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Research Article

Prospect of Small Hydropower Projects for Sustainable Development of Water Resources in Karbi Anglong District, Assam, India

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Abstract

The North Eastern Region (NER) of India has the highest hydropower potential, i.e., almost 40% of the country's total potential (55929 MW), out of which only 7027 MW has been harnessed so far. Contrary to the currently emphasized large hydro projects, which impart significant ecological changes on the river dynamics, the NER offers enormous Small Hydropower (SHP) potential which can be harnessed with a much lesser outlay cost. One of the objectives of India's small hydropower program is to encourage SHP projects, as these can provide an energy solution to rural, isolated, and hilly areas where the extension of the grid system would be relatively expensive. The present study area falling in Karbi-Anglong District of Assam has been selected for identification of potential sites for SHP through detailed hydrological study of the available water resources. The hilly district of Karbi-Anglong falls under Sixth Schedule Areas of the Constitution of India where majority of the population belongs to Scheduled Tribe Communities, is both industrially and economically backward. A total of 46 potential sites have been selected on eight streams present in the area. The results show that these watersheds can generate 48.4 MW of power via development of small to mini multipurpose hydropower projects. Using canal networks attached to these multipurpose projects, the natural gradient available in the hilly watershed can best utilized to irrigate downstream areas at a lower cost. These irrigation-based multipurpose projects will boost agriculture activity in the tribal areas of Karbi-Anglong and nearby districts and also be able to meet the captive requirement of power. Increased rural electrification can facilitate the development of industries dependent on agriculture and forestry, which will improve the area's economy and social upliftment of the whole area.

Keywords: North Eastern Region (NER), Small Hydropower (SHP), Water Resources, Karbi-Anglong, Assam

Introduction

A renewable source of energy in the form of hydropower is more sustainable (Siri *et al.,* 2021) with zero carbon footprints unlike the fossil fuels (Kusre *et al.,* 2010; Levasseur *et al.,* 2021) mainly in developing countries like India. India is blessed with immense amount of hydroelectric potential with estimated 1,33,410 MW of installed capacity, a major portion of which i.e., 55929.7 MW is estimated for the Northeastern region (NER) (CEA, 2023). But only 7027 MW has been harnessed or under various stages of construction, leaving bulk of the potential remains untapped. Usually, the large reservoirs associated with conventional large hydroelectric power plants have been responsible for large scale shifting of populations, damage to flora and fauna, downstream risk of flood and most importantly dramatic ecological changes in the river. However, hydroelectric power plants can also be constructed in an area by diverting flow of water from a river with no dam or water storage (Saraf and Kumar, 2006; Ramachandra *et al.,* 2004; Goyal *et al.,* 2015). These are known as Small Hydropower (SHP) projects (Subrahmanyam, 2013; Goyal *et al.,* 2015) and could be an effective alternative to the mega dams.

Northeastern States of India have a fairly good potential to develop SHP projects of about 3261.49 MW (MNRE, 2024). Despite this huge potential perceptible emphasis is given only to large hydropower projects. These large hydro projects are being criticized because of the geographical disadvantage of the region which experiences more often the problem of compound catastrophes like earthquake, landslide, and floods *etc.* (Baruah *et al.,* 2024a). On the other hand, small multipurpose hydro projects (less than 25 MW) could ensure the socio-economic upliftment, livelihood, water and food security (Quaranta *et al.,* 2022). These could be effective alternatives to mega dams. The hilly areas of the Assam have significant SHP potential (Baruah *et al.,* 2024a), particularly in the two hill districts – Karbi Anglong and Dima Hasao, which account for nearly 83 MW and 23 MW power generations respectively (Nath, 2015). However, very little work is being done to explore these hidden treasures of power so far.

The state of Assam, being an agro-based economy, irrigation plays an important role in the crop production. Most of the irrigation projects in Assam are lift based irrigation which are either

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electrically operated or diesel driven. But, because of inadequate power supply and high maintenance costs, most projects in Assam are currently not functional (Chetri and Kalita, 2024). A gravity or flow-based irrigation system that conveys water to the field by gravity could be a better alternative to overcome this problem. These schemes require low maintenance costs, no power supply and the natural gradient available in the hilly watershed can be best utilized to irrigate downstream areas. The excess water stored in the small reservoir of any SHP and the tailing water that comes out through the tail race tunnel (TRT) can be best utilized for irrigation purposes in the nearby area.

Located mostly in the hilly district of Karbi Anglong, Assam, the Karbis are one of the tribal groups in NER and make up the third largest tribal community. Majority of the population belongs to Scheduled Tribe Communities, is both industrially and economically backward and agriculture is the backbone of this tribal society (Rajkonwar and Neog, 2011). These irrigation-based small scale multipurpose hydropower projects can meet the captive requirement of power of the rural population as well as the water supply for irrigation activity. Increased rural electrification may facilitate the development of small industries dependent on agriculture and forestry. As a consequence, the residents will have lots of employment prospects, which will boost the local economy of the community as a whole.

Study Area

The present work focuses on identification of potential sites for multipurpose SHP projects in the tribal district of Karbi Anglong in central Assam (Fig. 1a) through detailed hydrological study of the existing streams. It is followed by estimation of discharge of these ungauged streams for assessment of power output and the irrigation potential of a few multipurpose projects in the area is then evaluated. The present study area is bounded by latitudes 26°0'N to 26°38'N and longitudes 93°10'22.4″ E to 93°56'41.3″ E having undulatory topography (Fig. 1b), with hilly terrains surrounding the area and several streams draining the region. Therefore, the natural setup of the region makes it a promising site for developing small scale multipurpose hydropower projects.

Geological Setting

Geologically, the area belongs to the eastern portion of the Mikir massif, which together with Shillong Plateau, marks the north-eastern extension of the Indian peninsular shield (Naqvi and Rogers, 1987). The Mikir massif is an inselberg amidst the alluvial tract of Assam bounded by E-W trending Himalayan fold and thrust belt to the north and NNE-SSW trending Indo-Burmese subduction orogene to the south and southeast. While Kopili Fault separates it from the Shillong plateau towards west, its eastern margin is defined by the Dhansiri Fault (Sharma *et al.,* 2018). The study area exposes rocks from Late-Archaean to Paleo-Proterozoic basement gneisses to Quaternary alluvium (Fig. 2a). The oldest unit comprises of gneissic rocks represented by migmatitic quartzo-feldspathic gneisses, grey and pink granitoids gneiss with irregular sporadic bodies of supracrustal enclave of amphibolites (Kumar *et al.,* 2017), together known as Assam- Meghalaya Gneissic Complex (AMGC). Thick pile of meta-sedimentary sequence of quartz mica schist and quartzite, collectively known as Shillong Group of rocks (Devi, 2024) acted as cover resting over the AMGC, exposed to the north of Kaliyani Shear Zone (KSZ). The Neo-Proterozoic felsic magmatism in the area are represented by variants of granites (both porphyritic and non-prophyritic granite), pegmatites and quartz veins emplaced within the AMGC and Shillong Group of metasedimentaries (Majumdar and Dutta, 2016), exposed in the north-western part of the study area. The low dipping tertiary sequence ranges from Paleocene-Eocene Shella Formation of Jaintia Group and Oligocene-Miocene Bokabil Formation of Surma Group, both occur in the southeastern part of the area, fringing the crystalline rocks and occupying the low, flat-topped hills and plains. Lithologically, the Shela Formation comprise of oldest ferruginous to arenaceous sandstone member, followed by fossiliferous limestone. Whereas, the overlying Bokabil Formation comprises of argillaceous assemblage of shale, silt and fine-grained sandstone exposed as patches. The thickness of the sediments increases towards south and southeast, which is the general dip direction of the sedimentary rocks. These sequences are covered by alluvial soils of the Quaternary period, with three distinctive surfaces *viz.*, S1, S2, and S3, in the order of decreasing antiquity earlier documented (Baruah *et al.,* 2024b) (Fig. 2b).

Material and Methods

There are eight numbers of major streams present in the study area namely Kaliyani, Daigurung, Nambar, Barneuria, Deopani, Jabrajan, Neperpatti and Harihajan. All these streams flow through the regional slope towards east and south-east directions to meet the Dhansiri River (Fig. 1b). The present work explores the possibilities of development of SHP on these eight numbers of streams. These eight watersheds are ungauged, with inadequate records of hydrological observations (Sivapalan *et al.,* 2003). The hydrology of these ungauged river basins heavily depends upon the seasonal distribution of rainfall patterns, especially for non-perennial streams. The present work gives a comprehensive review of the hydrometeorological condition of the area, followed by estimation of discharge of the ungauged streams for determination of power generation potential and finally to assess the irrigation potential of three selected sites.

Hydrometeorological Setup

The majority of water resource projects in India are planned and designed using historical data on water availability in the form of precipitation (Jain and Singh, 2023), which is considered as the primary water source. For water resources planning purposes, a long-term rainfall record is required (Tantanee *et al.,* 2005). The study of spatial variability and distribution of rainfall over the study area is particularly important because of the orographic effect which plays a major role in the rainfall distribution over the study area. The hydrometeorological study aims to examine the generic patterns of spatial variability of rainfall over the study area with the help of isohyetal maps of annual rainfall and calculating average precipitation by the isohyetal method using eq. 1.

$$P = \frac{\Sigma_{i=1}^{n} AiPi}{\Sigma_{i=1}^{n} AiPi} \quad (1)$$

Where, P is the average annual rainfall, Pi is the average rainfall between two adjacent isohyets, and Ai is the area within two adjacent isohyets.

The Rainfall data for the entire study area could not be collected in a regular grid manner because of the paucity of rain gauge stations in the hilly region of Karbi Anglong. The only data

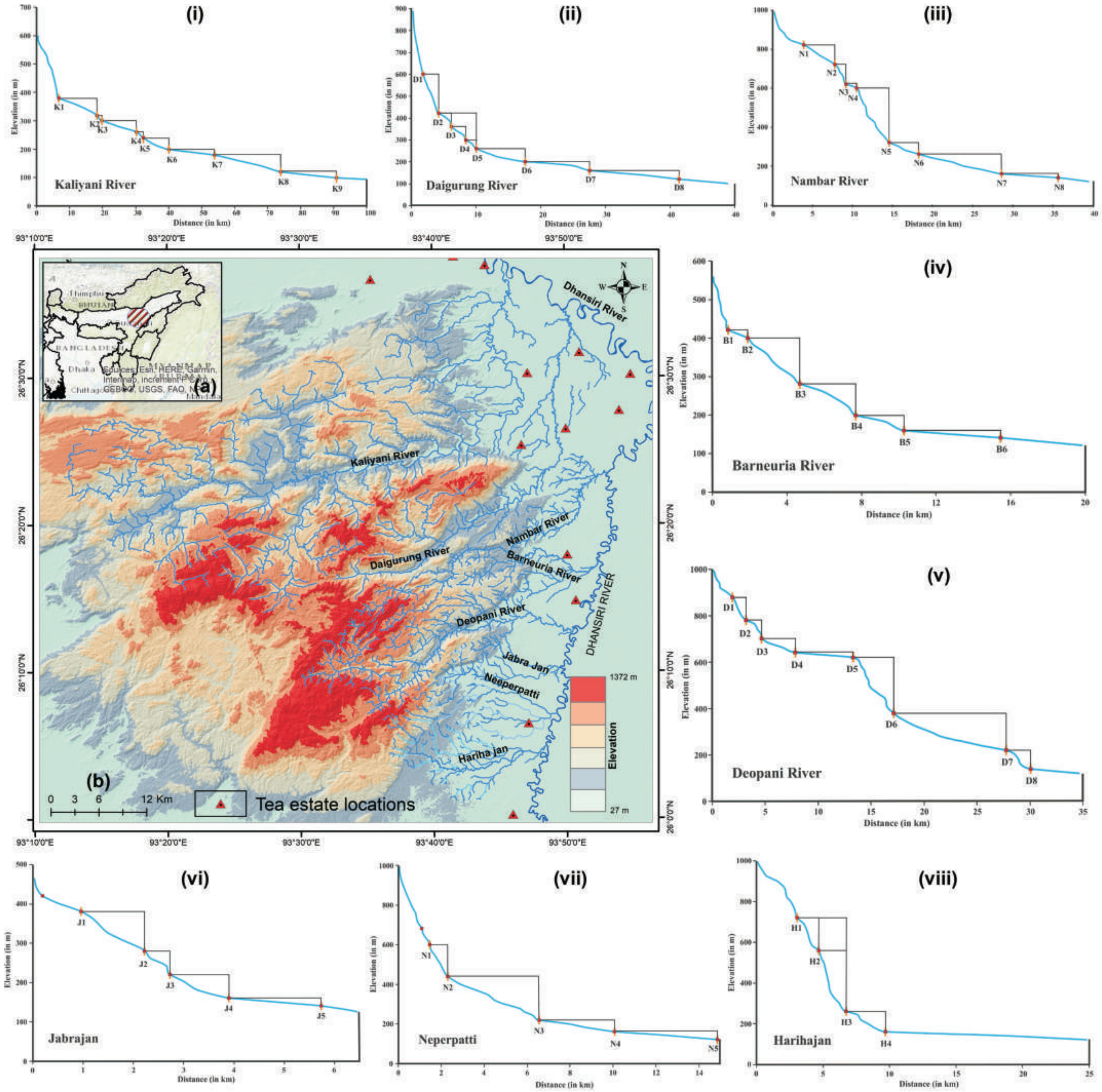

Fig. 1. (a) Geographical map of North-East India showing all eight numbers of states highlighting the present study area, **(b)** Drainage map superimposed over the physiography map of the area showing elevation differences in the area with locations of tea estates; Inset shows the longitudinal profiles of each stream with marked locations having significant head (H) for (i) Kaliyani, (ii) Daigurung, (iii) Nambar, (iv) Barneuria, (v) Deopani, (vi) Jabrajan, (vii) Neeparpati and (viii) Harihajan stream.

that has been collected is from the different tea estates located at the foothills. To study the rainfall distribution pattern, data have been collected from 13 rain gauge stations available within the area of investigation (Fig. 1b). The gauge stations are located either within or near the periphery of those catchments considered for the present study. This information of the long-term precipitation record is then extrapolated to cover the upstream catchment area for each river basin under investigation. Due to lack of rainfall data in the hilly, remote and inaccessible parts of the area we consider uniform precipitation over the catchment area while validating the discharge of the streams with the rainfall data.

Existing Water Resources and Site Identification

Assessment of hydropower potential of an ungauged stream requires identification of sites having suitable head and determination of flows at those selected sites. For the measurement of head, the available topographic map is analyzed in the ArcMap environment and the longitudinal profiles of all the eight numbers of streams have been generated using the existing elevation contour. Based on the steepness of the graded profiles of the streams, altogether 46 numbers of sites are identified as shown in Fig. 1 (i - viii). In the present investigation, the possibility of single as well as

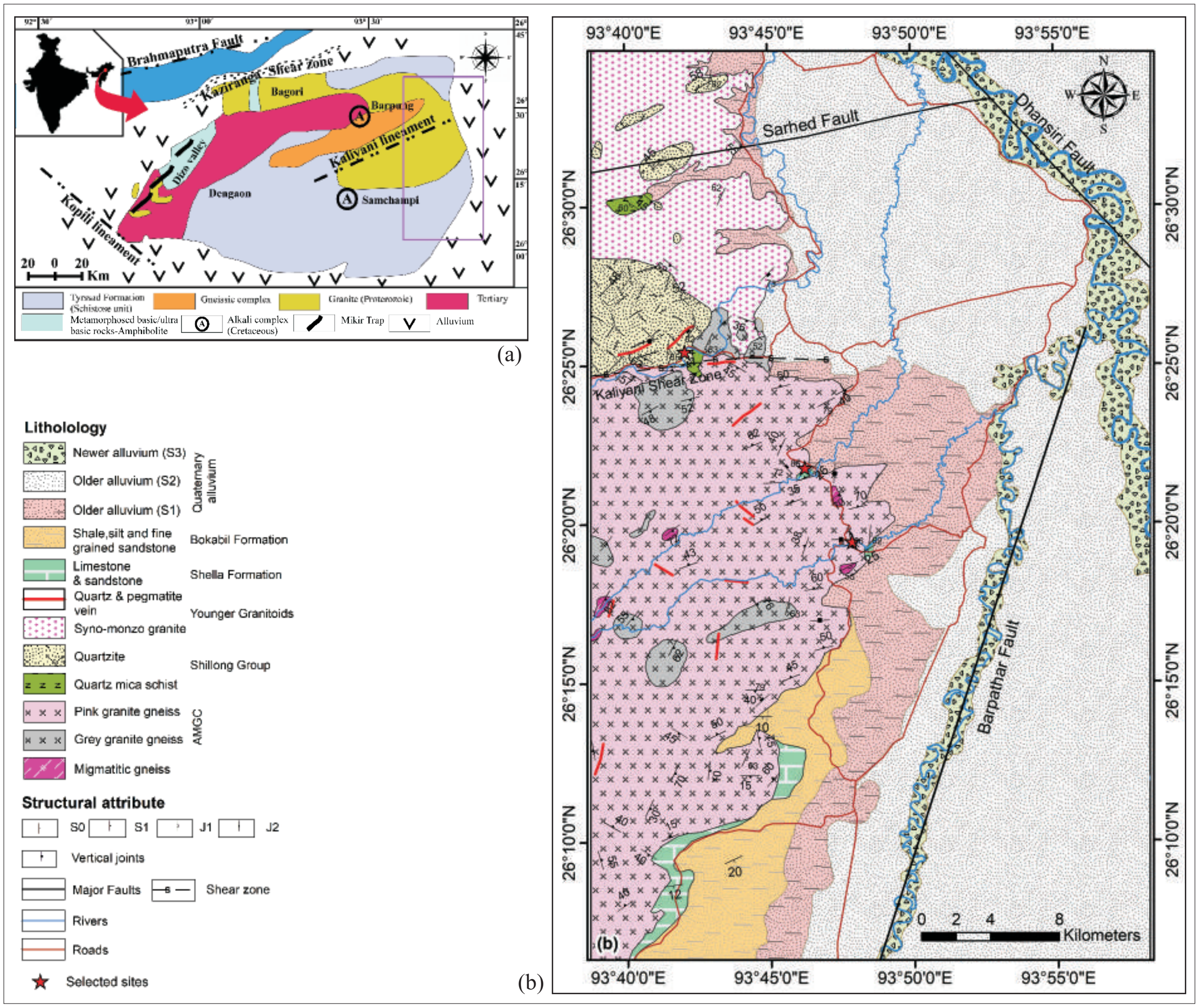

Fig. 2. (a) Regional geological map of Mikir massif (*modified after* Majumdar, 2010) showing the present area of investigation, **(b)** Geological map of the study area showing different lithologies with major faults and shear zones, red star marks show the location of three SHP sites on Kaliyani, Daigurung and Nambar stream.

cascade system has been explored for optimal use of water resources with high head gain.

As shown in the longitudinal profiles, for each stream, a series of hydropower plants are proposed in a cascade manner, such that the runoff discharge of one hydropower plant is used as intake discharge for the next hydropower plant located downstream. Steeper the stream gradient more is the availability of the potential head; thus, for a given discharge higher is the power potentiality (Kusre *et al.,* 2010). One of the crucial parameters in selection of sites for SHP is to keep cost criteria low as the return from investment is not so high (Roy and Roy, 2020). So, the selection of the 46 sites is made by considering the cost parameters as high vertical head gain in the minimum horizontal distance is always favorable than vice versa.

Hydrological Studies for SHP

The estimation of available discharge (Q) at the site is one of the essential components of a feasibility study of a hydropower plant. Determination of Q requires a long-term record of river or stream flow at the selected site, which is not available in the present case. Most of the identified sites located in the upstream of the catchments are inaccessible during the time of field visit; hence direct flow measurements cannot be possible at all sites. However, several indirect methods are available for the stimulation of the flow of an ungauged river site by extrapolation flow data from a nearby gauged catchment having similar catchment area (Jones, 1988). One such method is called the Area ratio method (Inversin, 1986; Flynn, 2003; Chin, 2006; Kasamba *et al.,* 2015; Ayele, 2020).

This technique is applied under the presumption that the nearby gauged and ungauged sites share comparable hydrological characteristics which include: topography, land use, lithology and geomorphology as well as similar precipitation. Flow values are transferred from a gauged site to the ungauged site using the following equation:

$$Q_{unguaged} = Q_{guaged} \times \left(\frac{A_{unguaged}}{A_{guaged}}\right) \tag{2}$$

Where, discharge (Q) of ungauged site is obtained from the gauged discharge by comparing the areas (A) of both the catchments.

In order to validate the results of estimated flow obtained from the Area ratio method, flow measurements have been taken at few sites at selected river basins using float techniques. The river basins considered for this purpose are Kaliyani, Daigurung, Nambar, Barneuria, Deopani and Jabrajan. The discharge measurement of the other two streams, namely Neperpatti and Harihajan could not be possible because of the unavailability of adequate water in the channel. Also, the measured location in each drainage basin is chosen in such a way that it should be easily accessible and possibly close to a nearby location where stream flow had been previously estimated. The measurements are taken in the months of March and October 2018 which represents the pre- and post-monsoon periods in the study area.

Estimation of Power Generation Potential

The available head (H) at all the selected sites when multiplied by the discharge (Q) and the acceleration due to gravity ($g=9.81 m/s^2$), gives the theoretical power (P) in Kilowatts (kW) (Fritz, 1984). Here only the natural gradient available in the stream has been considered as the head without considering the height of the weir. The height of the weir will further increase the water column and thus increases the overall head. This will finally enhance the power output for each site.

A general payout plan of a series of cascading SHP sites has been proposed where the location of the weir has been placed at the first point, followed by the power house location at the next successive points following the main stream (Fig. 1). The theoretical power output has been calculated using the elevation drop from weir to powerhouse location and the discharge data of the stream at the weir location. Possible alternative positions of weir and powerhouse has been explored in few catchments *viz.* Daigurung and Harihajan (Fig. 1 ii and viii) in order to increase the head which in turn increases the power output.

Irrigation Potential in the Area

In order to assess the irrigation potential in the study area, three sites have been selected out of 46 sites which is having the highest power generation potential, easily accessible and also having good occurrences of irrigable crop lands in the downstream areas. These sites are located in Kaliyani catchment at location K7, Daigurung catchment at D7 and one at Nambar catchment at N7. Geo-mechanical characterization of rocks at these three proposed sites has previously been done by Baruah *et al.* (2024a). The exposed rock units at the vicinity of the proposed sites are mainly the meta-sedimentary Quartzites and underlying Granite Gneisses (Fig. 2b). The bulk densities of the rocks are observed to be 2.6-2.8 gm/cm^3 for quartzite and 2.6-2.9 gm/cm^3 for granite gneiss. The Uniaxial Compressive Strength of rock samples varied from 51.6-103.7 MPa, 81.9-116.7 MPa, and 70.4-114.4 MPa for Kaliyani, Daigurung, and Nambar sites, respectively. The results of the Brazilian test show low tensile strength for rocks exposed at the Kaliyani site (2.02 MPa), owing to its vicinity near the Kaliyani Shear Zone (KSZ), whereas rocks exposed at the Daigurung and Nambar sites shows 6.66 and 6.44 MPa, respectively (Baruah *et al.,* 2024a). The results of the Rock Mass Rating class for each site indicate that all rock masses have fallen in Class-II, i.e., the 'Good' category, making them suitable for foundation strata (Baruah *et al.,* 2024a).

In the present scenario, an integrated scheme has been proposed by attaching an irrigation canal at the end of the tail race of the proposed SHP. These canals can carry the excess water further down the slope to feed water to the agricultural lands present in the vicinity of the projects. For this purpose, land use land cover (LULC) map has been prepared using Sentinel-2 data from Copernicus Programme, which is under the European Space Agency (ESA). There are number of 2^{nd} and 3^{rd} order dry channels which are present in the vicinity of the project site. These channels were earlier in flowing conditions but presently remain dry throughout the year and are utilized by the local people for some small paddy cultivation. These dry nalas offer the best alternatives for the irrigation canals as the natural gradient of these channels can be utilized for transporting water to the distant point possible without expending capital cost.

Results

Rainfall Distribution Pattern

The mean monthly rainfall recorded at the different rain-gauge stations are given in Tables 1 shows the monthly distribution of rainfall over the study area. As evident from Table 1, the Southwest monsoon plays its active role from June to September, accounting for more than 60% of the rainfall. The general distribution pattern of rainfall is more or less the same every year, *i.e.*, the intensity gradually increases from April onwards, gains significant momentum from June to August, and then gradually decreases to become scarce from December to February. July is invariably the period of maximum amount of rainfall received by the area (Table 1).

Table 1: Mean monthly rainfall data (in mm) for different rain gauge stations for the period of 2000 to 2016

Station/Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Difalu	10.02	24.04	56.89	200.6	233.52	274.15	314.38	258.01	200.66	103.79	16.51	9.64
Borsapori	10.19	27.01	65.1	236.89	280.13	334.55	397.33	321.46	224.69	115.05	21.47	6.99
Numaligarh	8.98	22.41	59.78	200.96	246.98	287.98	350.76	270.24	208.47	100.26	13.84	7.84
Dholaguri	9.81	29.93	57.87	172.56	214.58	283.33	337.71	280.76	229.41	129.79	35.1	11.85
Bukhial	13.08	25.53	70.87	210.69	235.8	316.98	333.46	263.52	283.87	121.87	17.75	8.84
Rangajan	14.06	13.97	45.64	170.18	236.09	292.82	372.91	275.17	238.51	88.9	17.15	10.8
Abhoyjan	17.99	33.68	69.34	233.02	270.6	335.78	360.65	351.51	319.03	141.97	17.03	5.86
Murphulani	11.89	25.49	53.2	192.74	253.01	311.82	302.58	277.87	236.28	100.09	13.6	12.73
Bogijan	10.88	19.38	52.97	167.7	217.77	318.05	275.82	248.67	257.71	100.84	13.06	4.99
Namburnadi	15.69	28.69	60.56	161.81	185.79	204.27	272.25	231.69	202.56	116.38	15.61	7.46
Banaspati	15.16	27.98	60.54	180.62	204.59	226.63	351.88	270.99	228.51	139.31	20.25	7.43
Bokajan	7.34	8.74	30.82	88.27	111.13	160.57	190.97	210.93	153.81	93.86	4.65	2.15
Lengrijan	9.31	18.44	43.68	116.96	155.21	218.29	228.23	237.79	173.04	106.9	14.87	3.25
Total	154.4	305.29	727.26	2333	2845.2	3565.22	4088.93	3498.61	2956.55	1459.01	220.89	99.83
Average	11.88	23.48	55.94	179.46	218.86	274.25	314.53	269.12	227.43	112.23	16.99	7.68

Based on the average rainfall data from 13 rain-gauge stations, an isohyetal map of the area has been prepared (Fig. 3). The frontal part of the karbi hills restricts the isolines on the western and southwestern sides, and the Dhansiri river course defines its northeast and eastern boundary due to the non-availability of rainfall records in the surrounding areas. It is observed that rainfall intensity generally increases from southwest to northeast. The highest rainfall is recorded at Abhoyjan tea estate near the confluence of the Dhansiri and Doyang Rivers whereas Bokajan tea estate recorded the lowest rainfall. The average annual rainfall over the study area as computed by the isohyetal method using eq. 1 is 1449.83 mm for the whole area. Thus, the study area receives a moderate amount of precipitation with significant spatial variability as shown in Fig. 3.

Estimation of Discharge at Selected Sites

In the present study, the available discharge of nearby Killing River having similar hydrological characteristics to the catchment of interest is considered. The available hydrological data of the Killing River is being used to assess the discharge of ungauged basins using Area ratio methods using eq. 2. In order to validate the results obtained by this method, the available rainfall data of each catchment area have been plotted against the discharge for the same period and the results are shown in Fig. 4.

To assess the reliability of any SHP in the area and also to select the hydraulic capacity of the plant, discharge at each site has been calculated corresponding to varying degrees of dependability

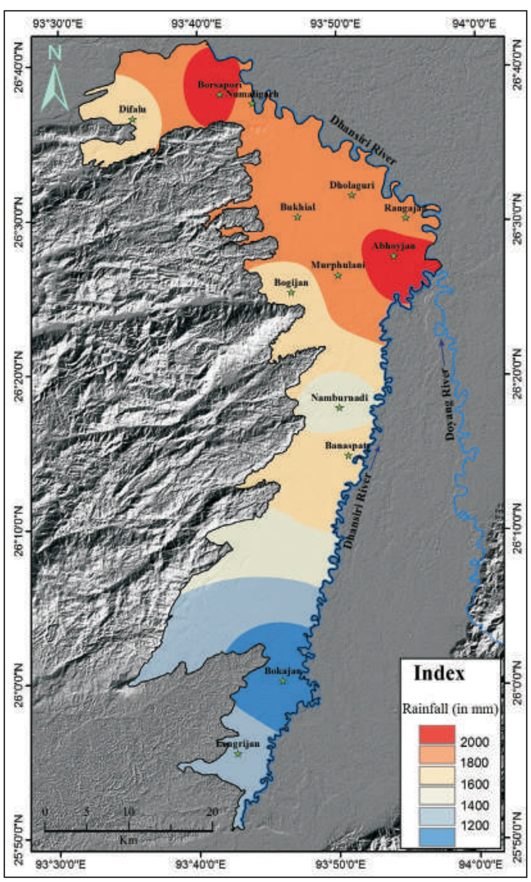

Fig. 3. Isohyetal map showing spatial distribution of annual rainfall in millimeter over the study area.

using Flow Duration Curve (FDC). Usually, for power estimation, 50%, 75% and 90% dependability discharge values are considered (Kusre *et al.,* 2010) and are being calculated for each identified site (Table 2).

The flow measurements taken in six of the eight watersheds in the month of March and October 2018 have been given in Table 3. The measured discharge in pre-monsoon period shows close resemblances with the estimated discharge at 75% dependency. Whereas, the stream discharge increases during the post-monsoon periods and accounts for 50% dependability flow of estimated discharge. In the present study, discharge at 50% dependability has been considered to estimate the hydropower potential for all the selected sites.

Power Generation Capacity of Each Watershed

Table 4 shows the results of estimated power output in kW at each site of all the eight numbers of watershed. Results obtained

Table 2: Estimated discharge at 46 locations of 8 streams at 50%, 75% and 90% dependability

River Basins	Estimated discharge (Q) in m3/sec at identified sites				
	Location	Area in km^2	Q 50%	Q 75%	Q 90%
Kaliyani	K 1	35.9	0.98	0.65	0.49
	K 2	84.9	2.33	1.54	1.17
	K 3	87.9	2.41	1.59	1.21
	K 4	257.2	7.06	4.65	3.53
	K 5	330.2	9.06	5.97	4.53
	K 6	355.2	9.75	6.42	4.88
	K 7	770.3	21.15	13.92	10.58
	K 8	924.8	25.39	16.72	12.70
Daigurung	D 1	2.4	0.07	0.04	0.03
	D 2	9.6	0.26	0.17	0.13
	D 3	24.6	0.68	0.45	0.34
	D 4	31.8	0.87	0.57	0.44
	D 5	35.8	0.98	0.65	0.49
	D 6	62.4	1.71	1.13	0.86
	D 7	166.6	4.58	3.01	2.29
Nambar	N 1	4.4	0.12	0.08	0.06
	N 2	12.4	0.34	0.22	0.17
	N 3	16.8	0.46	0.30	0.23
	N 4	23.3	0.64	0.42	0.32
	N 5	26.9	0.74	0.49	0.37
	N 6	58.0	1.59	1.05	0.80
	N 7	76.9	2.11	1.39	1.06
Barneuria	B 1	0.2	0.004	0.002	0.002
	B 2	1.8	0.05	0.03	0.02
	B 3	5.8	0.16	0.11	0.08
	B 4	13.2	0.36	0.24	0.18
	B 5	29.4	0.81	0.53	0.40
Deopani	Dp 1	4.5	0.12	0.08	0.06
	Dp 2	5.3	0.14	0.10	0.07
	Dp 3	9.7	0.27	0.17	0.13
	Dp 4	56.0	1.54	1.01	0.77
	Dp 5	65.8	1.81	1.19	0.90
	Dp 6	89.0	2.45	1.61	1.22
	Dp 7	146.9	4.04	2.65	2.01
Jabrajan	J 1	0.9	0.03	0.02	0.01
	J 2	2.0	0.06	0.04	0.03
	J 3	3.2	0.09	0.06	0.04
	J 4	8.6	0.24	0.16	0.12
Neperpatti	Np 1	1.5	0.04	0.03	0.02
	Np 2	3.6	0.10	0.06	0.05
	Np 3	9.8	0.27	0.18	0.13
	Np 4	14.4	0.40	0.26	0.20
Harihajan	H 1	3.4	0.09	0.06	0.05
	H 2	6.0	0.16	0.11	0.08
	H 3	7.1	0.19	0.13	0.10
	H 4	24.3	0.67	0.44	0.33

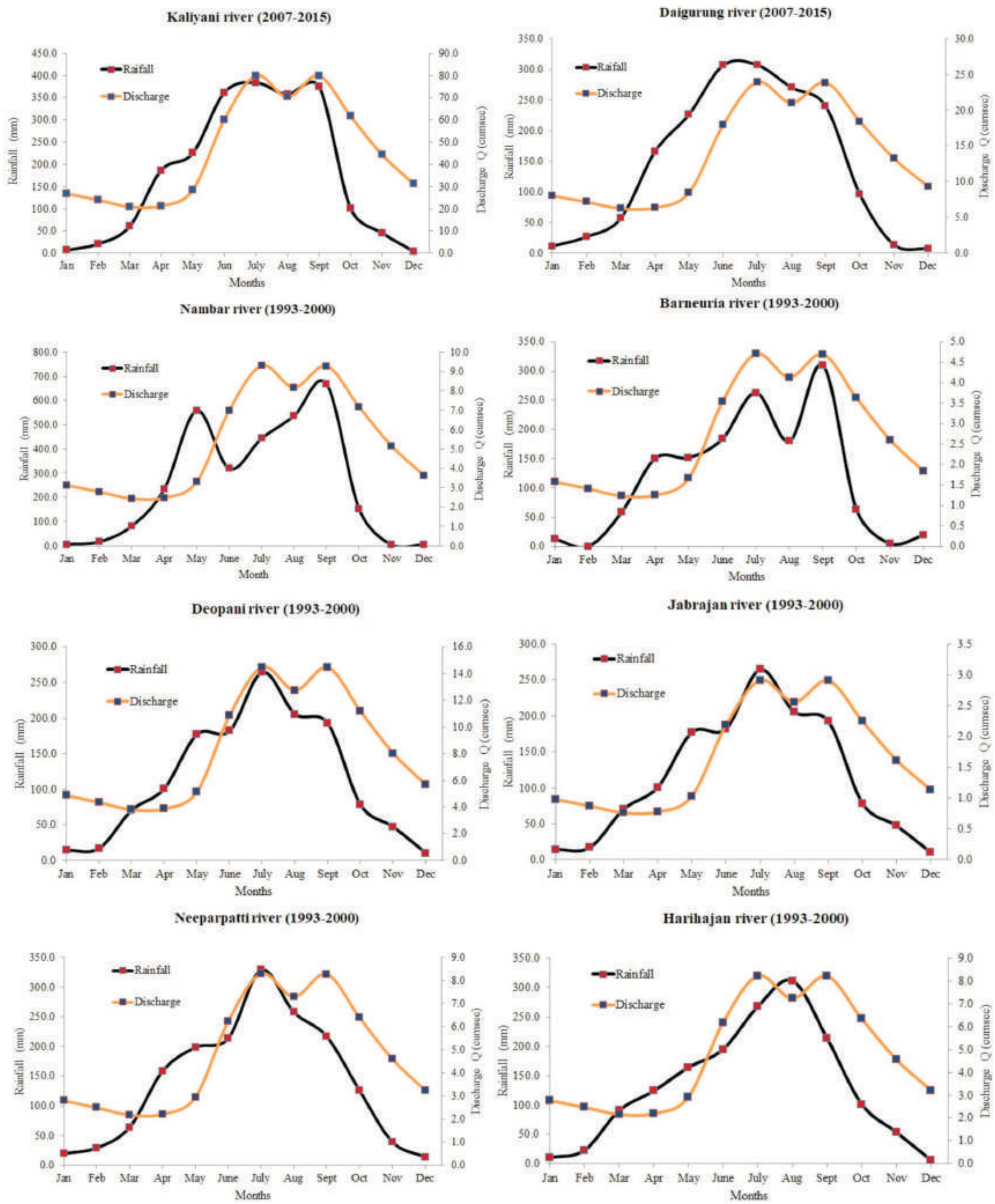

Fig. 4. Discharge vs. Average rainfall analysis of the eight river basins for the period of 1993-2000.

from the assessment of power generation potential indicate that the area has huge potential for small (2-25 MW) to mini (100 kW-2 MW) scale multipurpose hydro projects. The eight numbers of watersheds present in the study area have a total power generation potential of 48.4 MW. Out of which, 54.16% (26.24 MW) of power can be generated from the Kaliyani river alone. The maximum power output i.e., 12.4 MW, can be obtained in the case when the weir and powerhouse location is at K7 & K8 respectively. Next to Kaliyani river, the other major power outputs are 24.65 % (11.94 MW) for Deopani River, 9.72% (4.71 MW) for Nambar River and 6.53 % (3.16 MW) for Daigurung River. Daigurung watershed is having 7 numbers of scenarios where mini multipurpose hydropower projects can be developed. Out of these the maximum power can be generated in case of D7-D8 (898.6 kW), even though the head gain is only 20 m. In spite of having good amount of power generation potential, this site is not so favorable for the mini hydel project as 20 m of head is obtained at the expense of 7.60 km horizontal distance which is not a cost-effective design. In another case when the weir-powerhouse location is at D2 and D5, maximum head of 160 m can be obtained and 408.1 kW of energy can be harnessed within a relatively short horizontal distance of 5.74 km. The remaining 2.38 MW (4.92 %) of power can be generated from the Barneuria, Jabrajan, Neperpatti and Jabrajan streams.

Potential for Irrigation in the Vicinity

Fig. 5.a-c show the major land use pattern near the proposed SHP site on Kaliyani, Daigurung and Nambar Rivers. Near Kaliyani

Table 3: Shown the location of the gauged sites used for the discharge measurements with the results both for pre- and post-monsoon periods

Stream	Measured site	Channel Width (W) in m	Average channel Depth (D) in m	Cross sectional Area in m2	Surface velocity in m/Sec	Average velocity in m/sec	Dis-charge in m3/s
Pre-monsoon period							
Kaliyani	K8	51	0.533	27.2	0.697	0.558	15.18
Daigurung	D7	21.2	0.556	11.8	0.296	0.237	2.8
Nambar	N7	14.8	0.662	9.8	0.172	0.137	1.35
Barneuria	B5	8.4	0.976	8.2	0.076	0.061	0.5
Deopani	Dp7	25.4	0.44	11.2	0.358	0.286	3.21
Jabrajan	J4	3.5	0.171	0.6	0.25	0.2	0.12
Post-monsoon period							
Kaliyani	K8	53.7	0.562	30.179	0.982	0.7856	23.71
Daigurung	D7	21.6	0.606	13.090	0.391	0.3128	4.09
Nambar	N7	16.2	0.682	11.048	0.197	0.1576	1.74
Barneuria	B5	8.6	1.041	8.953	0.099	0.0792	0.71
Deopani	Dp7	26.8	0.451	12.087	0.741	0.5928	7.17
Jabrajan	J4	3.6	0.246	0.886	0.452	0.3616	0.32

site, the area is mainly covered by forests which constitute about 53.2 sq km of the area while the cropped lands comprise 22.9 sq km of area. An area of 15.2 sq km of barren lands is present near the proposed site which has not been utilized for agricultural activity. Other significant land use pattern includes: settlements covering 6.03 sq km of the area, grasslands constitute 2.67 sq km, tea garden 1.8 sq km and water bodies occupying the rest (Fig. 5a). For Daigurung site (Fig. 5b), 28.61 sq km area is occupied by dense mixed forest; 11.5 sq km area by croplands; 18.8 sq km is of barren lands; 1.6 sq km of settlements and the rest 1.29 sq km of the area occupied by water bodies. Likewise, the land use pattern near Nambar site is manly dominated by forest land which constitute 49.85 sq km area followed by 23.85 sq km area of crop lands, 10.58 sq km of settlements, 6.65 sq km of tea garden areas, 6.28 sq km of barren lands and 1.63 sq km occupied by rivers and other water bodies (Fig. 5c).

A plan for an irrigation canal system has been prepared for all three proposed sites (Fig. 5d-f). The main canal has been linked to the trail race tunnel (TRT) for each site. Trenches are proposed for maintaining the slope of the canal where required. The main canal

Table 4: Shown the results of estimated power output in kW at each site of all the eight numbers of watershed

River basins	Weir	Powerhouse	Elevation (m)		Head H (m)	Discharge Q (m3/sec)	HRT (in km)	Power in kW
			From	To				
Kaliyani	K1	K2	380	320	60	0.98	11.99	576.8
	K2	K3	320	300	20	2.33	1.60	457.1
	K3	K4	300	260	40	2.41	10.55	945.7
	K4	K5	260	240	20	7.06	2.12	1385.2
	K5	K6	240	200	40	9.06	7.90	3555.1
	K6	K7	200	180	20	9.75	14.20	1913.0
	K7	K8	180	120	60	21.15	20.10	12448.9
	K8	K9	120	100	20	25.39	10.52	4981.5
Daigurung	D1	D2	600	420	180	0.07	2.51	123.6
	D2	D3	420	360	60	0.26	1.97	153.0
	D3	D4	360	300	60	0.68	2.18	400.2
	D4	D5	300	260	40	0.87	1.59	341.4
	D5	D6	260	200	60	0.98	7.57	576.8
	D6	D7	200	160	40	1.71	9.98	671.0
	D7	D8	160	140	20	4.58	7.60	898.6
	D2	D5	420	260	160	0.26	5.74	408.1
Nambar	N1	N2	820	720	100	0.12	3.84	117.7
	N2	N3	720	620	100	0.34	1.45	333.5
	N3	N4	620	600	20	0.46	1.29	90.2
	N4	N5	600	320	280	0.64	4.06	1757.9
	N5	N6	320	260	60	0.74	3.66	435.5
	N6	N7	260	160	100	1.59	10.41	1559.7
	N7	N8	160	140	20	2.11	7.01	413.9
Barneuria	B1	B2	420	400	20	0.002	1.12	0.4
	B2	B3	400	280	120	0.03	2.74	35.3
	B3	B4	280	200	80	0.11	2.97	86.3
	B4	B5	200	140	60	0.24	7.79	141.5
	B5	B6	140	120	20	0.53	4.76	103.9
Deopani	Dp1	Dp2	860	780	80	0.12	1.03	94.2
	Dp2	Dp3	780	700	80	0.14	1.49	109.9
	Dp3	Dp4	700	640	60	0.27	3.13	158.9
	Dp4	Dp5	640	620	20	1.54	5.52	302.1
	Dp5	Dp6	620	380	240	1.81	3.81	4261.5
	Dp6	Dp7	380	220	160	2.45	10.60	3845.5
	Dp7	Dp8	220	140	80	4.04	2.30	3170.6
Jabrajan	J1	J2	360	260	100	0.03	1.14	29.4
	J2	J3	260	220	40	0.06	0.35	23.5
	J3	J4	220	160	60	0.09	1.18	52.9
	J4	J5	160	140	20	0.24	1.84	47.1
Neperpatti	Np1	Np2	600	440	160	0.04	0.84	62.7
	Np2	Np3	440	220	220	0.10	4.25	215.8
	Np3	Np4	220	160	60	0.27	3.53	158.9
	Np4	Np5	160	120	40	0.40	5.13	156.9
Harihajan	H1	H2	720	560	160	0.09	1.61	141.2
	H2	H3	560	260	300	0.16	2.05	470.8

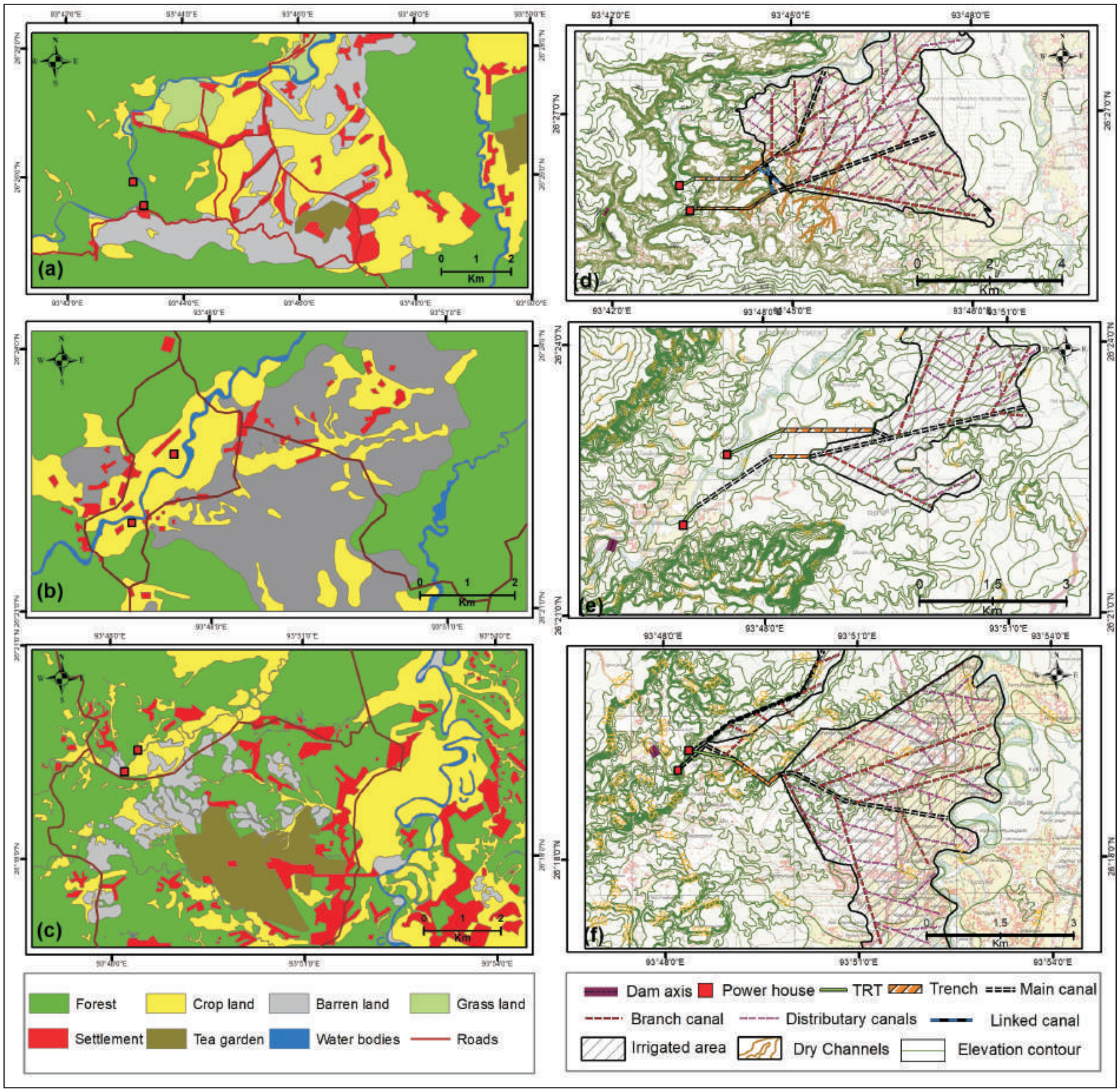

Fig 5. Showing land use land use pater of the area near the vicinity of proposed SHP sites (a, b, and c) and the plan for proposed canal networks used for supply of water to crop and barren lands near the vicinity of the proposed SHP sites at Kaliyani (d), Daigurung (e) and Nambar Rivers (f).

runs the maximum distance following the slope of the contours. Here in the plan, the available dry channels are used to attain the required gradient. The natural slope available in those dry channels can be best utilized to irrigate more areas present nearby. Only those areas falling on the left bank of the Dhansiri area are considered in the present study. Branch canals will carry the water from the main canal both towards the right and left, where suitable slopes are available. These are contour canals and spread more to cover the maximum area. The water is then distributed to the agriculture and barren lands by a network of distributary canals. Linked canals will connect two main canals as in the case for Kaliyani site.

Discussion

Studies on rainfall distribution over the study area show that the northeastern portion of the area received the highest amount of annual precipitation compared to the south-southwestern part of the area. This prominent low rainfall zone in the southern parts of the area results from the rain-shadow effect cast by the Meghalaya plateau that obstructs the southwest monsoons and induces heavy orographic rainfall on the windward hillslopes, leaving scanty moisture to be precipitated in the rain shadow areas. Similar trend has been observed in studies carried out by Das *et al.* (2024), where daily rainfall data for southwest monsoons during 1991–2020 over the entire NER depicts the prominent lows cast by the orographic effect. Bokajan tea estate, which recorded the lowest rainfall (1063.2 mm), falls in this zone.

Estimation of discharge of ungauged catchments has been attempted by many researchers around the globe, mostly after the launch of the Predictions in Ungaged Basins (PUB) initiative of the International Association of Hydrological Sciences (IAHS) (Sivapalan *et al.,* 2003). Area ratio methods have been considered the most effective techniques of flow estimation and have been tested in southern New England and New York State in the USA (Archfield and Vogel, 2010; Gianfagna *et al.,* 2015), in the Western Black Sea Region of Turkey (Ergen and Kentel, 2016), in northern

China by Li *et al.* (2019), and also in the Gumara River Basin, Ethiopia, by Ayele (2020). The effectiveness of the area ratio method was evaluated in predicting stream flow at ungauged locations in the Mahanadi River Basin, India (Nruthya and Srinivas, 2015). The present investigation also confirms close resemblance between the estimated discharge using area ratio methods when compared with the rainfall data for each catchment. From the discharge *vs.* rainfall plots in Fig. 4, it is observed that with every increase and decrease in the intensity of rainfall, there is a corresponding increase and decrease in discharge, at least in the same trend, which signifies the direct relationship between the rainfall intensity and discharge of the river. For the Daigurung River Basin, rainfall data is not available for the period under consideration; the only data available, *i.e.,* for the period 2007 to 2015, do not show the same trend as that of the discharge. Minor variations observed in the graphs are due to the fact that the rainfall data available is only from the tea estates located at the foothills of the Karbi hills. It is assumed that individual river basins as a whole receive the same amount of precipitation regardless of their position in the plains or in the hilly areas. The main objective of this comparative study is only to validate the results, which in turn were established successfully.

Hydropower assessment using FDCs enables determining discharge corresponding to three levels of dependability, *viz.*, 50%, 75%, and 90%. Kusre *et al.,* (2010) have estimated the theoretical achievable hydropower potential of nine streams in the Umkhen catchment of the nearby Kopili River in Meghalaya. Their works reported a power generation capacity of 132.18 MW, 18.18 MW, and 9.91 MW at 50%, 75%, and 90% dependability discharge, respectively, from Umkhen. A similar methodology has been adopted for hydropower assessment in the present study (Table 2) as used elsewhere in Sunkoshi River Basin in Nepal (Bhattarai *et al.,* 2024), in Hhaynu River-Mbulu, Tanzania (Ngoma, 2024) and in the Sangu River Basin of Bangladesh (Ahad and Shams, 2024).

From Table 3, it has been observed that the measured discharge during the post-monsoon period is generally higher than that of the pre-monsoon period. As all the streams under consideration are spring-fed ones, the flow of these streams largely depends upon the availability of water in the catchment area and also the position of the water table. During the monsoon period, the overall water availability in these hilly catchments increased considerably. This entrapped groundwater is then released to the rivulet of 1^{st} and 2^{nd} order drainage and finally to the main stream, hence maintaining a higher discharge in the post-monsoon period. The measured discharge shows close resemblances with the estimated discharge obtained from the FDC's (Table 2-3) and has been considered in estimating the power output at each previously identified 46 sites (Table 4).

The LULC map prepared for the proposed SHP sites on the Kaliyani, Daigurung, and Nambar rivers (Fig. 5 a-c) shows the enormous irrigable potential in the downstream areas using canal systems. The identified irrigation potential at Kaliyani site is 1745.09 hectares, which includes 1041.5 hectares of cropland where active cultivation is going on and 703.5 hectares of barren land, which can be upgraded to productive lands through the proposed irrigation system. Fig. 5e shows the proposed canal network system for the Daigurung site, through which a total area of 713.6 hectares, including 210.1 hectares of croplands and 503.5 hectares of barren lands, can be irrigated. Whereas, the proposed irrigation canal network for Nambar site will be able to supply water to 810.9 hectares of agricultural lands, 122.9 hectares of barren lands and 169.1 hectares of tea plantation areas present in the vicinity (Fig. 5f).

Besides the provision of adequate power supply to the locale, the proposed SHP projects will additionally supply irrigation waters to the nearby plain areas in Karbi Anglong and adjacent Golaghat Districts of Assam, thus boosting agricultural activities in these tribal areas. Furthermore, increased rural electrification can facilitate the development of industries dependent on agriculture and forestry, which will improve the area's economy and social upliftment of the whole area.

Conclusions

The hydrological studies of existing surface water resources present in one of the tribal areas of central Assam indicate its enormous hydropower potential. The region has the capacity to generate 48.4 MW of power in eight numbers of watersheds which also have good irrigation potential. Decentralized power generation through numbers of SHPs in the area coupled with flow-based canal system can be able to resolve the rural electrification problem and also boots agricultural activity in this remotest part. This is important as the state of Assam is presently a power deficit state, despite having huge water resources. The tribal communities mainly the Karbi peoples reside in the Karbi Anglong are having poor economic conditions, and agriculture is the backbone of the tribal society. Therefore, an irrigation-based small-scale multipurpose hydropower project is the only way forward for the sustainable development of the region. The present study emphasizes only three sites out of 46, to highlight the enormous irrigation potential of these hilly watersheds. Thus, the area demands future detailed studies for sustainable development of all the water resources in the area.

Authors' Contributions

MPB: Study, Conception and Design, Analysis, Data Collection, Draft Manuscript Preparation, Interpretation of Results. **DBB:** Conception and Design, Analysis and Interpretation of Results, Reviewing and Editing. **UG:** Analysis and Interpretation of Results, Reviewing and Editing. **TKG:** Analysis and Interpretation of Results

Conflict of Interest

The authors do not have any conflict of interest.

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