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Assessing Hydropower Potential in Nepal's Babai River Basin: An Integrated GIS and SWAT Hydrological Modeling Approach

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Abstract. Nepal has great potential for hydropower development because of its steep landscape, many rivers, and favorable climate. This study examines the run-of-river (RoR) hydropower potential of the Babai River Basin using a combined approach of Geographic Information System (GIS) tools and the Soil and Water Assessment Tool (SWAT) model. The basin was divided into sub-basins using a 30 m resolution Digital Elevation Model (DEM), and important data such as soil, land use/land cover, slope, and weather records were used in the analysis. The SWAT model was calibrated for the period 1990–2000 and validated for 2000–2006 using the SUFI-2 method in SWAT-CUP, and its performance was evaluated using R^2, Nash–Sutcliffe Efficiency (NSE), and Percent Bias (PBIAS). The results showed a satisfactory range for the calibration and validation processes. Hydropower potential was estimated using simulated river discharge and available head at different flow levels, and the total potential of the basin was found to be about 80.3 MW at Q_{40}. Two technically suitable sites were also identified, with estimated capacities of around 8.3 MW and 4.8 MW. Overall, the study shows that the Babai River Basin has good potential for small- to medium-scale hydropower development and provides a practical method for hydropower planning in regions with limited data.

Keywords: Hydropower potential, GIS, SWAT model, Run-of-river, Babai River Basin.

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1. INTRODUCTION

Nepal has one of the highest hydropower potentials in the world due to its steep topography, large elevation differences, and more than 6,000 rivers. Although the theoretical capacity is estimated at around 83,000 MW, only a small portion has been developed so far [1]. Traditionally, hydropower development and studies have mainly focused on large snow-fed rivers such as the Koshi River and Karnali River, where large-scale projects are more common. However, this study shifts attention toward the rain-fed Babai River Basin, which originates in the Mahabharat range and offers strong potential for Run-of-River (RoR) hydropower development.

The research gap addressed in this study is the lack of reliable hydrological data and limited studies on the Babai River Basin, making it difficult to estimate streamflow and hydropower potential accurately. The novelty of this study lies in the use of the SWAT model integrated with GIS, which is suitable for data-scarce basins as it simulates hydrological processes using available spatial and climatic data, along with dependable flow estimation and knickpoint analysis to assess hydropower potential [2].

2. STUDY AREA AND DATA

2.1. **Study Area.** The Babai River Basin, located in Lumbini Province, covers about 3,227.74 km^2 and shows a sharp elevation range from 3,000 m in the Mahabharat range down to 150 m in the Terai plains. The basin is located between latitudes 27°30'N to 28°40'N and longitudes 81°30'E to 82°30'E. It is a rain-fed basin dominated by the South Asian monsoon, receiving nearly 80% of its annual rainfall between June and September [3].

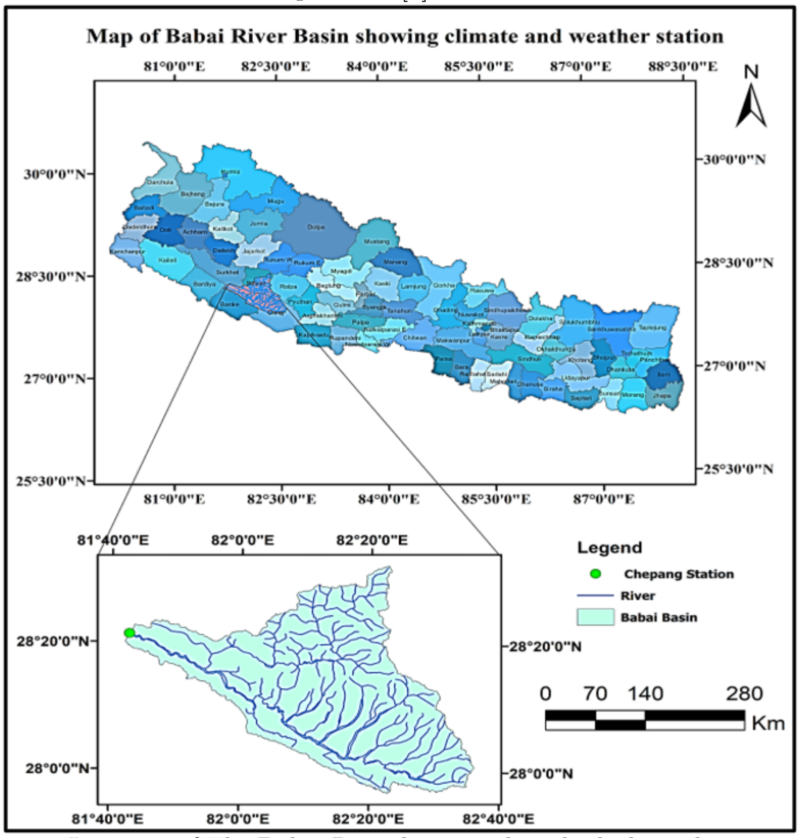

FIGURE 1. Location of The Babai River basin with its hydrological station (Chepang station)

2.2. **Data Sources.**

2.2.1. *Digital Elevation Model (DEM).* The Digital Elevation Model (DEM) is the foundational dataset for watershed delineation. In this study, a high-resolution (30 m) DEM was utilized from ASTER Global DEM. The DEM is instrumental in extracting topographical characteristics such as stream networks, sub-basin boundaries, and flow accumulation.It also facilitates the determination of hydraulic heads.

2.2.2. *Soil and Land Cover Data.* The soil map was obtained from the SOTER-Nepal database. This dataset provides critical physical attributes such as soil texture, depth, bulk density, and hydraulic conductivity (SOL_K). The LULC data for the Babai basin (30 m resolution) was sourced from ICIMOD. Land cover determines Manning's roughness coefficient (n) and the SCS Curve Number (CN_2), which influence the velocity of overland flow and evapotranspiration rates. The classification includes categories such as Broadleaved Forest, Agricultural land, Grassland, and Water bodies.

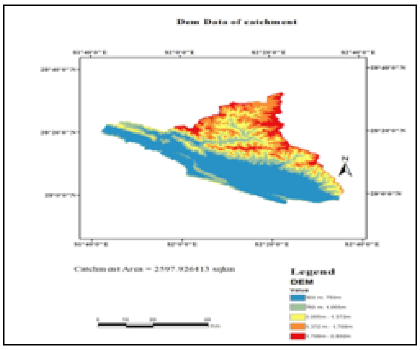

FIGURE 2. DEM OF Babai Basin

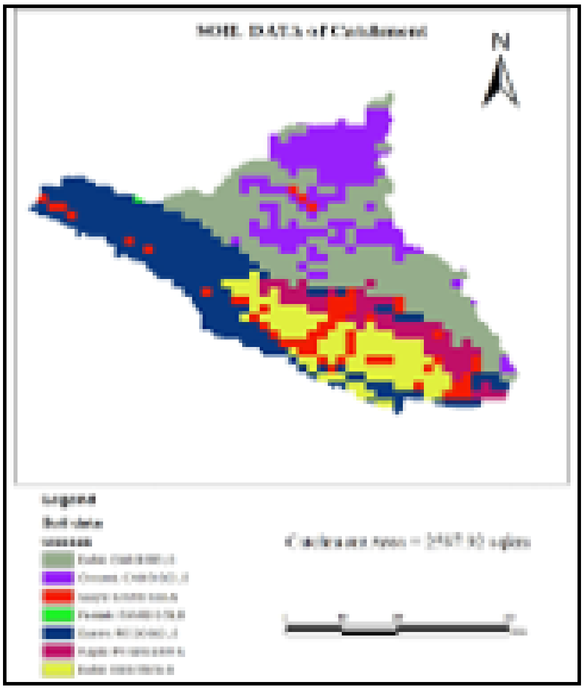

FIGURE 3. Soil data of Babai basin

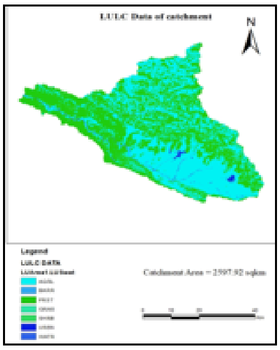

FIGURE 4. LULC data of Babai basin

2.2.3. *Streamflow and Meteorological Data.* Hydrological modeling requires continuous time-series data for calibration and validation. For this study, the primary data was sourced from the Department of Hydrology and Meteorology (DHM), Nepal. Out of the 11 meteorological stations in the study area, four stations measure the daily minimum and maximum temperature, and all seven stations measure daily rainfall data, as shown in Figure ??. Missing data were handled using the long-term average method to maintain data consistency. Although hydrological modeling ideally requires at least 30 years of data, this study used 17 years (1989–2006) due to the limited availability of continuous and reliable discharge records at the Chepang Hydrological Station.

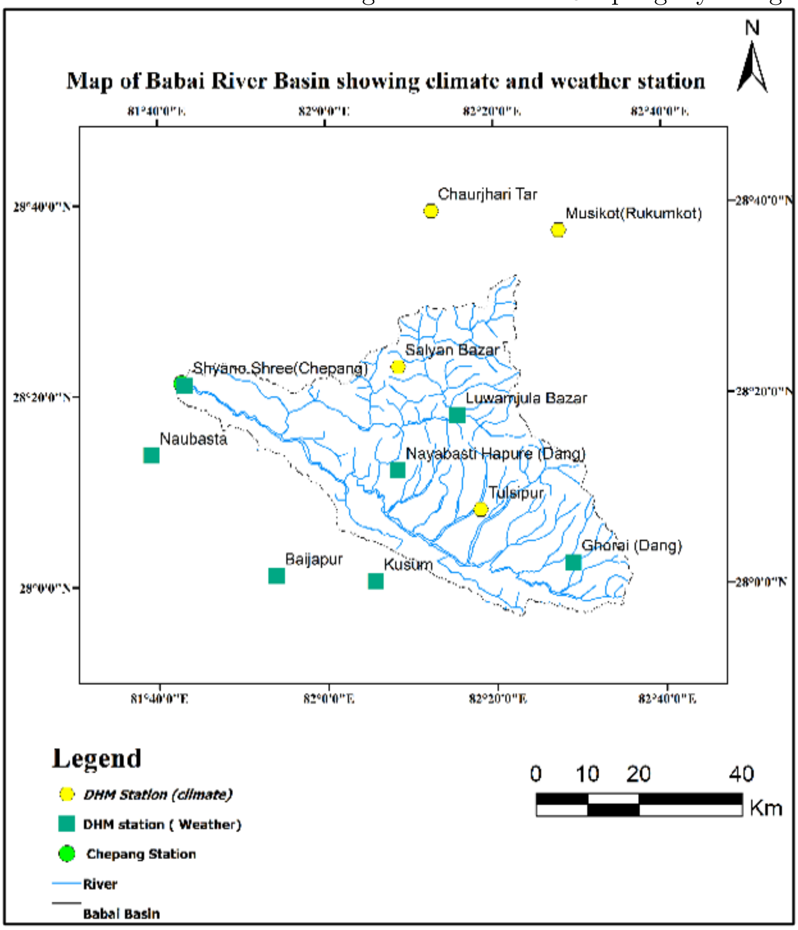

FIGURE 5. Babai River Basin Showing DHM Station (Climate and Weather

Table 1. Basic Info of Climate Stations Near Babai Basin

Station No	**Name**	**Latitude (°N)**	**Longitude (°E)**	**Elevation (m)**
0508	Tulsipur_TMP	28.13175	82.30278	683.00
0511	SalyanBazar_TMP	28.38210	82.14225	1557.00
0513	Chaurjharitar_TMP	28.65399	82.21031	992.67
0514	Musikot_TMP	28.61844	82.46220	1694.92

Table 2. Basic Info About Weather Stations Around Babai Basin

Station No	**Name**	**Latitude (°N)**	**Longitude (°E)**	**Elevation (m)**
0407	Kusum_PCP	28.00750	82.09389	200.00
0412	Naubasta_PCP	28.23023	81.65270	161.00
0413	Shyanoshree_PCP	28.35306	81.79170	510.00
0414	Baijapur_PCP	28.18360	81.89852	150.00
0507	Nayabasti hapre_PCP	28.02132	82.13939	685.00
0515	Ghorai_PCP	28.05000	82.50000	725.00
0512	Luwamjula bazar_PCP	28.29676	82.25801	895.00

Table 3. Basic Info About Hydrological Station in Babai River

Station No	**River Name**	**Location**	**Latitude (°N)**	**Longitude (°E)**
289.95	Babai River	Chepang	28.35674	81.71374

3. METHODOLOGY

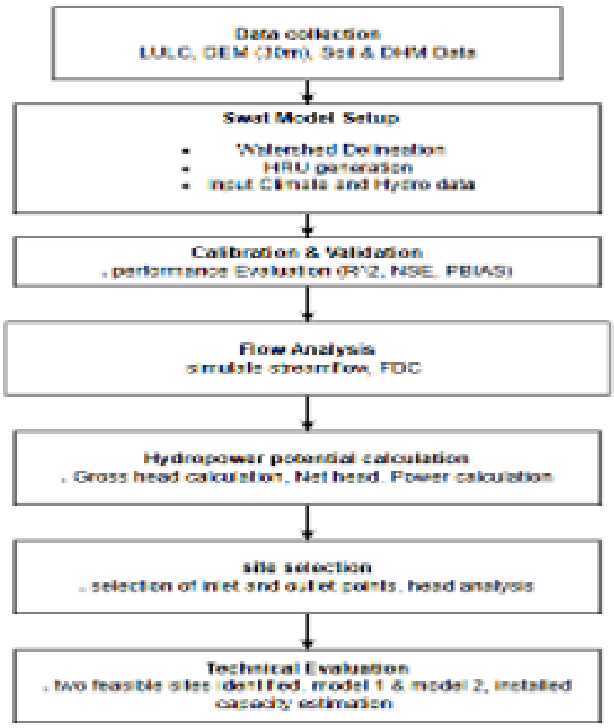

Figure 6. Methodological Flowchart

3.1. **SWAT Model Setup, Calibration, and Validation.** The hydrological processes of the Babai River Basin were simulated using the Soil and Water Assessment Tool (SWAT), a spatially semi-distributed, physically based, continuous-time model used to assess the impacts of climate variability and land-use change on water yield[4, 5]. The model was developed using ArcSWAT 2012 within the ArcGIS environment, where the watershed was delineated into sub-basins using a 30 m Digital Elevation Model (DEM) and further divided into Hydrologic Response Units (HRUs) using a 10% threshold for land use, soil, and slope to focus on major hydrological contributors. To account for strong altitude variation, 500 m elevation bands were applied in each sub-basin to reduce orographic effects on precipitation and temperature, and a 2–3 year warm-up period was included to stabilize model conditions before simulation. Model calibration and validation were carried out using the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm in SWAT-CUP by matching simulated discharge with observed data from the Chepang station. The calibration period was 1990–2000 for parameter optimization, while validation was conducted for 2000–2006 using an independent dataset to test model reliability.

3.2. **Performance Evaluation.** Statistical indices such as the coefficient of determination (R^2), Nash–Sutcliffe Efficiency (NSE), and Percentage Bias (PBIAS) were used to check how well the model performed. R^2 shows how strongly the observed and simulated values are related and how much of the variation is explained by the model. NSE tells how closely the simulated data matches the observed data; a value of 1 means a perfect match, 0 means the model is only as good as using the average observed value, and values below 0 show poor performance. PBIAS indicates whether the model is overestimating or underestimating the values, with zero being the ideal result. Positive values mean overestimation, while negative values mean underestimation[6].The formula is given by:

$$\mathrm{PBIAS} = \frac{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i})}{\sum_{i=1}^{n} Q_{\mathrm{obs},i}} \times 100 \tag{1}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - \bar{Q}_{\mathrm{obs}})(Q_{\mathrm{sim},i} - \bar{Q}_{\mathrm{sim}})}{\sqrt{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - \bar{Q}_{\mathrm{obs}})^2}\sqrt{\sum_{i=1}^{n}(Q_{\mathrm{sim},i} - \bar{Q}_{\mathrm{sim}})^2}} \right)^2 \tag{2}$$

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i})^2}{\sum_{i=1}^{n}(Q_{\mathrm{obs},i} - \bar{Q}_{\mathrm{obs}})^2} \tag{3}$$

Where Q_{obs} is the observed discharge, Q_{sim} is the simulated discharge, and $\bar{Q}$ denotes mean values.

Table 4. Performance Evaluation Criteria Ranges

Statistical Index	**Satisfactory Range**
R^2	> 0.60
NSE	> 0.50
PBIAS	$< \pm 25\%$

3.3. **Analysis of Gross and net head.** The gross topographical head was calculated by overlaying the Digital Elevation Model (DEM) with the sub-basin boundaries in ArcGIS. Outlet points for each sub-basin were added, and the corresponding elevation values were extracted from the DEM. The gross head was then determined as the elevation difference between the outlet points of consecutive sub-basins. To account for hydraulic losses in conveyance and other system components, an additional 10% head loss was considered, and the net head was estimated accordingly.

3.4. **Hydropower Potential Optimization.** After running the SWAT model, discharge at intake points was calculated. Calibration and validation were carried out using SWAT CUP software with discharge data from the Chepang station. Plotting the flow duration curve (FDC) and determining the percentile discharges were the goals of the discharge analysis. Hydropower potential is a function of head drop and discharge at a certain flow exceedance. The theoretical run of-river (ROR)hydropower potential is calculated using the equation:

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

where, η = Efficiency (%), P = Power generated in Watt (W), ρ = Mass density of water (kg/m^3), g = Acceleration due to gravity (m/s^2), Q = Discharge (m^3/s), H = Gross head drop (m). [7]. According to WECS (Water and Energy Commission Secretariat), in preliminary hydropower potential studies, a simplified approach is used where about 10% of gross head is considered as head loss in the water conductor system, and the overall efficiency of the plant is assumed to be about 80–90% (we adopt 85%) for estimating installed capacity [8].

4. RESULTS AND DISCUSSION

Graphically, it can be observed that the simulated flow closely replicates the observed flow in almost all years. Figure 7 present the monthly flow calibration at Chepang station for the period 1990–2000 with a two-year warm-up period. The monthly simulated discharge values at Chepang station were compared with the observed discharge for model validation, as shown in Figure 8. The validation was conducted for the period 2000–2006. The Calibration and validation Performance evaluation indices is given in Table 5.
There is a strong relationship between precipitation and runoff generation across the land surface. Rainfall serves as the primary source of water for rivers within a basin and is influenced by underlying surface conditions, topography, geomorphology, and climatic factors.

4.1. **Performance Evaluation Results.** Calibration and validation performance metrics demonstrate strong correlation between observed and simulated streamflows.

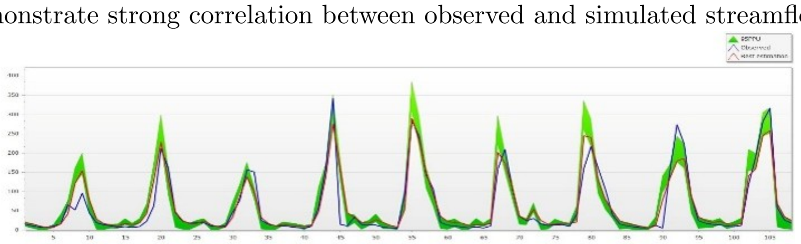

FIGURE 7. Monthly flow Calibration at Chepang Station

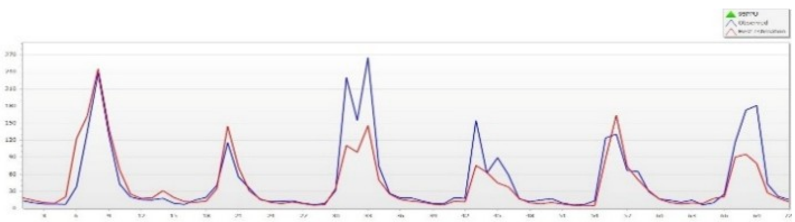

FIGURE 8. Monthly flow Validation at Chepang Station

TABLE 5. Calibration and Validation Performance Evaluation Indices

Index	Calibration (1990–2000)	Validation (2000–2006)
R^2	0.88	0.75
PBIAS (%)	−5.8	14.9
NSE	0.87	0.73

4.2. **Sensitivity Analysis of Babai Basin.** Based on the simulation, the parameters related to surface runoff (CN2) and groundwater (GW_DELAY, ALPHA_BF) were found to be the most sensitive for the Babai River Basin. This high sensitivity is attributed to the basin's diverse topography, ranging from the rugged Mid-hills to the Chure region, which significantly influences infiltration and baseflow contribution.

4.3. **FDC of Inlet and Outlet.** The flow duration curve (FDC) was constructed at both the inlet point and the hydrological station to analyze flow characteristics. For these, some discharge percentiles were taken, such as Q_{25}, Q_{30}, Q_{35}, Q_{40}, Q_{50}, and so on.

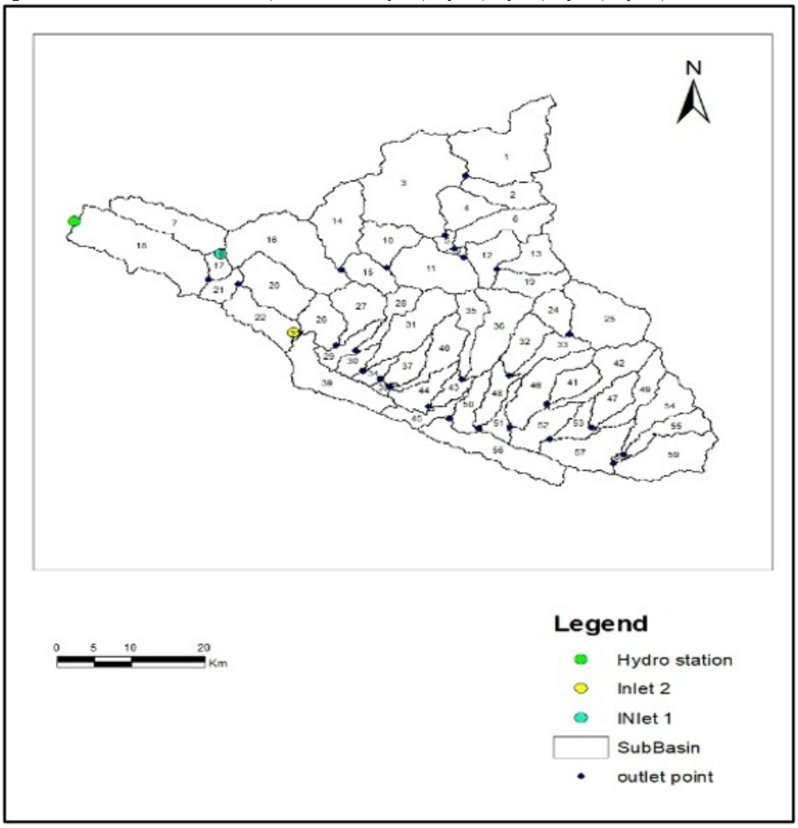

Figure 9. Sub-Basin, Inlet and Outlet points

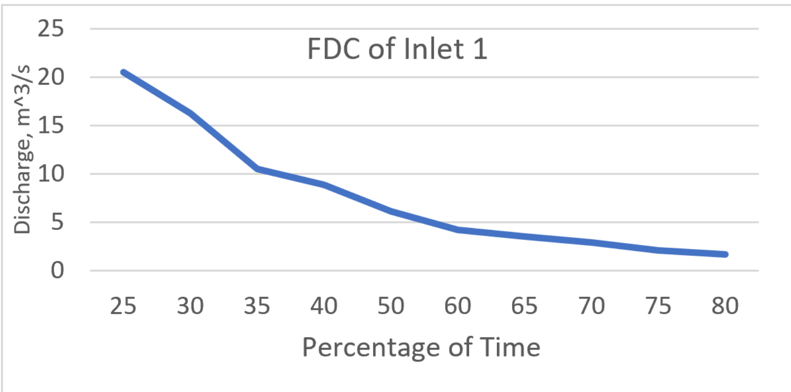

Figure 10. FDC of Inlet 1

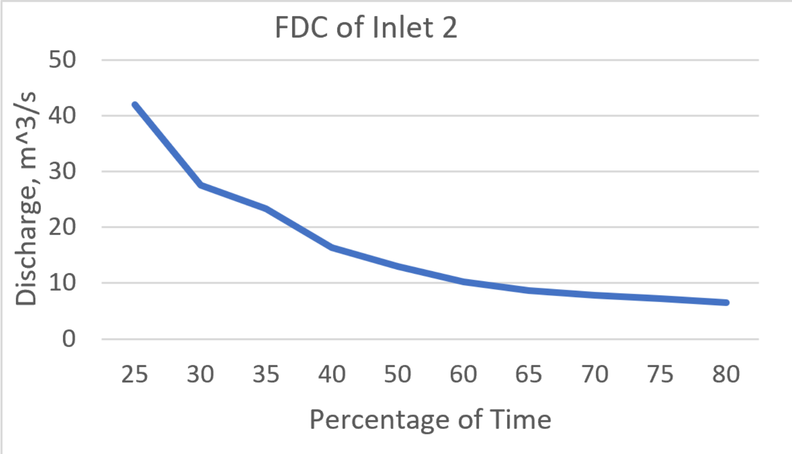

FIGURE 11. FDC of Inlet 2

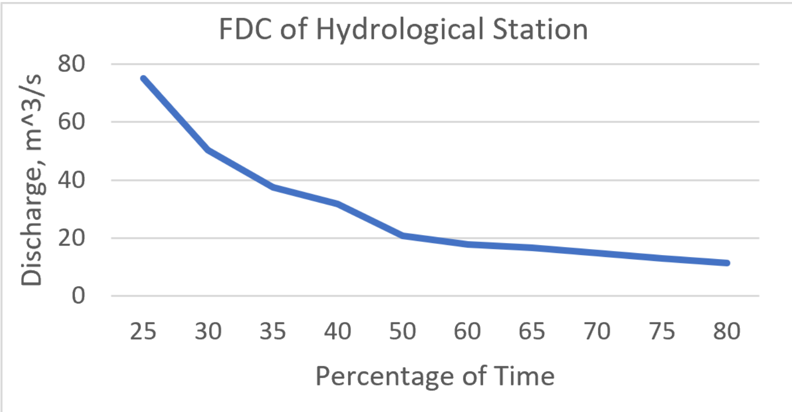

FIGURE 12. FDC of hydrological station (outlet 18)

4.4. **Hydropower Potential Calculation.** According to the WECS approach, the total net theoretical power potential of the Babai River Basin was found to be approximately 187.9 MW at Q_{25}, 136.07 MW at Q_{30}, 103.7 MW at Q_{35}, 80.3 MW at Q_{40}, and 58.1 MW at Q_{50}. This value already accounts for 10% head loss and a turbine efficiency of 0.85 [9]. Although power was calculated for several flow percentiles, Q_{40} flow was selected for further evaluation and analysis. The Q_{40} discharge represents a relatively reliable flow condition that balances energy generation with flow availability. Therefore, Q_{40} flow was adopted as the reference discharge for subsequent optimization and site evaluation [10].

The net power for sub-basins and total net power of the overall Babai River Basin are calculated, where P_{25}, P_{30}, P_{35}, P_{40}, and P_{50} are the net hydropower potentials at the corresponding discharges Q_{25}, Q_{30}, Q_{35}, Q_{40}, and Q_{50}, respectively. The net hydropower potential of the Babai River Basin is the cumulative net power of all sub-basins, where Q_{25}, Q_{30}, Q_{35}, Q_{40}, and Q_{50} represent percentile discharges.

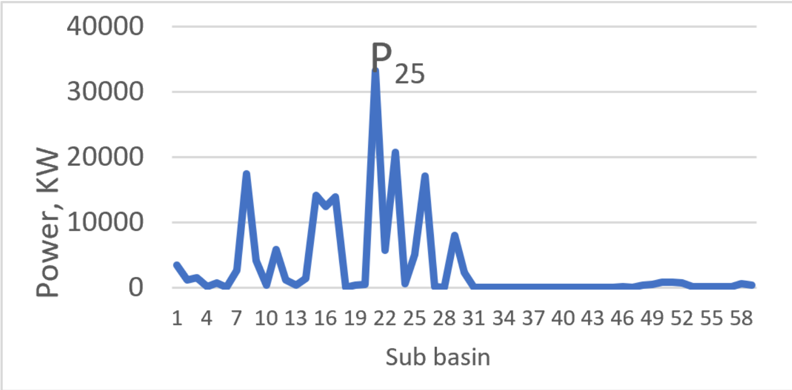

FIGURE 13. power at 25% of time at different sub basin

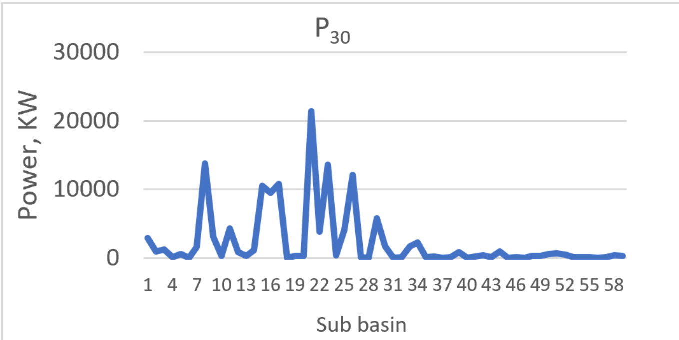

FIGURE 14. power at 30% of time at different sub basin

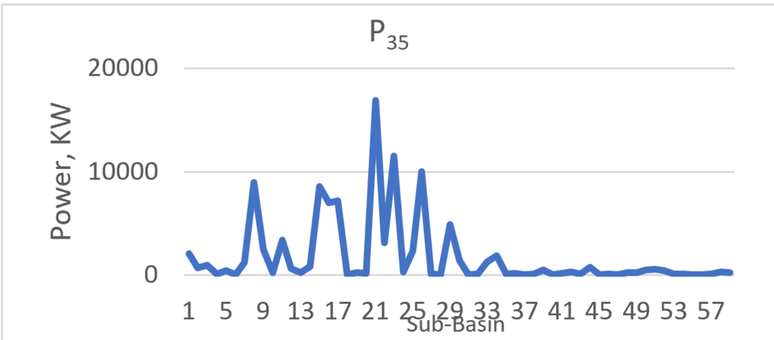

FIGURE 15. power at 35% of time at different sub basin

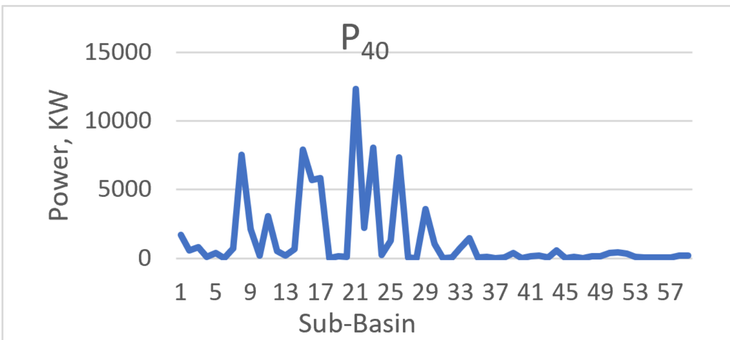

FIGURE 16. power at 40% of time at different sub basin

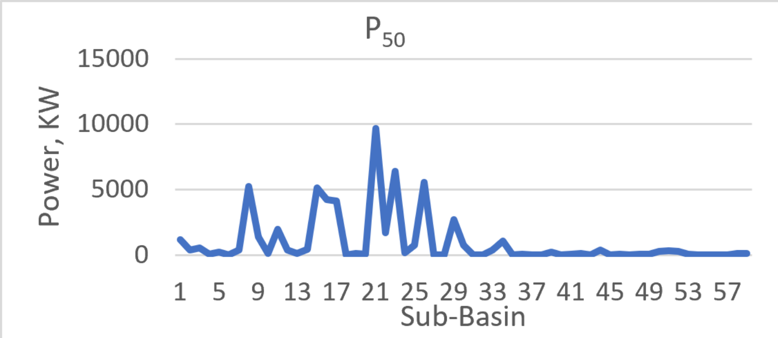

FIGURE 17. power at 50% of time at different sub basin

4.5. **Technical Evaluation of Potential Hydropower Sites.** The selection of the inlet (intake) and outlet (powerhouse/tailrace) points was not arbitrary; it was derived from a systematic optimization of the primary hydropower variables: hydraulic head (H) and river discharge (Q). Using the Digital Elevation Model (DEM) in GIS and the flow accumulation outputs from SWAT, the selected nodes (Sub-basin 8, 23, 17, and a point X) were identified as the optimal locations for maximizing power generation potential. Here, Model 1 represents Inlet 8 and Outlet 17, and Model 2 represents Inlet 23 and Outlet X, as shown in Figure 17 and Figure 18, respectively, where power (P) is in kW and discharge (Q) is in m^3/s.

TABLE 6. Power Calculation for Model-1

Location	Sub-basin / Node	Elevation (m)	Head (m)
Inlet	Sub-basin 8	513.976	Gross: 112.779
Outlet	Sub-basin 17	401.197	Net (10% loss): 101.501

Percentile	25%	30%	35%	40%	50%
Discharge, Q (m^3/s)	20.525	16.307	10.5415	8.8766	6.174
Power, P (kW)	19301.87	15335.23	9913.31	8347.62	5806.07

TABLE 7. Power Calculation for Model-2

Location	Sub-basin / Node	Elevation (m)	Head (m)
Inlet	Sub-basin 23	484.902	Gross: 39.902
Outlet	Point X	445.000	Net (10% loss): 35.911

Percentile	25%	30%	35%	40%	50%
Discharge, Q (m^3/s)	41.945	27.503	23.2705	16.298	12.975
Power, P (kW)	12560.17	8235.60	6968.20	4880.33	3885.28

TABLE 8. Geographic Coordinates and Elevations of Site Nodes

Point	Latitude (°N)	Longitude (°E)	Elevation (m)	Remarks
Subbasin 8	28.30245	81.92089	513.98	Inlet 1
Subbasin 17	28.26383	81.90428	401.20	Outlet 1
Subbasin 23	28.18197	82.02040	484.90	Inlet 2
Node X	28.21300	81.96800	445.00	Outlet 2

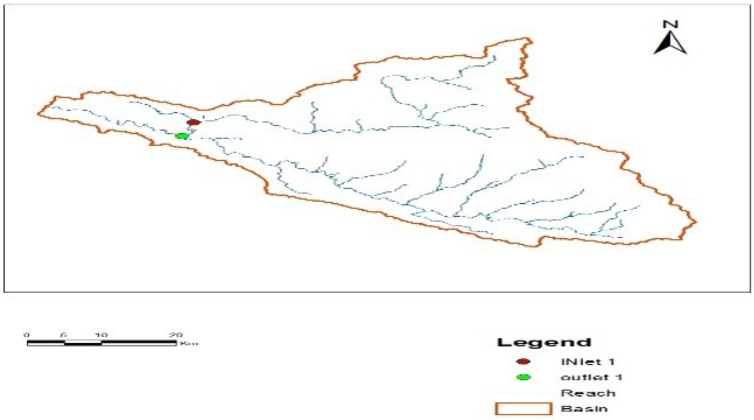

Figure 18. Model 1 (inlet 1 and outlet 1) (sub basin8-17)

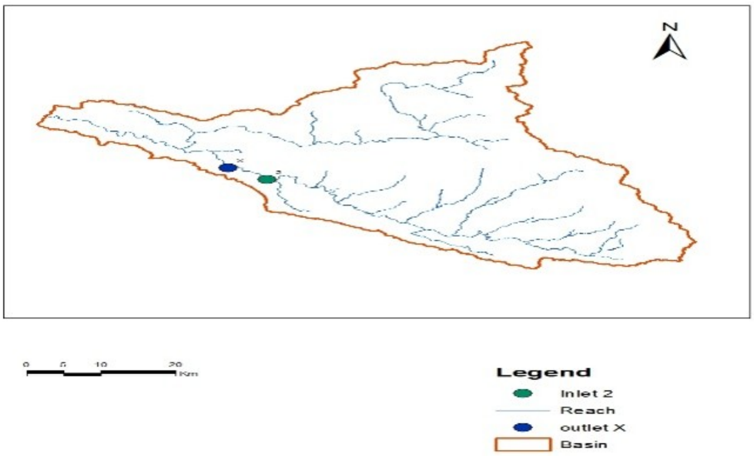

Figure 19. Model 2(inlet 2 And outlet 2) (subbasin23-x)

4.5.1. *Technical Potential Evaulation.* The technical potential of the two identified sites is based on the interaction between topographical gradient (Head) and hydrological yield (Discharge).

Table 9. Comparison of Key Parameters for Model-1 and Model-2

Parameter	**Model-1 (Basin 8–17)**	**Model-2 (Basin 23–X)**
Gross Head	112.779 m	39.902 m
Net Head (10% Loss)	101.501 m	35.911 m
Max Discharge (Q_{40})	8.8766 m^3/s	16.298 m^3/s
Installed Capacity (P_{40})	8347.625 kW ($\sim$ 8.3 MW)	4880.336 kW ($\sim$ 4.8 MW)

Model-1 follows a high-head strategy in the Babai River Basin, generating significant power from a large vertical drop despite lower discharge. In contrast, Model-2 is a volume-driven scheme with lower head but higher flow, allowing steady and reliable power production. Both projects are designed as Run-of-River (RoR) systems. A Francis turbine is selected for Model-1 due to its efficiency in medium-to-high head conditions, while Model-2 may use either a Francis or Kaplan turbine depending on seasonal flow variation, as Kaplan performs better under high discharge and fluctuating conditions.

4.5.2. *Site Selection Criteria Analysis.* The selection of Sub-basins 8–17 and 23–X in the Babai River Basin is mainly based on hydropower potential, flow conditions, and system integration. Model-1 is located at a high-head knickpoint in a smaller tributary, making it suitable for efficient power generation with limited discharge. Model-2 is placed on a higher-order stream with much larger flow and is strategically designed to utilize additional water from the Bheri-Babai Diversion Multipurpose Project, especially during dry seasons. Both sites are planned as Run-of-River (RoR) systems to ensure water is returned downstream and to protect the operation of the Babai Irrigation Project. The spacing between the sites also supports smooth cascade operation without hydraulic interference, while ensuring basic environmental flow and manageable sediment conditions for long-term sustainability [11].

4.6. **Discussion.** The present study estimated a total Run-of-River (RoR) hydropower potential of approximately 80.3 MW at Q_{40} in the Babai River Basin using an integrated GIS-SWAT approach. The SWAT model demonstrated satisfactory performance ($R^2 = 0.88$ and NSE $= 0.87$), indicating reliable streamflow simulation for hydropower assessment. These findings are consistent with previous studies by Bhattarai et al. [12] in the Sunkoshi River Basin and Joshi and Mishra [13] in the Marsyangdi River Basin, which also concluded that integrating GIS, SWAT, and Flow Duration Curve analysis provides a reliable approach for identifying feasible Run-of-River hydropower sites. However, the estimated hydropower potential of the Babai Basin is lower than that of the Sunkoshi and Marsyangdi basins due to its smaller catchment area, lower river discharge, and rain-fed hydrological regime. Nevertheless, the identified potential confirms that the Babai River Basin is suitable for small- to medium-scale sustainable hydropower development, demonstrating the applicability of GIS-SWAT modeling for hydropower planning in data-limited river basins.

5. CONCLUSION AND RECOMMENDATIONS

5.1. **Conclusion.** This study evaluated the hydropower potential of the Babai River Basin using integrated GIS and the Soil and Water Assessment Tool (SWAT) to simulate long-term river flow in this rain-fed watershed. The model was successfully calibrated and validated using discharge data from the Chepang station, showing reliable performance for streamflow estimation. The analysis identified surface runoff and groundwater interaction as the major hydrological factors controlling river flow. Based on Flow Duration Curve (FDC) analysis, the basin was estimated to have a dependable Run-of-River (RoR) hydropower potential of about 80.3 MW under Q_{40} conditions. Two feasible hydropower sites were identified: Model-1, a high-head scheme with an estimated capacity of 8.3 MW, and Model-2, with a capacity of about 4.8 MW supported by additional flow from the Bheri-Babai Diversion Multipurpose Project (BBDMP). Both projects are designed as environmentally sustainable RoR systems that return water back to the river, helping protect irrigation demands and the ecosystem near Bardiya National Park. Overall, the study shows that GIS–SWAT modeling can provide a practical and reliable approach for sustainable hydropower planning in rain-fed river basins.

5.2. **Recommendations.** The study recommends the use of Francis turbine for both hydropower models due to their high efficiency and suitability for varying flow conditions in the Babai River Basin. Because the basin carries high sediment loads from the Churia region, proper sediment management systems and HVOF-coated turbine runners are necessary to reduce damage and improve durability. The projects should operate strictly as Run-of-River (RoR) schemes so that all diverted water is returned to the river, ensuring the water requirements of the Babai Irrigation Project are maintained. Model-2 should also take advantage of the additional flow from the Bheri-Babai Diversion Multipurpose Project, particularly during the dry season. To protect aquatic ecosystems near Bardiya National Park, a minimum environmental flow must be maintained at all times. Overall, the study provides a strong hydrological foundation for future civil design, cost estimation, and environmental assessment of sustainable hydropower development in the Babai Basin.

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