A. P., . . . Kurniawan, T. A. J. R. (2019). Exploring renewable energy resources using remote sensing and GIS—A review. *8*(3), 149.
12. Bahadar, I., Shafique, M., Khan, T., Tabassum, I., & Ali, M. Z. J. J. o. H. E. S. (2015). Flood hazard assessment using hydro-dynamic model and GIS/RS tools: A case study of Babuzai-Kabal tehsil Swat Basin, Pakistan. *48*(2).
13. Bank, W. (2017). *World development report 2017: Governance and the law*: The World Bank.
14. de Oliveira Tiezzi, R., Vieira, N. D. B., & Simões, A. F. J. J. S. D. (2018). Impacts of climate change on hydroelectric power generation–a case study focused in the Paranapanema Basin, Brazil. *11*(1), 140.

15. Fuentes-Bargues, J. L., & Ferrer-Gisbert, P. S. J. E. E. (2015). Selecting a small run-of-river hydropower plant by the analytic hierarchy process (AHP): A case study of Miño-Sil river basin, Spain. *85*, 307-316.
16. Ghafoor, A., ur Rehman, T., Munir, A., Ahmad, M., Iqbal, M. J. R., & Reviews, S. E. (2016). Current status and overview of renewable energy potential in Pakistan for continuous energy sustainability. *60*, 1332-1342.
17. Goyal, M. K., Singh, V., & Meena, A. H. J. W. R. M. (2015). Geospatial and hydrological modeling to assess hydropower potential zones and site location over rainfall dependent Inland catchment. *29*(8), 2875-2894.
18. Ha, L. T., Bastiaanssen, W. G., Van Griensven, A., Van Dijk, A. I., & Senay, G. B. J. W. (2018). Calibration of spatially distributed hydrological processes and model parameters in SWAT using remote sensing data and an auto-calibration procedure: A case study in a Vietnamese river basin. *10*(2), 212.
19. Hasan, M. M., Wyseure, G. J. W. S., & Engineering. (2018). Impact of climate change on hydropower generation in Rio Jubones Basin, Ecuador. *11*(2), 157-166.
20. Hennig, T., & Harlan, T. J. G. E. C. (2018). Shades of green energy: geographies of small hydropower in Yunnan, China and the challenges of over-development. *49*, 116-128.
21. Ibrahim, M., Imam, Y., & Ghanem, A. J. R. E. (2019). Optimal planning and design of run-of-river hydroelectric power projects. *141*, 858-873.
22. IEA. (2012). *Hydropower*: OECD.

23. Inglesi-Lotz, R., & Dogan, E. J. R. E. (2018). The role of renewable versus non-renewable energy to the level of CO2 emissions a panel analysis of sub-Saharan Africa's Big 10 electricity generators. *123*, 36-43.
24. Jawahar, C., Michael, P. A. J. R., & Reviews, S. E. (2017). A review on turbines for micro hydro power plant. *72*, 882-887.
25. Kahia, M., Aïssa, M. S. B., Lanouar, C. J. R., & Reviews, S. E. (2017). Renewable and non-renewable energy use-economic growth nexus: The case of MENA Net Oil Importing Countries. *71*, 127-140.
26. Kelly-Richards, S., Silber-Coats, N., Crootof, A., Tecklin, D., & Bauer, C. J. E. P. (2017). Governing the transition to renewable energy: A review of impacts and policy issues in the small hydropower boom. *101*, 251-264.
27. Khan, N., Shahid, S., bin Ismail, T., & Wang, X.-J. (2018). Spatial distribution of unidirectional trends in temperature and temperature extremes in Pakistan.
28. Kusre, B., Baruah, D., Bordoloi, P., & Patra, S. J. A. E. (2010). Assessment of hydropower potential using GIS and hydrological modeling technique in Kopili River basin in Assam (India). *87*(1), 298-309.
29. Mahmood, R., & Jia, S. J. W. (2016). Assessment of impacts of climate change on the water resources of the transboundary Jhelum River basin of Pakistan and India. *8*(6), 246.
30. Mahmood, S., & Rahman, A.-u. J. E. e. s. (2019). Flash flood susceptibility modeling using geo-morphometric and hydrological approaches in Panjkora Basin, Eastern Hindu Kush, Pakistan. *78*(1), 43.

31. Narsimlu, B., Gosain, A. K., Chahar, B. R., Singh, S. K., & Srivastava, P. K. J. E. P. (2015). SWAT model calibration and uncertainty analysis for streamflow prediction in the Kunwari River Basin, India, using sequential uncertainty fitting. *2*(1), 79-95.
32. Nistoran, D. E. G., Abdelal, D., Ionescu, C. S., Opriş, I., & Costinaş, S. (2017). *A simple method to assess theoretical hydropower potential of a river*. Paper presented at the 2017 10th International Symposium on Advanced Topics in Electrical Engineering (ATEE).
33. Padhiary, J., Das, D., Patra, K., Sahoo, B., & Singh, K. J. J. o. A. (2018). Prediction of climate change impact on streamflow and evapotranspiration in Baitarani basin using SWAT model. *20*(4), 325.
34. Pandey, A., Lalrempuia, D., & Jain, S. K. J. H. S. J. (2015). Assessment of hydropower potential using spatial technology and SWAT modelling in the Mat River, southern Mizoram, India. *60*(10), 1651-1665.
35. Rojanamon, P., Chaisomphob, T., Bureekul, T. J. R., & Reviews, S. E. (2009). Application of geographical information system to site selection of small run-of-river hydropower project by considering engineering/economic/environmental criteria and social impact. *13*(9), 2336-2348.
36. Romanelli, J. P., Silva, L. G., Horta, A., & Picoli, R. A. J. J. o. E. E. (2018). Site selection for hydropower development: a GIS-based framework to improve planning in Brazil. *144*(7), 04018051.

37. Sadiqa, A., Gulagi, A., & Breyer, C. J. E. (2018). Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. *147*, 518-533.
38. Sakulphan, K., & Bohez, E. L. J. E. (2018). A New Optimal Selection Method with Seasonal Flow and Irrigation Variability for Hydro Turbine Type and Size. *11*(11), 3212.
39. Shabbir, N., Usman, M., Jawad, M., Zafar, M. H., Iqbal, M. N., & Kütt, L. J. R. E. (2020). Economic analysis and impact on national grid by domestic photovoltaic system installations in Pakistan. *153*, 509-521.
40. Shah, S., Zhou, P., Walasai, G., & Mohsin, M. J. E. I. (2019). Energy security and environmental sustainability index of South Asian countries: A composite index approach. *106*, 105507.
41. Shah, S. A. A., Solangi, Y. A. J. E. S., & Research, P. (2019). A sustainable solution for electricity crisis in Pakistan: opportunities, barriers, and policy implications for 100% renewable energy. *26*(29), 29687-29703.
42. Tahir, M. H., Malik, A., Saeed, M. A., Zaffar, N., Adeel, H. M., & Amjad, H. M. S. (2019). Experimental Performance Evaluation of 600 W Small Wind Turbine to Overcome Energy Crisis in Pakistan.
43. Tarroja, B., Forrest, K., Chiang, F., AghaKouchak, A., & Samuelsen, S. J. A. E. (2019). Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California. *237*, 353-366.
44. Wallace, C. W., Flanagan, D. C., & Engel, B. A. J. W. (2018). Evaluating the effects of watershed size on SWAT calibration. *10*(7), 898.

45. Wang, B., Wang, Q., Wei, Y.-M., Li, Z.-P. J. R., & reviews, s. e. (2018). Role of renewable energy in China’s energy security and climate change mitigation: An index decomposition analysis. *90*, 187-194.
46. Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., . . . Harrison, I. J. S. (2016). Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *351*(6269), 128-129.
47. Zafar, M. W., Shahbaz, M., Hou, F., & Sinha, A. J. J. o. c. p. (2019). From nonrenewable to renewable energy and its impact on economic growth: the role of research & development expenditures in Asia-Pacific Economic Cooperation countries. *212*, 1166-1178.
48. Zhou, Q., Hanasaki, N., Fujimori, S., Masaki, Y., & Hijioka, Y. J. C. c. (2018). Economic consequences of global climate change and mitigation on future hydropower generation. *147*(1), 77-90.

Appendix 1: Flow duration curve value at both percentiles.

SHP	P60 (m^3s)	P40 (m^3s)	SHP	P60 (m^3s)	P40 (m^3s)
1	2.18	0.50	32	1.01	0.29
2	2.26	0.62	33	1.01	0.29
3	2.90	0.72	34	1.29	0.35
4	2.90	0.72	35	1.38	0.36
5	3.20	0.79	36	1.39	0.37
6	3.33	0.80	37	1.71	0.44
7	3.99	0.98	38	1.80	0.46
8	3.99	0.98	39	1.93	0.49
9	5.89	1.38	40	2.09	0.52
10	6.36	1.52	41	2.25	0.57
11	2.20	0.49	42	3.01	0.79
12	2.26	0.51	43	3.10	0.93
13	2.26	0.51	44	3.24	1.06
14	2.27	0.52	45	3.26	1.01
15	2.57	0.64	46	3.30	1.02
16	2.87	0.74	47	3.50	1.02
17	2.68	0.68	48	3.52	1.03
18	3.35	0.73	49	3.53	1.08
19	3.50	0.77	50	5.05	1.40
20	3.71	0.99	51	0.83	0.22
21	4.19	1.02	52	1.14	0.34
22	4.58	1.03	53	1.17	0.37
23	4.13	1.06	54	1.38	0.40
24	15.29	3.25	55	1.57	0.46
25	3.33	0.74	56	1.80	0.52
26	10.52	2.41	57	1.80	0.52
27	11.14	2.78	58	2.39	0.67
28	12.89	3.61	59	7.01	2.30
29	14.80	3.39	60	10.99	2.99
30	74.30	20.06	61	17.33	5.84
31	79.69	20.13	62	18.75	6.66

Appendix 2: Location of hydropower proposed sites and theoretical power potential.

Subbasin	Lat	Long	Power Potential at P40 (KW)	Power Potential at P60 (KW)
1	35.591	72.434	19621.543	2365.908
2	35.664	72.664	3879.669	16276.16
3	35.507	72.036	2853.567	9457.67
4	35.486	72.205	1075.369	4147.496
5	35.287	71.930	118.348	408.880
6	35.106	71.918	0	0
7	35.183	72.159	3518.381	11075.2
8	35.119	71.716	101.220	345.176
9	35.030	72.308	0	0
10	35.202	72.535	14769.005	56944.88
17	34.733	71.799	1340.069	3775.554