IEEESEM

Assessment of Hydropower Potential using SWAT modeling and Spatial Technology in the Seti Gandaki River, Kaski, Nepal

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ABSTRACT

The surprising difference in elevation present within a small width, no doubt gives enough head for hydropower generation in most of the rivers of Nepal. The hydropower potential of any river can be assessed by realistic, up to date and useful information from recent advances in remote sensing, geographic information system and hydrological modelling [1]. This research aims for the assessment of the RoR hydropower potential using spatial technology and SWAT (Soil and Water Assessment Tool) modeling in Seti Gandaki River, Kaski, Nepal. The DEM, daily precipitation, minimum and maximum temperature data, discharge records, land use and soil data were used for the SWAT model setup and simulation. The model was calibrated (2000-2010) and validated (2011-2015) with model performance of 0.85 R^2, 0.85 E_{NS} and 2.19 % PBAIS. One hundred seventy-one potential hydropower locations were identified that fulfilled the criterions of sufficient head (determined from DEM processing and analysis) and sufficient discharge. Then, validated SWAT model was used to simulate the river flow discharge at the potential hydropower points. The final potential locations were compared with the existing and under construction DoED (Department of Electricity Development) hydropower projects running along the Seti River for validity check. A total potential of 529.97 MW was obtained at 40 % exceedance in the Seti Gandaki River. Economic, environmental and social sustainability of each location were also examined. The study revealed that the hydropower potential of a river basin can be correctly assessed by employing a digital elevation model, stream network data and a hydrological model, such as the SWAT model, within a GIS framework.

Keywords : Watershed Model, Hydrological Model, Run-off River, Land Use Land Cover, GIS.

1 INTRODUCTION

Infrangible tie between population and energy is well known to all and is the main reason of today's global energy demand. To fulfill this demand, different types of sources like thermal, nuclear, solar and hydropower are continuously being used. Being a developing country in verge of industrialization, there is an increasing demand of the electricity in Nepal; it is estimated that power demand will rise above 18000MW per day by 2040 AD [2].

Hydropower has the higher efficiency, is eco-friendlier and has gained important fascination among all other energy sources. It is the power derived from the water which is clean, renewable and also, reliable energy source [3]. Hydropower has immense benefits: it is environmentally friendly, cost-effective and unlike oil and other commodities, independent from international trade.

The geographic characteristic of Nepal has great potential for hydropower. The possibilities of world's largest hydropower projects can be seen in Nepal due to its topography and perennial nature of rivers. The variation in altitude (masl) of the country cross section along NS direction ranges from 8848 m (Mt Everest) in north to 64 m in south within the range of 150 km [4]. Due to this, various national and international agencies are showing large interest towards hydropower development in Nepal. The study [5] conducted by Dr. Hariman Shrestha in 1986 suggested that there is potential of 83,000 MW (megawatts) and among which 43,000 MW is economically exploitable. Similar type of study suggested the total potential of run of river hydropower plant as 53386 MW [6]. Despite of this huge potential, current hydropower

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generating capacity is 803 MW [2] which is less than 1 % of the national energy consumption [7]. So, there is urgent need to prepare the energy master plan and implement accordingly. The results of past studies done for hydropower assessment in Nepal were based on limited and insufficient hydrological, meteorological and topographic data. Besides, the projections merely accounted sustainability and environmental suitability. Now, the hydropower potential of any river can be assessed by realistic, up to date and useful information from recent advances in remote sensing (RS), geographic information system (GIS) and hydrological modelling [1] without an actual site visit. Also now with availability of land use data, topography and other administrative data, it has been easier to calculate hydropower capacity, model the simulated discharge considering economical and sustainability factor too. This has been a time and resource friendly approach.
Numerous hydropower projects are proposed and under construction on the Seti Gandaki river system. Hydropower assessment in this area will be a tool for validation and reference for planners and hydropower enthusiasts to further investigate development and investment potentials in sustainable hydropower of Nepal. This research aimed the assessment of the Hydropower Potential using Spatial Technology and SWAT Modeling in Seti Gandaki River, Kaski, Nepal. It has also looked upon the sustainability of potential RoR hydropower sites.
The study area is the East Seti watershed which is drained by Seti Gandaki river; an important tributary of the Gandaki basin system of Nepal (Fig. 1).

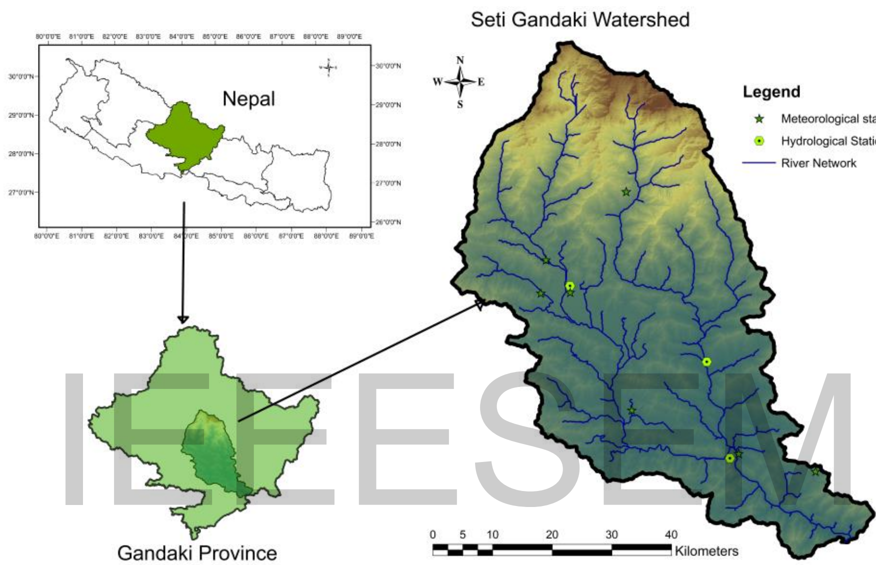

Fig. 1. Location of the Study Area.

The river has its origin near the base of the Mount Machhapuchhre (6,997 m) and the Mount Annapurna IV (7,525 m) at 28°27'40" N and 84°0'0" E approx. and is fed by the glaciers. Then, it flows south and south-east past Pokhara and Damauli to join the Trishuli River at 27°49'15" N and 84°27'15" E approx. near Devghat [8]. Mardi and Vijaypur are the major tributaries; Bhurjung Khola, Fusre Khola, Bagadi Khola, Bange Khola, Oltang Khola, and Madi River are smaller tributaries of the Seti River. The morphometric parameters of the watershed are presented in Table 1.

TABLE 1: MORPHOMETRY OF SETI GANDAKI WATERSHED [8].

Parameters	**Value**
Drainage Area	2951.16 km^2
Perimeter	310.60 km
Waterhed Length	146.79 km
Flow length	454.45 km
Drainage density	0.15
Watershed slope	0.05
Circularity ratio	0.38
Elongation ratio	0.42
Form factor	0.14

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2 DATA/MATERIALS USED

The main inputs of SWAT are topographical data or Digital Elevation Model (DEM), soil type data, land use/ land cover data, and weather data such as temperature and precipitation. The datasets, their sources/resolution used in this study are presented in Table 2.

TABLE 2: SOURCES OF DATASETS.

Data Type	Resolution/Frequency	Source
Digital Elevation Model (DEM)	30 m	Aster Global DEM https://earthexplorer.usgs.gov
Land Cover data	30 m	Landsat-8 Enhanced Thematic Mapper Plus (ETM+) http://earthexplorer.usgs.gov
Soil data	1:50,000	SOTER, ISRIC World Soil Information
Rainfall and Temperature	Daily	Department of Hydrology and Meteorology (DHM), Nepal
Discharge	Daily	Department of Hydrology and Meteorology (DHM), Nepal

2.1 Stream Flow Data

Daily discharge data of Seti river at Damauli station (Station no.430.5) was collected from DHM for 2000 to 2015 (Fig. 2). The peak observed flow of 3259 m^3/s was recorded in 22nd August, 2001 for Seti River at Damauli Station.

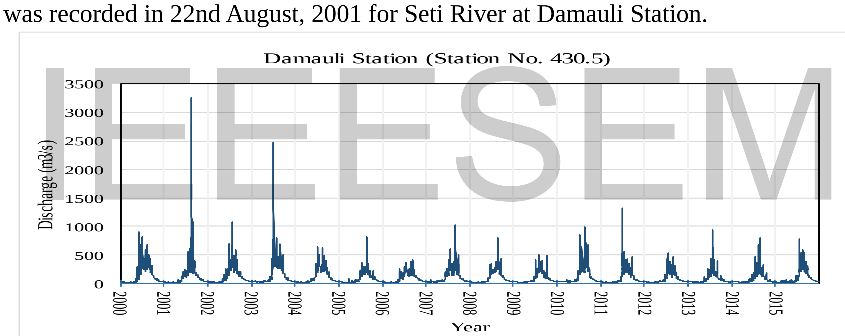

Fig. 2. Time series discharge data at Damauli Station (2000-2015).

2.2 Rainfall Data

The rainfall data from seven stations within study area having different climate type were used. The rainfall pattern was observed similar in all seven stations with maximum rainfall during the wet monsoon season and minimum rainfall during dry winter season (Fig. 3).

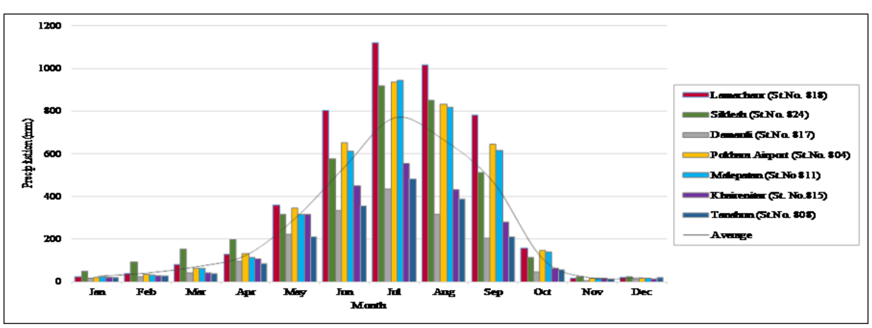

Fig. 3. Observed monthly rainfall at various stations (1980-2018).

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2.3 Temperature Data

Daily observed temperature was collected from three stations inside the watershed. The maximum recorded temperature recorded was 41°C at Khairenitar station and the minimum temperature recorded was -1°C at Malepatan station (Fig. 4).

Majority of weather data used were authentic and complete with some cases of missing data. The missing temperature data were filled by mean/median value of the data of previous and next year. Whereas, missing rainfall data were filled by bias correction of APHRODITE (Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation) data. Aphrodite daily gridded precipitation is the only long-term (1951 onward) continental-scale daily product that contains a dense network of daily rain-gauge data for Asia including the Himalayas, South and Southeast Asia and mountainous areas in the Middle East.

2.4 Digital Elevation Model

The Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) of 30 m resolution available in Geo TIFF file format with latitude and longitude in geographic coordinates referenced to the WGS 1984 was used. The elevation ranges from 173 m to 7921mm (Fig. 5).

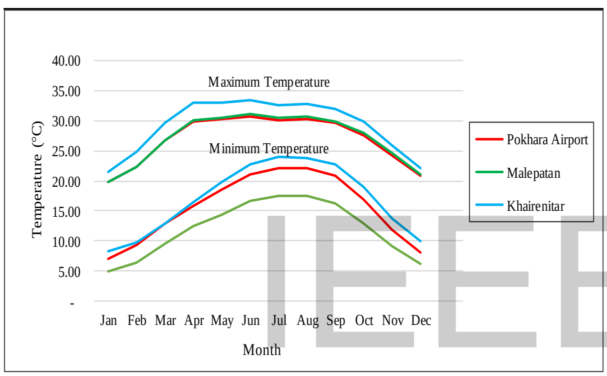

Fig. 4. Average monthly maximum and minimum temperature at various stations (1980-2018).

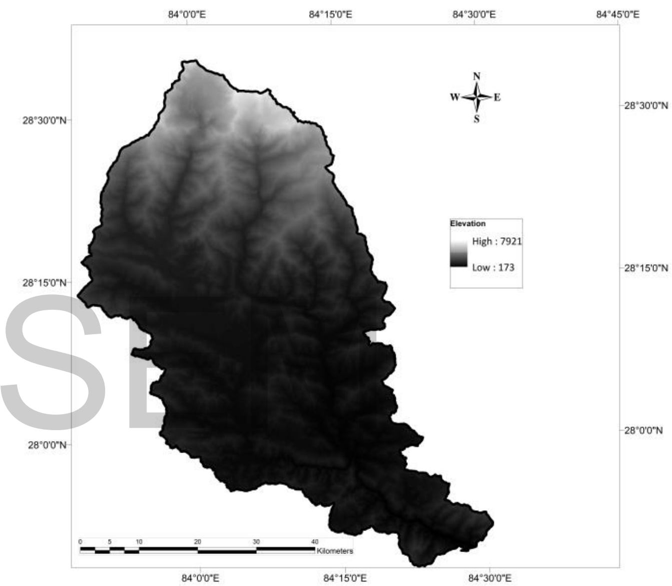

Fig. 5. Digital elevation model of Seti watershed.

2.5 Sotor Soil Data

Seven different soil types were identified inside the watershed using the Sotor data obtained from official website of Sotor Nepal (Fig. 6 (a), Table 3) dominant being Eutic Cambisols.

2.6 Land Use Data

Landsat-8 image (30 m resolution) from USGS earth explorer was reclassified to generate land use map in ArcMap. Majority of the basin area is covered by forest and shrub land. Agricultural land and barren land cover moderate area whereas; the build-up area is significantly lesser as compared to other classes (Fig. 6 (b), Table 4).

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TABLE 3: SOIL TYPE DISTRIBUTION IN SETI GANDAKI WATERSHED.

Dominant Type of Soil	% Coverage
Eutic Cambisols	48.40
Humic Cambisols	12.60
Gelic Leptosols	12.20
Chromic Cambisols	10.11
Eutric Regosols	6.50
Gleyic Cambisols	5.50
Chromic Luvisols	4.60
Total	100.00

TABLE 4: LAND USE DISTRIBUTION IN SETI GANDAKI WATERSHED.

Features	% Coverage
Snow/Glacier	9.50
Barren Land	19.23
Forest	41.60
Lake	0.21
Built-Up	0.70
Agricultural Land	5.71
Shrub Land	20.32
River	2.73
Total	100.00

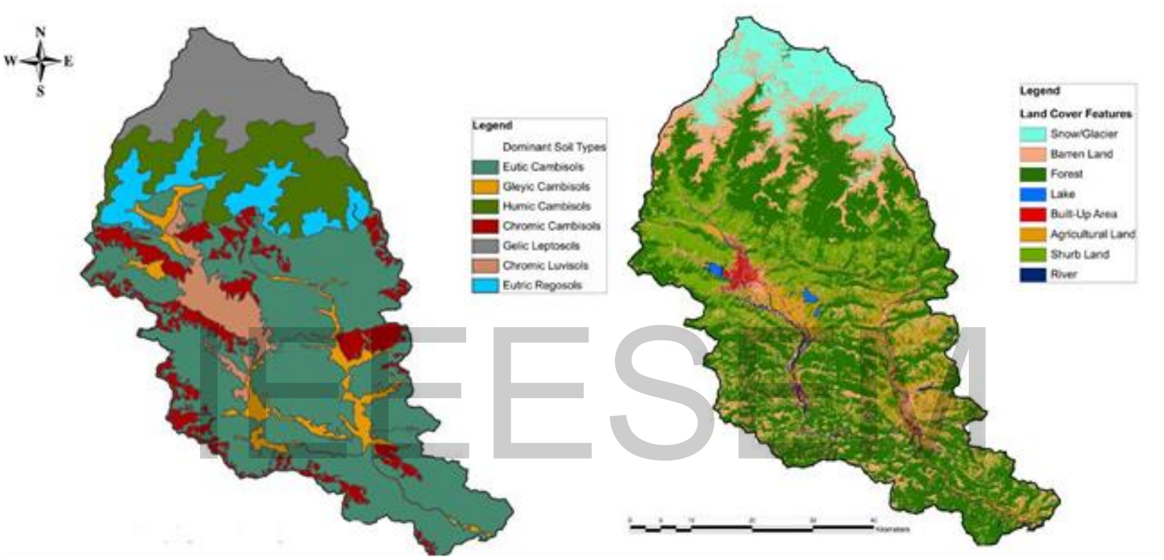

Fig. 6. a) Soil classification of Seti Gandaki watershed and b) Land Use of Seti gandaki.

3 METHODOLOGY

The DEM of the study area was used to calculate the flow direction and accumulation which was used further to analyze stream network and stream order. Based on the criteria set up for the study, the potential points were identified and gross head calculation for each site was done. SWAT model was setup, selected parameters were calibrated, and model was validated at Damauli gauge station. Using the validated SWAT model, discharge simulation at each identified potential site were done. Then, power calculation at 40 % exceedance was done for all the sites. The summation of power calculated at each site gave the overall RoR hydropower potential of the Seti Gandaki River. The overall methodology is presented in the flowchart (Fig. 7). The hydraulic head and the availability of flow are the two major components of hydro-power generation [1]. Potential sites were selected based on criterion for identification of sites and gross head for each site were calculated as elevation difference between the purposed weir location and powerhouse location.

3.1 Criterion for Identification of Sites

Selection of location started from the farthest point in the stream and moving downwards by minimum of 2 km. Since the research was based on small to medium scale hydropower locations, for selection of the potential sites for a hydropower project, the following criteria were adopted:

- Order of stream: All order of stream with the threshold drainage area of 5 km^2 was considered for the potential site selection of ROR type hydropower plant.
- Distance between Weir & Power House Plant: The minimum distance between weir/diversion dam and power house was considered no less than 2 km whereas the maximum distance not more than 5 km. The criteria of maximum distance helped in limiting the length of penstock pipe.

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- Head Availability: At least of 40m head was considered for each potential site.

Besides these, sites at a reasonable distance from the residential area, avoiding meandering locations and far from any disaster prone area were selected for sustainable hydropower approach.

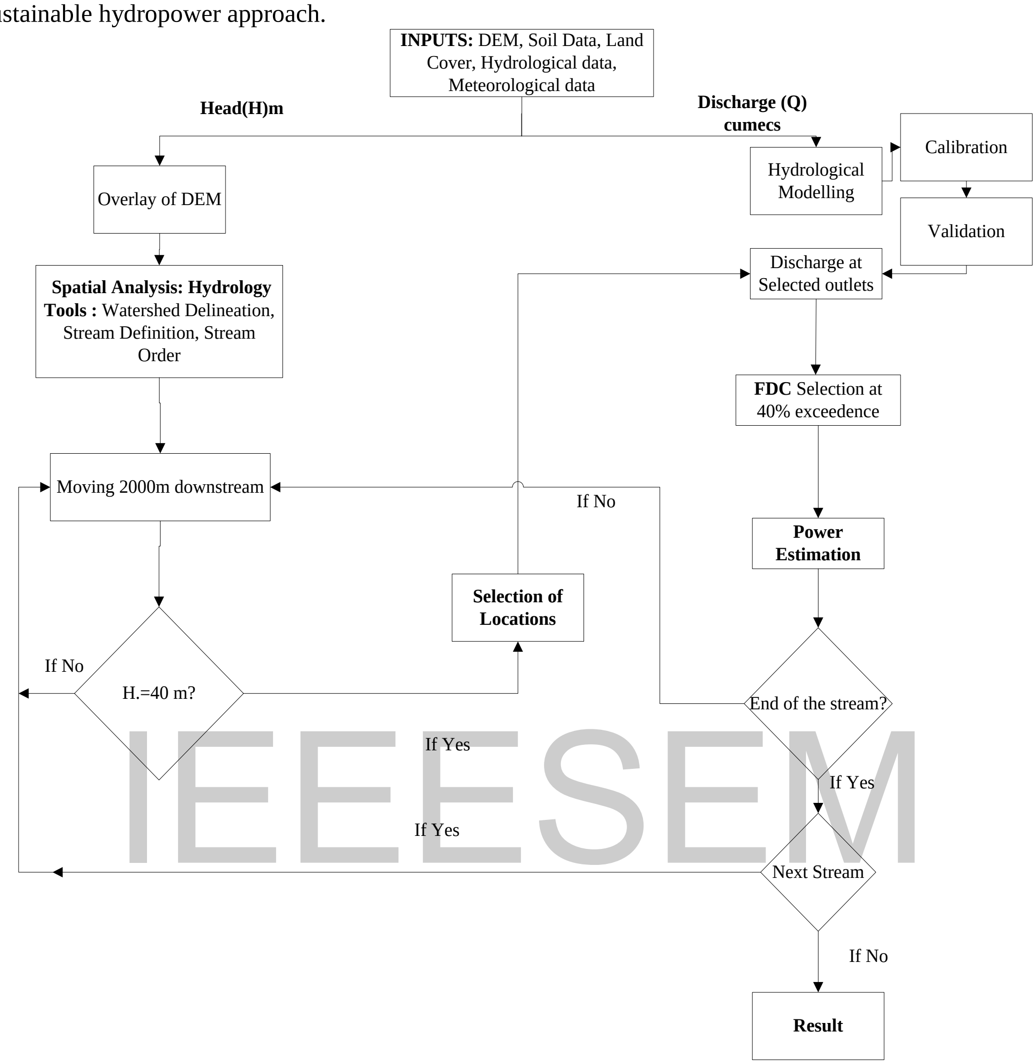

Fig. 7. Flowchart for Overall Methodology.

3.2 Hydrological Modeling

A SWAT model was setup to assess the discharge at various hydropower potential points. The model simulates the hydrological process taking into account of precipitation, evaporation, snow melt and different losses which are governed by land use and soil properties to generate runoff at various points. This runoff generated at the outlet of the sub basin was compared with the observed discharge at the gauge station for calibration and validation of the model. The framework for setting up the SWAT modeling is shown in Fig. 8.

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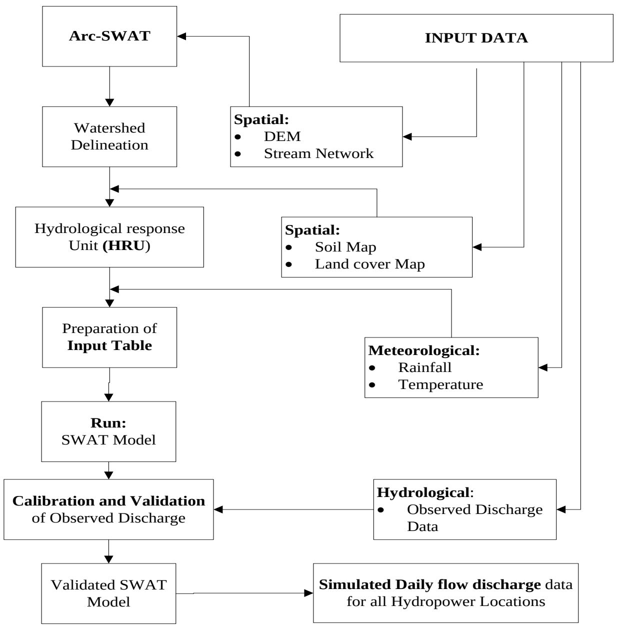

Fig. 8. Framework for hydrological modelling in SWAT.

TABLE 5: NUMBER OF POTENTIAL SITES OF HYDROPOWER ACCORDING TO GROSS HEAD.

Head Range	No of Sites
>500	17
500-400	2
300-400	8
200-300	18
100-200	41
50-100	53
40-50	32
Total	171

3.3 Evaluation of Model Performance

The model performance can be evaluated from a comparison of simulated and observed discharge data in terms of mean, standard deviation, maximum daily discharge and total discharge using commonly-used indices [9; 10]. Three statistical indices; Coefficient of Determination (R^2), Nash-Sutcliffe Efficiency (E_{NS}) and Percentage Bias (PBAIS) were used to evaluate the model performance.

$$R^2 = \frac{\Sigma(Q_{obs}-\overline{Q_{obs}})^2-\Sigma(Q_{sim}-\overline{Q_{sim}})^2}{(Q_{obs}-\overline{Q_{obs}})^2} \quad (1)$$

$$E_{NS} = 1 - \Sigma\frac{(Q_{obs}-Q_{sim})^2}{\Sigma(Q_{obs}-Q_{sim})} \times 100 \quad (2)$$

$$PBAIS = \frac{\Sigma(Q_{obs}-Q_{sim})}{\Sigma(Q_{obs})} \times 100 \quad (3)$$

where, Q_{obs} denotes the observed discharge and Q_{sim} denotes simulated discharge. And, the bar denotes mean of the values.

3.4 Power Estimation

The amount of power generated when a discharge Q is allowed to fall through a head difference of H is given by:

$$P = \rho\eta gQH \quad (4)$$

Where, P is power in watts, η is the overall efficiency of the plant, ρ is the density of water in kilograms per cubic meter =1000 kg/m^3, Q is the flow (m^3/s), g is the acceleration due to gravity = 9.81 m/s2 and H is the gross head. Here, Q was calculated as per the percentage exceedance from flow duration curve plotted using the simulated discharge data. In Nepal, generally, 40 % exceedance is considered for power estimation.

3.5 Sustainability Check

Sustainable Development is the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs as defined by the World Commission on Environment and Development (the Brundtland Commission). Sustainable Development must balance the needs of society, the economy, and the environment. Sustainable Indicators (SI) are various statistical values that collectively measure the capacity to meet present and future needs. Social, economic and environmental indicators were considered for the sustainability of the hydropower sites. Each was subdivided as; a) Economic (total power generated and minimum distance from nearest highway) b) Environmental (forest area affected and GHGs emission) and c) Social (number of households affected and agricultural land affected).

Besides Power generated, other five are minimizing quantitative indicators. The minimum distance from nearest highway was measured in

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ArcGIS overlaying road network data (source: ICIMOD, 2020). Forest area acquired and agricultural area affected were acquired by considering buffer zone of 1.5 km radius around the identified sites in land use map. For no. of households affected, the population of each VDC was acquired from official website of open data source HDX (2018). Relating the area of VDC and buffer area, relative figure of no of households affected were calculated. About 2–5 kg CO_2-eq/ MWh is emitted by small ROR hydropower sites [11]. The average of which is 3.5kg Co_2-eq/MWh is considered for the study. Standardization was done converting each indicator to single unit. [12] used a standardization method given as:

$$P_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \tag{5}$$

$$P_i = \frac{x_{max} - x_i}{x_{max} - x_{min}} \tag{6}$$

where Pi is the standardization of the indicator data; xi is the original index data for the ith original indicator data; xmax is the highest index value in overall; and xmin is the lowest index value in overall. Equation (5) is for maximization type of indicator and (6) is for minimization type of indicator. The standardized indicators were multiplied with respective weights and resultant final weight of each was employed to rank the sustainability of any potential point under different probable scenarios.

4 RESULTS AND DISCUSSION

4.1 Preprocessing of DEM

The raw DEM was first filled to generate flow accumulation and flow direction raster sets. With the threshold area 5 km^2 Strahler method identified five categories of stream order in the river network of Seti Gandaki River (Fig. 9).

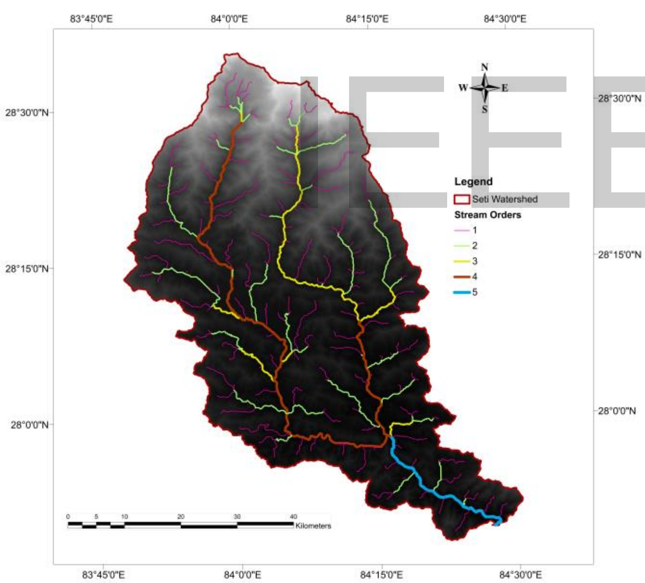

Fig.9. Stream orders in study watershed.

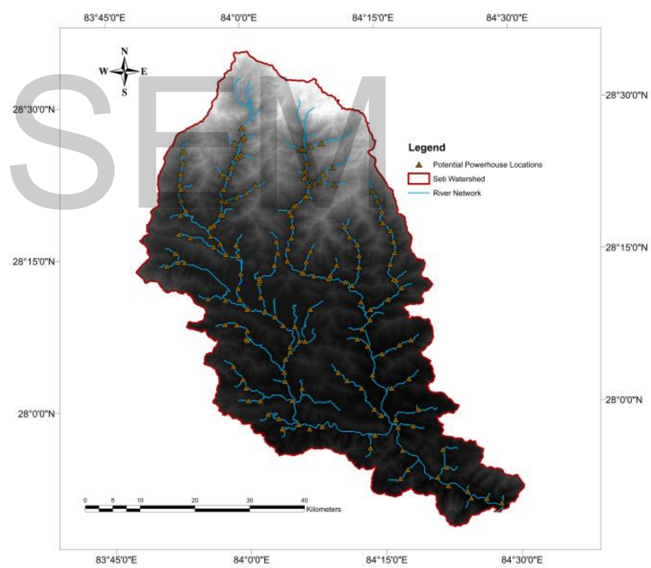

Fig. 10. Potential Powerhouse locations in study watershed.

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4.2 RoR Hydropower Potential Sites

A total of 189 sites were spotted for potential sites. Out of which, 18 sites were spotted within the glacier buffer zone hence, were discarded. Out of remaining 171 points (Fig. 10), 88 were spotted along the tributaries of Seti River, 72 were spotted along the tributaries of Madi River and 11 were spotted downstream after the confluence of Seti and Madi River.

Most of the hydropower sites were identified in the elevation range (500 - 1000) m. The elevation of 243m was the lowest and 2955 m was the highest elevation for hydropower sites. Also, the gross head of the potential sites was observed in the range (40-1000 m. Most of them have the gross head range of (50-100) m (Table 5).

4.3 SWAT Model

The watershed delineation of Seti Gandaki watershed in SWAT generated area of 2941.43 km^2. With the threshold area of 5 km^2, 334 sub basins were generated according to the automatically generated outlet based on points of confluences (Fig. 11).

Land use map, soil map and slope data, derived from DEM are required for the definition of Hydrologic Response Unit (HRU). Within 334 sub basins, 4143 HRUs were generated by SWAT Model.

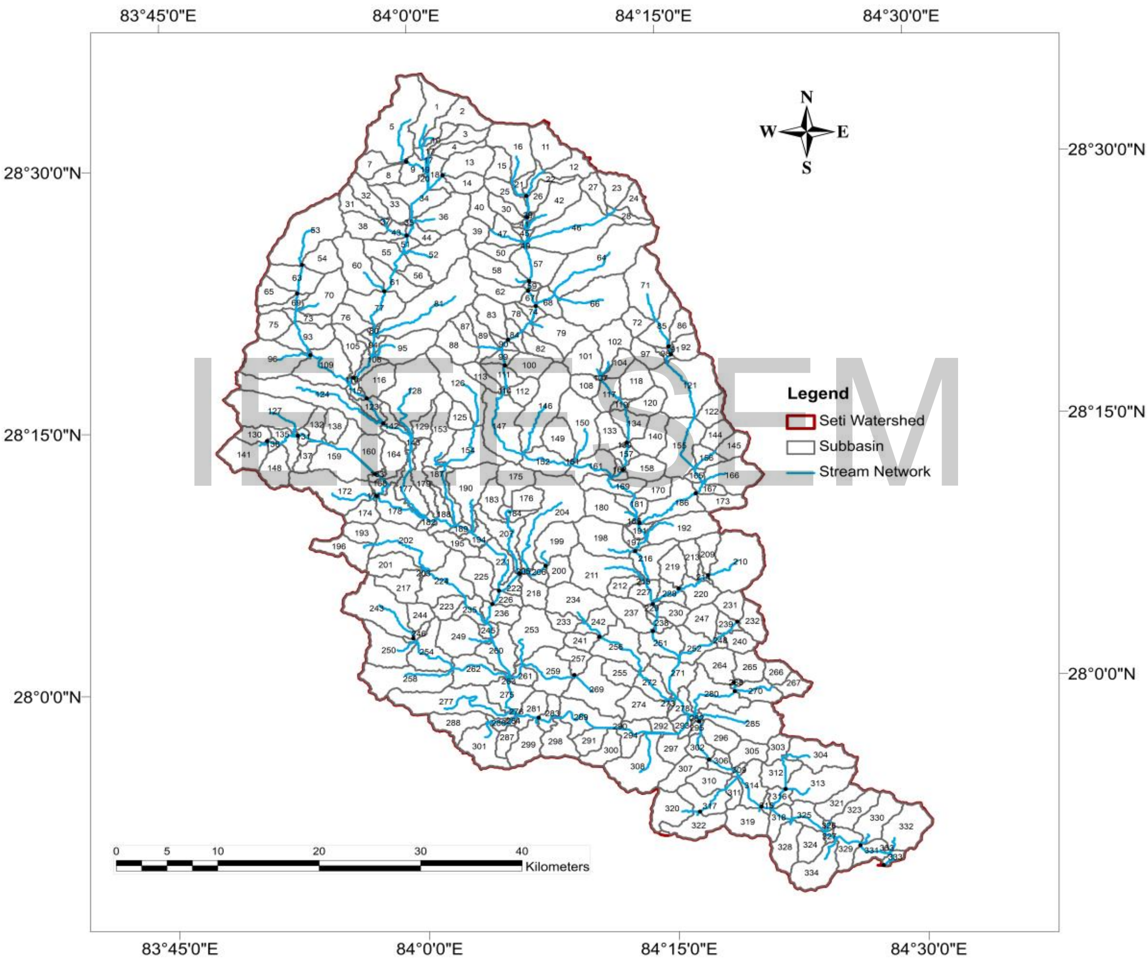

Fig. 11. Watershed Delineation of the study area.

4.4 Sensitivity Analysis

Sensitivity analysis is carried out to examine the relative changes in the model output with respect to changes in model input variables. From the sensitivity analysis, it is possible to determine which variables need to be precisely estimated to make an accurate prediction of watershed yields [13].

Using Sufi-2 SWAT-CUP, the parameters like CH_N2, ALPHA_BF, CH_N1, CH_K2 and CN2 were identified as the most sensitive parameters (Table 6). The most sensitive parameters have the p value less than 0.05 and also high t value [14].

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4.5 Calibration and Validation

Model calibration is the adjustment of model parameters within a recommended range so that the model output matches the observed data as closely as possible. The calibration tool of Arc SWAT enables adjustment of different parameters through user intervention. These parameters can be adjusted manually or automatically. Sequential uncertainty fitting-2 algorithm (SUFI-2) of SWAT-Calibration Uncertainty Program (SWAT-CUP) tool was employed for calibration and sensitivity analysis of parameters in this study.
In SUFI-2, the parameter optimization is applied to a parameter set and the parameter uncertainties are described by the final ranges of the parameter sets [14] and generally, the optimization algorithms include the simplex method, random searching algorithm and competitive co evolutionary algorithm [15], and the global analysis methods of LH (Latin-Hypercube) is used in SUFI-2 [14].
In this study, the discharge data for 2000-2010 were used for calibration of the model. The SWAT model was calibrated and validated for the flow at Damauli station (Station no. 430.5) situated at Damauli, Tanahun. The data for the flow was available from 2000 to 2015. After statistical data analysis, significant change in rainfall runoff relationship and abrupt deviation in double mass curve was not identified. Hence, considering the availability of short time frame data, the calibration and validation period was separated such that two-third of available data were used for calibration and one-third were used for validation. The calibration and validation period were selected in such a way that they represented both dry and wet year and extreme events. The calibration period for stream was 2000- 2010 with three years of warm-up from 1997-1999 and validation period was from 2011- 2015.
Thirty-one parameters that were selected based on desk study for runoff simulation were calibrated and sensitive parameters respectively ranked are presented in Table 6. The calibration of model was initiated with comparing the observed daily flow with the simulated flow at the outlet. The sensitive parameters were adjusted in the permissible range to obtain the best fit of the observed and simulated flow. Fig. 12 and Fig 13 show the plot of daily calibration and validation with rescpecte to observed discharge and observed rainfall respectively.

TABLE 6: ADJUSTED PARAMETERS FOR SWAT CALIBRATION, THEIR SENSITIVITY RANK AND THEIR FITTED VALUE.

Rank	Parameter	Definition	Fitted Value	Range
1	CH_N2	Manning's "n" value for the main channel.	0.23	0.22-0.25
2	ALPHA_BF	Baseflow alpha factor (days).	0.29	0.28-0.35
3	CH_N1	Manning's "n" value for the tributary channels.	0.18	0.17-0.20
4	CH_K2	Effective hydraulic conductivity in main channel alluvium.	463.6	460.15-464.56
5	CN2	SCS runoff curve number f	0.23	0.22-0.25
6	LAT_TTIME	Lateral flow travel time.	23.18	23.17-25.05
7	TLAPS	Temperature lapse rate.	-0.41	-0.41--0.38
8	SURLAG	Surface runoff lag time.	0.63	0.59-0.63
9	SOL_BD	Moist bulk density.	0.29	0.29-0.3
10	GW_SPYLD	Specific yield of the shallow aquifer (m^3/m^3).	0.34	0.34-0.35
11	GW_DELAY	Groundwater delay (days).	8.11	7.78-8.83
12	SOL_AWC	Available water capacity of the soil layer.	0.06	0.05-0.06
13	GW_REVAP	Groundwater "revap" coefficient.	0.07	0.07-0.08
14	SNOCOVMX	Minimum snow water content that corresponds to 100% snow cover.	118.63	112.06-146.61
15	GDRAIN	Drain tile lag time.	88.99	88.30-89.30
16	GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm).	1140.16	1134.38-1167.08
17	RCHRG_DP	Deep aquifer percolation fraction.	0.02	0.01-0.04
18	ESCO	Soil evaporation compensation factor.	0.24	0.23-0.25
19	SHALLST	Initial depth of water in the shallow aquifer (mm).	19575.25	18492.92-20327.39
20	EPCO	Plant uptake compensation factor.	0.08	0.084-0.09
21	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).	422.2	421.7-424.9
22	SLSUBBSN	Average slope length.	11.01	10.96-11.12
23	CH_L1	Longest tributary channel length in subbasin.	2.18	2.06-2.54
24	OV_N	Manning's "n" value for overland flow.	13.75	13.60-14.21
25	SMFMN	Minimum melt rate for snow during the year (occurs on winter solstice).	1.53	1.504-1.611
26	SOL_ALB	Moist soil albedo.	0.2	0.19-0.2
27	SOL_K	Saturated hydraulic conductivity.	-0.13	-0.13--0.12
28	DEEPST	Initial depth of water in the deep aquifer (mm).	13090.77	12540.10-13473.44
29	CANMX	Maximum canopy storage.	15.45	14.00-15.7
30	TIMP	Snow pack temperature lag factor.	0.16	0.15-0.32
31	SFTMP	[OPTIMAL] Snowfall temperature.	-0.75	-1-1

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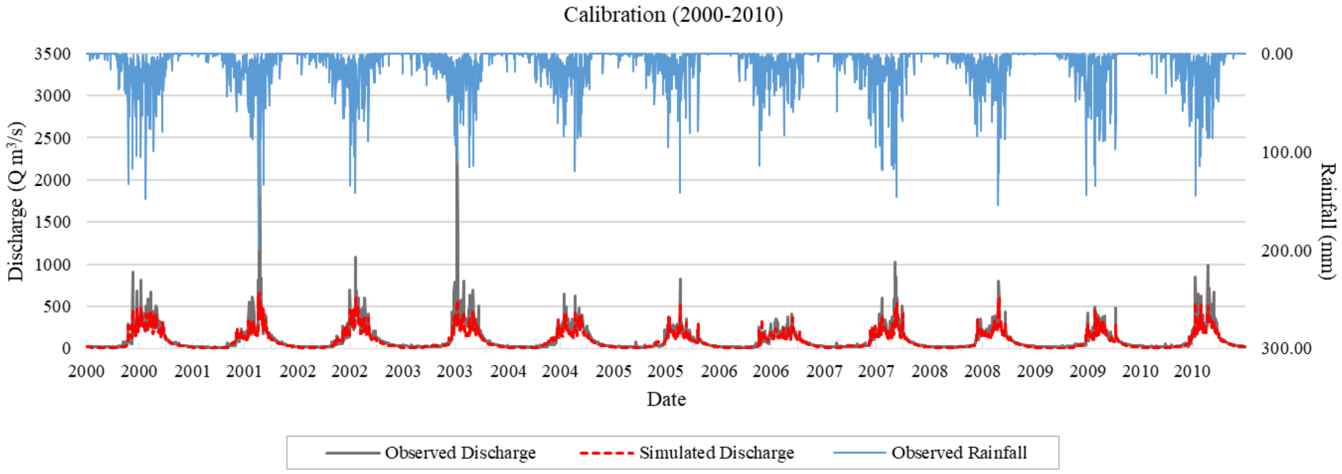

Fig. 12. Daily flow calibration (2000-2010) at Damauli station.

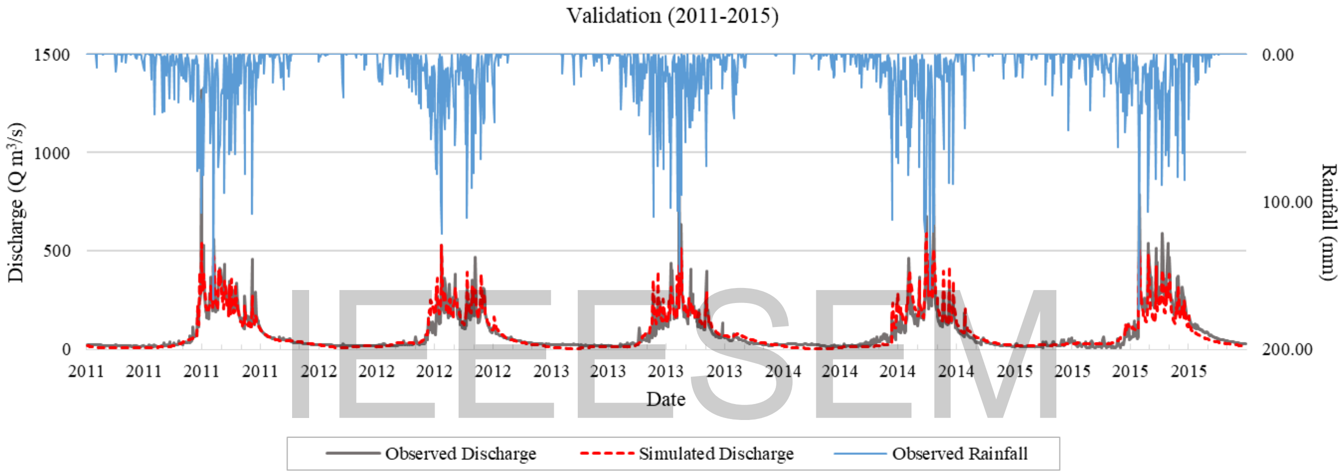

Fig. 13. Daily flow validation (2011-2015) at Damauli station.

Graphically, it can be observed that the simulated flow is replicating observed flow in almost all the years with the perfect match of flow peaks and low flows of both simulated and observed flows.

Validation is the process of determining the degree to which a model or simulation is a correct representation of the observed behavior from the perspective of the intended uses. The values of simulated discharge at a specified location are compared with the observed discharge for validation of the model [10].

The validation of the model discharge was also done in Damauli station (Station no. 430.5). Fig. 14 and Fig. 15 show the daily calibration and validation statistically. Similar to calibration period, simulated flow matched observed flow in almost all the years during validation too.

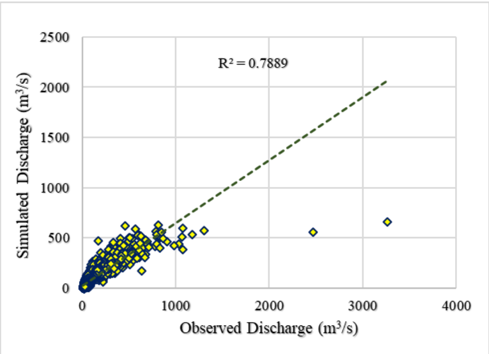

Fig. 14. Coefficient of determination for daily flow calibration (2000-2010) at Damauli station.

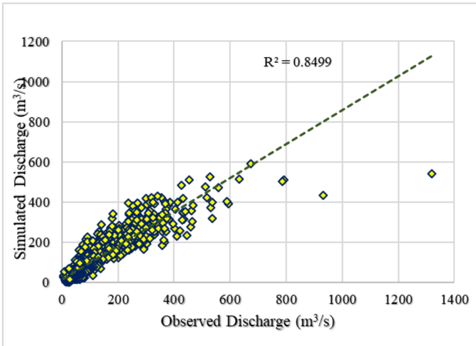

Fig. 15. Coefficient of determination for daily flow validation (2011-2015) at Damauli station.

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4.6 Statistical Evaluation of Model

The performance of the model is considered to be satisfactory if both R^2 and E_{NS} are greater than 0.6 for each observation and simulation [16;17] and PBIAS value is less than 15 % [17;18].
The overall summary of statistical evaluation of model (Table 7) showed a good performance of the model. The comparatively higher PBAIS in calibration period than in validation period was observed because of use of latest DEM, soil data and land use data for model preparation.

4.7 Performance during Monsoon Season and Dry Season

The overall performance of the SWAT model was judged by statistical analysis of the discharge data for all the years splitting into respective monsoon season and dry season too (Table 8, Fig. 16 and Fig. 17). High values of R^2 (0.79), ENS (0.76) indicated a close relationship between the observed and modelled discharge, while PBAIS (13.59) indicated that although simulated discharge is under estimated (positive PBAIS), the simulated discharge by the model is well within the acceptable limit.
The dry season flow of perennial rivers is most important for water availability of a river system: in the dry season, water availability in the river will be at a minimum, so dry season analysis is important for the design and operation of hydropower projects [1]. Hence, the performance of the model was evaluated for dry period data. The model performance was also evaluated for monsoon period. The scatter plots showed that the points are fairly evenly located around the 1:1 line (Fig. 17). A high value of E_{NS} (0.81, 0.73) indicated a reasonably good agreement between the observed and simulated discharge, and PBAIS (12.64, 14.46) indicated that the overall predicted discharge within the acceptable limit [17;18] for monsoon flow too.

TABLE 7: RESULT SUMMARY OF CALIBRATION AND VALIDATION FOR DAILY AND MONTHLY TIME STEP.

	Calibration (2000-2010)		Validation (2011-2015)	
Statistical Evaluation Criteria	Daily Time step	Monthly Time Step	Daily Time step	Monthly Time Step
R^2	0.79	0.96	0.85	0.94
NS	0.74	0.90	0.85	0.94
PBAIS	14.64	14.55	2.19	2.18

TABLE 8: STATISTICAL MODEL PERFORMANCE ANALYSIS FOR THE COMBINED PERIOD, DRY PERIOD AND MONSOON PERIOD FOR THE YEARS (2000-2015).

Statistical evaluation Criteria	Combined all years	Monsoon Season	Dry Season
R^2	0.79	0.83	0.79
NS	0.76	0.81	0.73
PBAIS	13.59	12.64	14.46

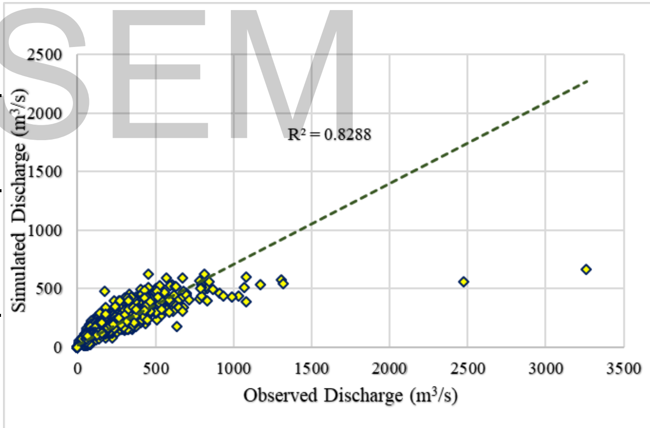

Fig. 17. Comparison between simulated and observed discharge for the monsoon period.

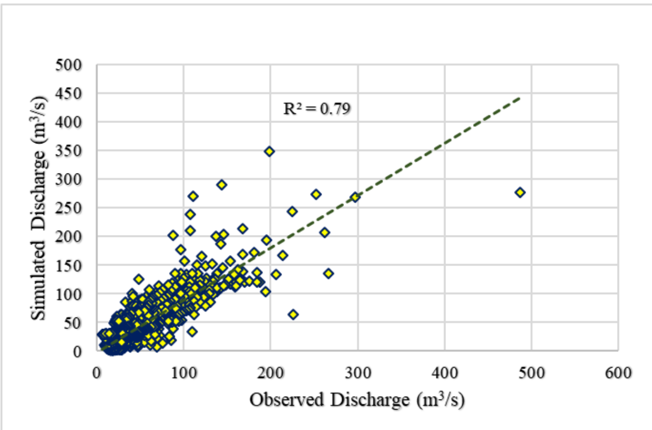

Fig. 16. Comparison between simulated and observed discharge for the dry period.

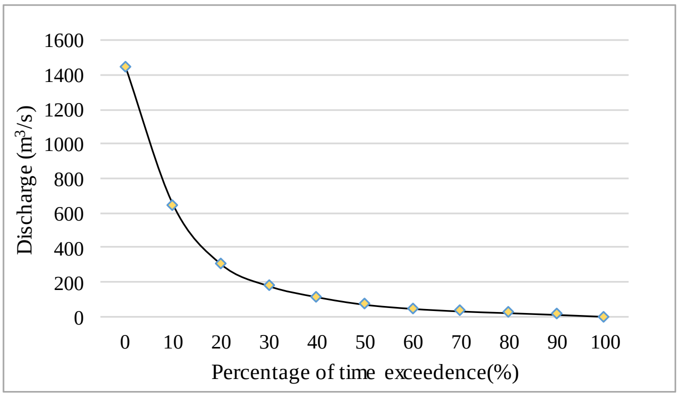

Fig. 18. FDC at the watershed outlet

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4.8 Hydropower Assessment using Flow duration curve

Flow-duration curve (FDC) is the basic tool for hydropower planning. It is a plot of discharge vs. percent of time that a particular discharge was equaled or exceeded. The validated SWAT model simulated discharge data at each sub basins outlets. As mentioned earlier, flow out of 334 sub-basins generated by SWAT individually were applied to create their respective FDCs. The FDC curve of sub basin with final outlet is represented in Fig. 18.

As discussed in the previous section 171 potential sites were selected. The FDC for a site was taken from a sub basin such that the plat utilizes the discharge of the sub basin. Generally, FDC construction requires long-term flow data. However, in the present study, 19 years (2000-2018) simulated discharges have been considered due to the unavailability of long term weather data in the study location. The physically based hydrological model describes the physical processes of the watershed. It is assumed that the simulated discharge provided by hydrological model would appropriately represent hydrological phenomena over a long period of time. The assumption has valid ground, because not much change in the land use and land cover are anticipated in the study watershed. FDCs enabled to determine discharge corresponding to varying degree of dependability. Normally for power estimation, 40% dependability discharge values are considered and for this study four levels (40%, 50%, 60% and 95%) dependability flows have been considered (Table 9). The energy calculation was done assuming a full year operation of the projects.

After characterizing the streams in terms of head and FDC, the available hydropower at the identified sites were estimated using established power equation. The discharge used for power calculation is after deduction of environmental flow. The environmental flow is taken as 10% of average monthly discharge [19]. This is also according to the hydropower development policy introduced in 2001 of Nepal.

The environmental flow was deducted from the Q40 of the sub basin outlet and the final discharge was calculated assuming 90 % overall efficiency of the plant.

Out of 171 potential sites, only 29 were identified as small hydropower projects, other as medium hydropower projects (Table 10). As mentioned earlier, only naturally available sites, where power could be generated without constructing reservoir, were identified. The objective of the study was to demonstrate the strength of GIS and modeling techniques for assessment of hydropower potential in inaccessible region of Western Nepal. The sites identified in the present investigation are only theoretically potential sites identified based on model outputs. Further investigation will be required to identify the practically feasible sites.

4.9 Comparison with DOED assessed HP Sites

From the DOED (Department of Electricity Development, Nepal) assessed hydropower potential sites 42 potential sites (including operating, issued survey license and issued generation license) were identified in the study watershed with total power capacity of 608.254 MW. Whereas this study identified 171 sites with total potential of 529.97 MW. Fig. 19 shows the different hydropower sites in the East Seti watershed. From the figure, it can be observed that although locations are not the exact same, but they are very near between the results and government assessed sites. Also the power potential was observed very near to the DOED sites.

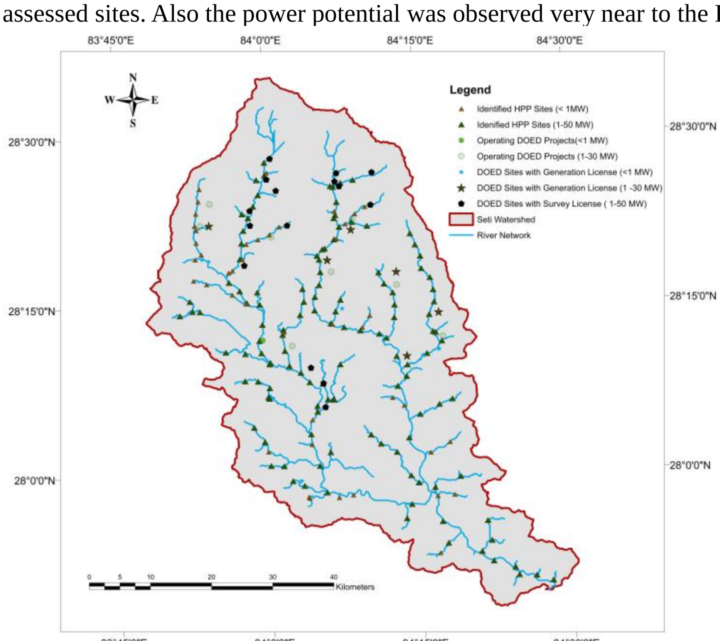

Fig. 19. DOED Vs Research assessed hydropower sites.

TABLE 9: ESTIMATED THEORETICALLY ACHIEVABLE HYDROPOWER AT THREE LEVELS OF DEPENDABILITY IN SETI GANDAKI RIVER, MW.

% Exceedance	Power (MW)	Power (GWh)
95	73.24	641.58
60	186.51	1633.82
50	288.42	2526.56
40	529.97	4642.53

TABLE 10: CATEGORY WISE BREAK-UP OF ESTIMATED HYDROPOWER SITES IN SETI GANDAKI RIVER AT 40% DEPENDABILITY FLOW.

Category	No. of sites	Total Power (MW)	%
15-30	20	92.3	17.42
5-15	24	170.64	32.20
1-5	98	244.76	46.18
0.5-1	25	18.02	3.40
< 0.5	4	4.25	0.80
Total	171	529.97	100

4.10 Sustainability check

Fig. 20 shows the standardized value of each; economic, environmental and social indicators for top 50 hydropower sites in terms of power. Fig. 20 (a) is the graphical distribution of standardized value of economic indicators (power and shortest distance from nearest highway for top 50 hydropower locations in terms of Power. Similarly, Fig. 20 (b) and Fig. 20 (c) are the graphical representation of environmental (Forest area in buffer zone and possible Co2 emission) and social indicators (No. of households in buffer zone and Agricultural area in buffer zone) for top 50 hydropower locations in terms of power. Nearer the value to 1, more sustainable is the selected site in terms of respective indicator.

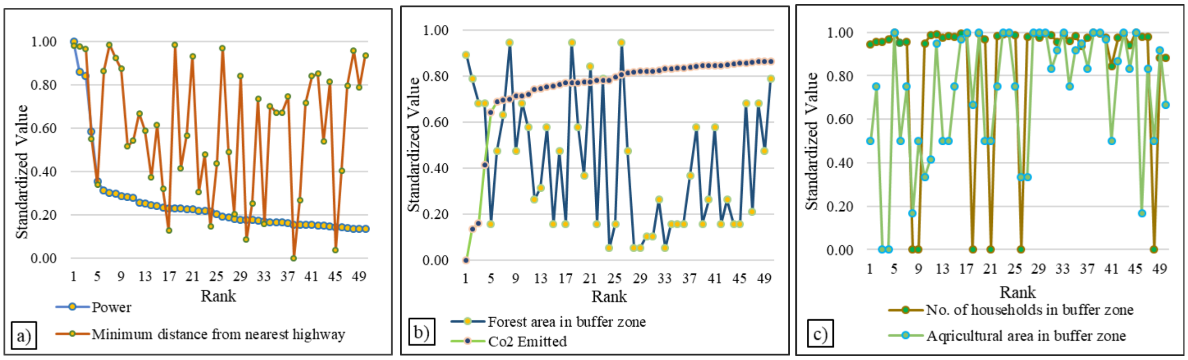

Fig. 20. a) Standardized Economic Indicators, b) Standardized Environmental Indicators and c) Standardized Social Indicators; for top 50 hydropower locations.

After the standardization of each Sustainability indicator (SI) was done for individual site, weights were added for each indicator. The weights were given according to scenarios with realistic assumptions. Four cases were studied: a) Equal weightage, b) Economic Scenario, c) Environmental scenario, and d) Social Scenario. In the first case, all of them were given equal weight, then in second the weight of economic scenario was increased and less weight were added to other two scenarios, and likewise different scenarios was considered with different assumptions with one indicator being biased to the other two. Different weights of indicator considering different scenarios are presented in the Fig. 21.

All the standardized value of each sub indicators of different scenarios was multiplied by weights to give the final value for each scenario and they were ranked according to the value in each scenario. Fig. 22 shows the top 20 potential points in each scenario. Although economic scenario is prioritized in developing country like Nepal, if environmental and social sustainability is not considered, long run benefit from the plant may not be obtained. The total potential of top 50 sites in economic scenario was observed to be the highest, followed by equal weightage scenario, social scenario and least total potential was observed in environmental scenario (Table 11). Sustainability not always focuses on maximum economic benefit but balances the overall economic social and environmental factors.

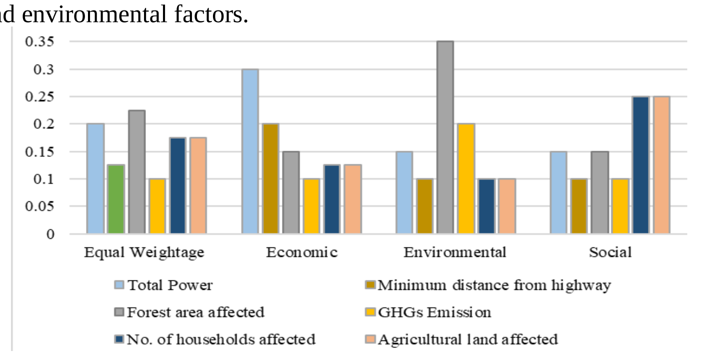

Fig. 21. Weight of Indicators considering different sustainability scenarios.

TABLE 11: TOTAL POWER POTENTIAL OF TOP 50 SITES UNDER DIFFERENT SCENARIOS.

Scenario	Total Potential of Top 50 sites(MW)
Equal Weightage	180.33
Economic Scenario	200.62
Environmental Scenario	161.42
Social Scenario	168.03

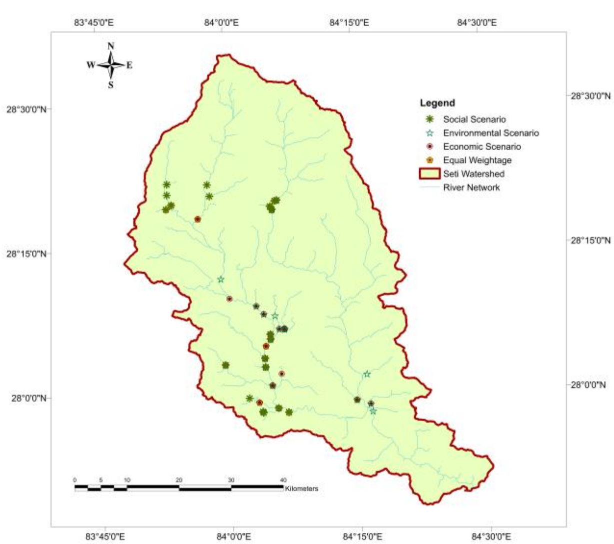

Fig. 22. Top 20 Hydropower sites in all four sustainability scenarios.

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4.11 Comparison with previous Studies on Hydropower Assessment

[6] estimated the total RoR potential of the Seti Basin to be 1257.5 MW and [20] estimated the total potential of the Seti Basin to be 745.87 MW. Whereas, estimated potential of Seti basin is 529.97 MW in this study.

The discharge estimation on both the studies was based on relative interpolation or hydrological analysis by mere use of discharge data from gauging stations. Whereas, in this study, discharge was simulated at sub basins level individually. In course of that, since model have underestimated discharge (PBAIS 13.59) the simulated discharge used for power estimation was assumed to be less than exact discharge. This has resulted to smaller figure of total power potential. Regarding the use of spatial data, both the studies used 100 m resolution data whereas, this study used 30 m resolution data. Besides that, head was calculated as the difference of elevation stream origin and confluence to next stream in [6]. This would address extra head that won't contribute for exact hydropower generation. Also, river bed gradient was not considered in both the studies as a majority of stream lengths are not usually feasible for hydropower plants. In addition to that, environmental flow considerations were not made. All these accumulated errors were avoided in this study. In addition to that, 31 parameters were calibrated for the Seti Gandaki watershed using Sufi-2. It was not done on individual basin level for this watershed before. This can be an important tool for watershed based study in this watershed in future.

Besides, sustainable hydropower project sites are identified considering different scenarios, which is a very important aspect of hydropower infrastructure that needs to be explored. Hence, it is expected that the results presented in this study are much closer to reality.

5 CONCLUSIONS

This framework consisting of SWAT and Arc GIS purposes a methodology to identify the hydropower sites of large area basin with remote access. Calibration and validation of the SWAT model for the Seti gandaki watershed have shown that the model is able to give realistic output for assessment of hydropower potential by generating flow at selected potential sites. The study area has few river gauging stations and meteorological stations, which is a major obstacle in correctly assessing hydropower potential of the catchment. A well-calibrated distributed model can be used to assess the flows at various locations in the catchment. The results of the sensitivity analysis revealed that the important parameters of the SWAT model in respect of their sensitivity for the Seti gandaki watershed are: (a) Manning's "n" value for the main channel (CH_N2); (b) Groundwater base flow alpha factor (days) (ALPHA_BF); (c) Manning's "n" value for the tributary channels (CH_N1); (d) Effective hydraulic conductivity in main channel alluvium (CH_K2); and (e) SCS runoff curve number (CN2). A total of 171 sites with 529.97 MW of hydropower capacity at 40% dependability were located which is a huge power capacity by only using natural head and discharge. This energy should be tapped and be used for the economic benefit of the country. Run of- river (ROR) hydropower plants, utilizing instantaneous river flow and having no pondage at the upstream headworks, were suggested for the study area. Besides, sustainability was explored for each identified hydropower sites making the use of administrative and spatial data. The ranking of hydropower with different sustainability scenario was done in the research. Government can plan to construct hydropower prioritizing scenario according to its policy and involved stakeholders.

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