ACADEMICIA

ISSN: 2249-7137 Vol. 11, Issue 7, July 2021 Impact Factor: SJIF 2021 = 7.492

ACADEMICIA
An International Multidisciplinary Research Journal
(Double Blind Refereed & Peer Reviewed Journal)

DOI: 10.5958/2249-7137.2021.01741.9

SELECTION OF BEST LOCATION FOR SMALL HYDROPOWER PLANT (SHP) ALONG CHAMKHAR RIVER, BHUTANUSING ANALYTICAL HIERARCHY PROCESS (AHP)

Leki Dorji*; Phuntsho Tashi; Jamyang Seldon***; Dorji Letho******

*Civil Engineering and Engineering Geology Department,
College of Science and Technology, Royal University of BHUTAN
Email id: lekidorji.cst@rub.edu.bt

ABSTRACT

Hydropower development activities have been playing an indispensable role in enhancing Bhutan's economy and driving towards its goal of becoming a self-reliant nation. Hydropower being a renewable source of energy with minimal environmental impacts has always synchronized with Bhutan's strict environmental regulations and policies. Despite having remarkable hydropower potential, it has been able to harness only a fraction of the total potential hydropower production only due to various challenges faced by the hydropower sector. There is a lack of in-house resources and experienced local expertise to carry out the specific assessment. Large-scale hydropower projects not only have high upfront cost and risk but also posing severe threats to the environment of terrestrial and riverine ecosystems. Run-off-river small hydropower plants (SHP) are considered to be most cost-effective and more importantly, they have relatively lesser impacts on the environment. It has been understood that river systems in Bhutan have numerous potential sites for SHPs despite facing a challenge in the selection of a suitable location. Hydropower development is a multi-dimensional approach that pivots on various factors and requires a multi-criteria decision analysis (MCDA). This study focuses on criteria prioritization of seven different criteria of locating an SHP along Chamkharriver that has been notable of its potentiality. The analytical hierarchy process (AHP) of MCDA is the most suitable method for selecting the most feasible locations of a hydropower plant in this study. From the total of ten potential sites that have been considered feasible through technical studies, eventually, seven were taken for further suitable analysis. Hence, the five quantitative and two qualitative criteria were used to scale down to the most suitable location using the AHP method. This paper's model resulted that among the criteria, the sanctuary buffer distance *(environmental aspect) to be a top priority criterion, followed by heritage (social aspect) and the next was the project cost (economic aspect).*

KEYWORDS: *SHP, Alternatives, AHP, Weight Age, Decision-Making*

1. INTRODUCTION

Bhutan, located at latitude 27.5142°N and longitude 90.4336°E is landlocked between India to the south and China to the north. It stretches across the southern belt of the Himalayas having an average elevation of about 8000 feet above mean sea level. The rich vegetative cover and abundant precipitation contribute to the continuous flow of water in its basin systems. Owing to its sloping steep terrain and perennial rivers, Bhutan has higher hydropower potential as most of the river systems are being fed by glaciers of the northern part of Bhutan. It has been estimated the feasible hydropower potential of 23760 MW from which only 2326 MW(6.3%) have been harnessed as of 2019 and RGoB anticipates achievinga minimum of 5000 MW by 2030 (RGoB, 2020).

Hydropower is a renewable and eco-friendly source of energy that has a minimal impact on the environment that accords with Bhutan's environment policy of maintaining 60% of land under forest cover for all times. Since the commencement of the first major hydropower plant (336 MW Chukha Hydropower Project) in 1974, hydropower has contributed to its regional development and economic progression through export to neighboring countries in surplus of the domestic requirements. The hydropower sector is responsible for 14% of the country's GDP and 27% of national revenue generated (Electric & Company, 2019). It has become the cynosure of Bhutan's goal towards achieving self-reliance and economic stability.

SHP scenario in Bhutan

Due to the narrow valley and swift-flowing rivers, a storage type of hydropower plant is usually not preferred in Bhutan with exception of a few hydropower plants like Puntsangchhu I and II. Due to its geographical features, a run-of-river hydropower plant is the most suited scheme for a country like Bhutan. Such a hydropower scheme is not only renewable but also has low greenhouse emissions and lesser environmental impacts (Lata et al., 2013).

Rural electrification has been one of the main challenges faced due to isolated villages in mountains and its difficulty in transmitting electricity through sloping terrain and thick forests. Rural Electrification Strategy of RGoB of 8th five-year plan (1998-2002) envisaged electrification of remote districts like Tashigang through decentralized small and mini-hydropower plants(OEZA, n.d.).

To stimulate regional development and boost economic growth in eastern Bhutan, RGoB and the Austrian Government through bilateral agreement started construction of 1.1 MW Tanjung SHP on 17th June 1993. The SHP faced economic viability deterioration at the initial stage caused by an increased cost of foreign components due to the devaluation of Bhutanese currency. It was later doubled its capacity to 2.2 MW in August 1994 and showed improvement in its economic viability. The initial completion deadline couldn't be met due to redesign work and inexperienced local contractors. The plant was completed and inaugurated on 22nd April 1996. It also suffered destabilization of headrace slope caused by heavy rainfall in 1995 which was later rehabilitated through foreign expertise. Some of the major challenges faced by other SHP like 600 kW Khaling and 750 kW Chenery hydropower plants were not being able to produce full output due to technical problems and insufficient water flow, especially during lean seasons(OEZA, n.d.).

Challenges and growing concerns of hydropower development in Bhutan

Even though Bhutan is a water-abundant country, some regions have been suffering from water scarcity provoked by the uneven distribution of annual water supply. Climate change may also take a toll on the country's hydropower development activities leading to drying up of rivers, reducing its discharge and decline in power generation, and downturn of economic benefits. A study conducted by NEC in 2016 revealed that some of the districts like Thimphu (Capital city), Haa, and Zhemgang may suffer water shortages by 2030 (Ranjan, 2018). On the other hand, the melting of glaciers has imposed threats to dams and adjoining settlements that may result from the flood occurrence such as Glacier Lake Outbreak Flood (GLOF).

Bhutan is highly reliant on external resources and expertise for its hydropower development currently. Hydropower debt in the last two years has amounted to Nu.16.2B which constitutes 58% of the country's total debt of Nu.28B as reported in Kuensel news 2020.The hydropower sector in Bhutan has been remarkably dependent on India for its financial aid and technical expert assistance.

The poorly implemented Environmental Impact Assessments have led to ramifications on its biodiversity, forest cover, water quality, air quality, and so on (Gawel & Ahsan, 2014). The National Environmental Commission (NEC) responsible for assessing various impacts of projects cannot enforce its assessment before an agreement of project development between two nations. This has led to the assessments being too late and irrelevant (Walker, 2016).

2. STUDY AREA

Chamkharchu basin lies roughly at latitude 27°00'00" N to 28°07'30" N and longitude 90°30'00" E to 91°00'00" E with an area about 3172.8 m² and elevation ranging from 300 m to 6900 m above mean sea level. Chamkharriver flows through Bumthang valley in the north to narrow gorges of Zhemgang to the south, meeting Mangdechhu and the Manas river, and then finally outlet to Brahmaputra River in the Assam state of India.

The river due to its high discharge and perennial nature endows substantial hydropower potential. However, after years of study, the plan for 770MW Chamkharchu-1 was withdrawn by National Assembly in May 2019 due to the anticipation of adverse environmental impacts and the expensive project that could be benefited from the proposed plant (Dendup, 2019). This decision has left many local people in zhemgang disappointed who were anxiously looking for the commencement of hydropower plant construction as its location lies near a protected area (Thrumshingla National Park) and biological corridor.

The immense hydropower potential of the river cannot be disregarded at times and hencethe possibility of developing an alternative location can be performed with the least adverse environment impacts criteria. As it has been studied that large-scale hydropower projects generally have massive repercussions on the environment despite being a "clean" form of energy. These impacts are such a displacement of settlements, loss of ecological habitat, and the extinction of endangered species. On the other hand, small-scale run-of-river schemes have minimal environmental effects requiring small investments.

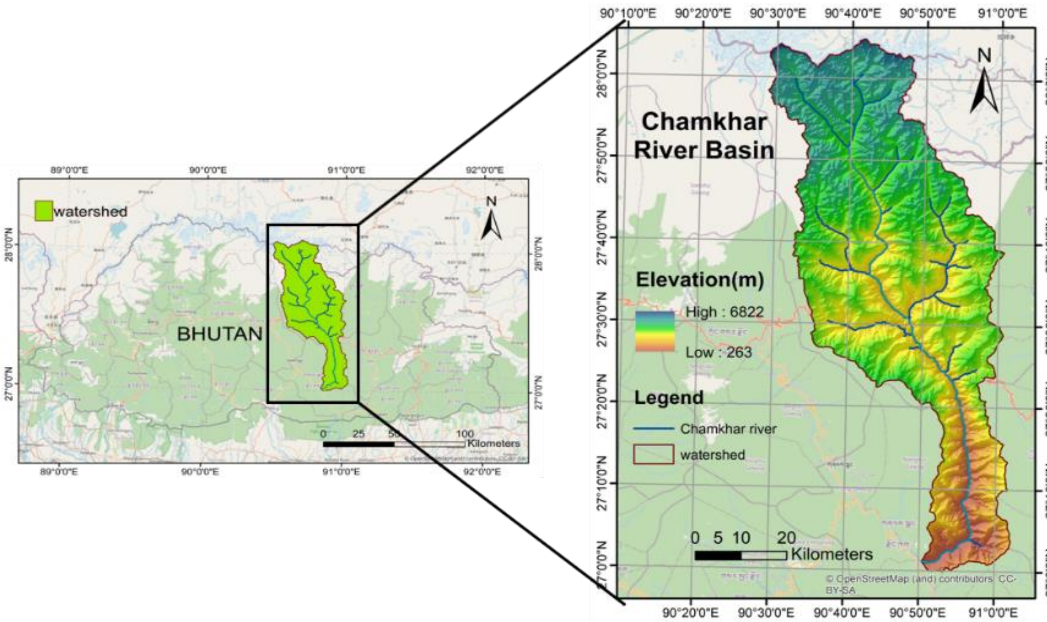


Fig.1 Chamkharchu basin (study area)

3. METHODOLOGY

The main objective of this study is to find the most suitable location for a small hydropower plant along the Chamkharriver that gives the most socio-economic benefits with minimal environmental impacts. A better understanding of factors affecting the development of SHP is a prerequisite in achieving this objective. By breaking down various alternatives and criteria, comparing these alternatives and synthesizing preferences can aid in solving complex decisions involved in hydropower development.

Analytical Hierarchy Process (AHP) is one of the methods of multi-criteria decision making developed by Thomas L. Eigenvector method has been adopted as prioritized calculation for weighing criteria asalternatives (Saaty, R. W. 1987). A hierarchical framework was adopted to rank the most suitable alternatives based on the goals and criteria developed.

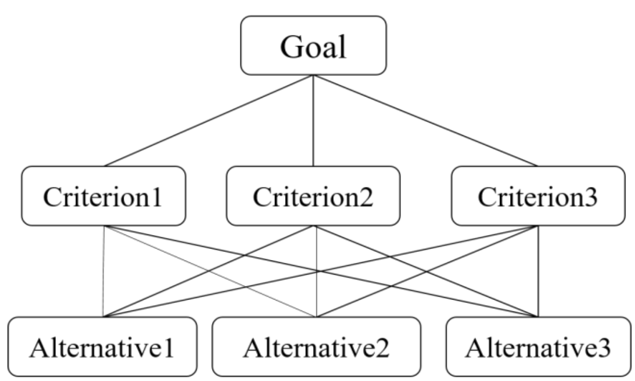


Fig. 2 Hierarchical framework

MCDA in hydropower development

Hydropower development involves various facets of technical, environmental, economic, and social factors that necessitate a multidisciplinary team of stakeholders at its planning phase. The development of hydropower has long-term investments with various associated risks that make decision-making more complex.

Among the variety of MCDM methods, Analytical Hierarchy Process (AHP) has been adopted in research relating to hydropower projects for criteria prioritization as it has some advantages in certain ways.The AHP method has been engaged successfully across many similar studies in the location analysis of small hydropower (Saaty et al. 1987). AHP method in the research has adoptedto select the most suitable location for SHP in Ranoli Canal, Gujarat (India) and to optimize criteria weightage (Rana & Patel 2020).The methodology developed to integrate the multi-criteria decision-making with stakeholder analysis for the development of hydropower plants in mountainous areas where the outcome was based on the ranking of the alternatives (Rosso M, et al 2014).

A Multi-criteria decision analysis was performed to determine the feasibility of developing small-scale hydropower projects in Thailand's Ping River Basin and to evaluate the pros and cons of the projects based on five key criteria such as electricity generation, engineering, and economics, socio-economics, environment, and stakeholder engagement (Supriyasilp et al, 2009). They assessed the environment criteria to be the most important in the opinion of experts (Supriyasilp et al., 2009). Likewise, the importance given to each criterion would depend on the area of study and the regulations in place.

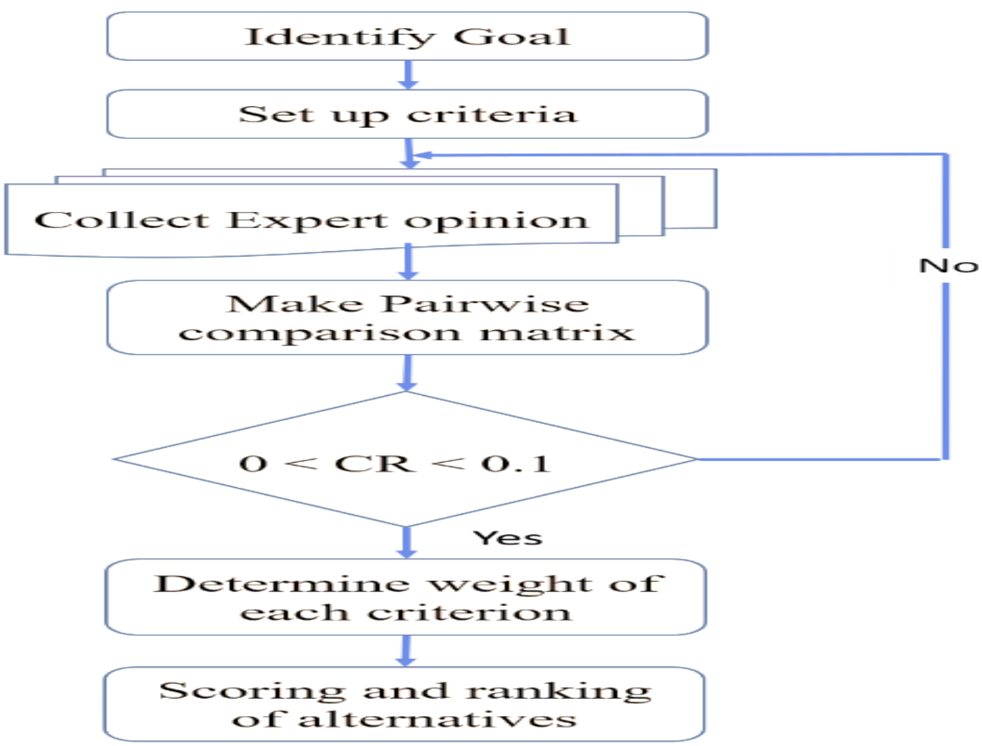
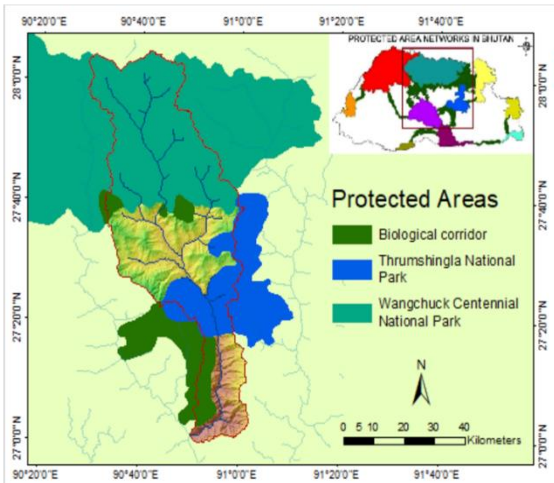


Fig.3 AHP (Methodology)

Identifying alternatives

Hydrologic modeling and technical studies were carried out to develop a search algorithm in the Chamkhar basin to determine the feasible locations. After filtering out the locations that fell into the protected areas and taking into consideration the installed capacity, the ten most feasible locations were identified along the rivers shown in table 1.



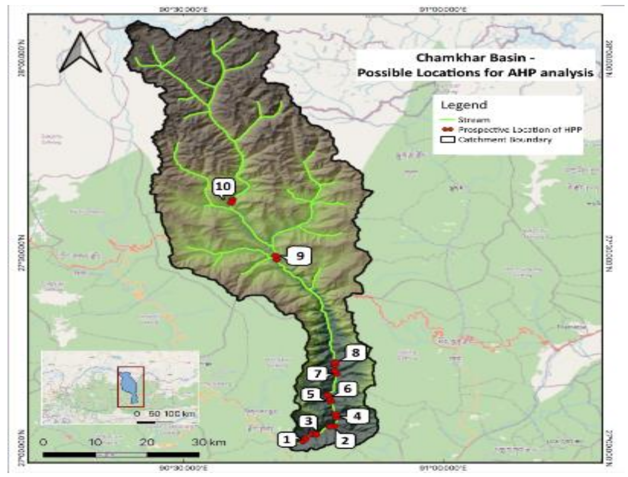


Fig.4 Protected areas in the basinFig.5 Prospective feasible locations

TABLE 1 PROSPECTIVE FEASIBLE LOCATIONS AS PER TECHNICAL STUDIES

Prospective Location	Elevation at intake (m)	Elevation at powerhouse (m)	Elevation difference (m)	Drainage Area (m^2)	Power (MW)
1	2675.73	2655.06	20.67	1034.67	5.097
2	2504.02	2465.38	38.64	2263.72	20.841
3	1009.10	952.00	57.10	2731.23	33.756
4	904.01	878.03	25.97	2845.23	15.524
5	752.00	732.24	19.58	2895.01	11.798
6	732.05	688.01	44.04	2944.56	27.232
7	620.08	595.21	24.87	2983.23	15.589
8	507.07	425.08	81.99	3001.31	51.697
9	377.10	344.13	31.97	3096.55	20.795
10	318.06	298.05	20.01	3168.80	13.322

3.1. Establishing Criteria

Hydropower project development is a complex decision-making process, which requires the involvement of different stakeholders, and their opinions based on the perceptions of various aspects. The seven most feasible key criteria which comprise both qualitative and quantitative attributes identified are land cover type, the proximity of nearest settlement, sanctuary buffer distance, project cost, heritage, population density, and nearest transmission line distance.

The land cover type and heritage criteria are the qualitative types where a scoring system needs to be adopted. Considering the various types of the land cover type identified along the basin, the intensity of the effect on these land cover types by a hydropower project a scoring system was adopted for land cover type. There are numerous cultural heritage sites located in the study area and based on the number of heritage sites located within a certain radial distance of the prospective locations, a scoring system was developed as shown in table 2.

TABLE 2 SCORING OF QUALITATIVE PARAMETERS

Parameters (Score)	Land cover type	Heritage (Buffer (m))
0	-	
1	Forest	>2 sites within a 1 km distance
2	Urban	2 sites within a 1 km distance
3	Agricultural	2 sites within a 2 km distance
4	Industrial	1 site within 2 km distance
5	Uninhabited	No site within 2 km distance

For these quantitative criteria: proximity of nearest settlement, sanctuary buffer distance, and nearest transmission line distance, the distance was measured in kilometers from the alternative locations using google earth. The population map by region for different gewogs in the basin in person per sq. km was obtained from the latest data available for NSB.

The cost-sensitive parameters of SHP are head and installed capacity Regression analysis performed to derive the correlation between these parameters and the developed correlation that was verified with cost data through which it was developed (Mishra et al. 2012). A maximum deviation of ±10% was noticed, indicating a good correlation for the cost estimate of SHP at the pre-feasibility stage. The developed correlation is given by equation (1).

$$C = 6.882 \, x \, H^{-0.0782} x \, P^{0.6369} \quad (1)$$

Where, C = Cost per kW in Indian Rupees, P = Installed capacity in kW, and H = Head in meters

TABLE 3 DECISION MATRIX

Prospective Locations	Land cover type	The proximity of the nearest settlement	Sanctuary buffer distance	Project cost	Heritage	Population density	Nearest transmission line distance
1	1	7.69	2.771	1659.31	4	9.15	20.47
2	1	1.91	2.24	1769.84	5	8.6	25.57
3	1	2.82	1.986	2061.14	5	8.6	26.64
4	1	2.54	1.53	1060.413	5	8.6	27.04
5	1	1.07	2.52	3556.83	5	8.6	24.01
6	1	1.49	3.62	2418.06	5	8.6	24.59
7	1	1.72	4.78	2422.839	5	8.6	26.09
8	1	1.04	3.24	1553.04	5	4.14	26.52

9	3	0.92	1.06	2801.274	5	8.5	21.4
10	3	0.1	1.27	2252.06	4	4.38	26.56

TABLE 4 NORMALIZED DECISION MATRIX

Prospective Locations	Land cover type	The proximity of nearest settlement	Sanctuary buffer distance	Project cost	Heritage	Population density	Nearest transmission line distance
1	0.333	1.000	0.580	0.639	0.800	1.000	1.000
2	0.333	0.248	0.469	0.599	1.000	0.940	0.801
3	0.333	0.367	0.415	0.514	1.000	0.940	0.768
4	0.333	0.330	0.320	1.000	1.000	0.940	0.757
5	0.333	0.139	0.527	0.298	1.000	0.940	0.853
6	0.333	0.194	0.757	0.439	1.000	0.940	0.832
7	0.333	0.224	1.000	0.438	1.000	0.940	0.785
8	0.333	0.135	0.678	0.683	1.000	0.452	0.772
9	1.000	0.120	0.222	0.788	1.000	0.929	0.957
10	1.000	0.013	0.266	0.471	0.800	0.479	0.771

Deriving weightage of criteria

A survey questionnaire was conducted where 15 responses were collected from stakeholders working under various hydropower projects and corporations. Saaty's 1-9 scale, as shown in Table 5 was used to determine the scale of the relative importance of each pair, and the aggregation of judgments of the comparison matrix was performed using the geometric mean method. Moreover, the pairwise comparison matrix was formed through an aggregation procedure to derive the weights of each criterion.

TABLE 5 SAATY'S SCALE OF RELATIVE IMPORTANCE

Intensity of importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Absolute importance
2,4,6,8	Intermediate values

The geometric mean is found using the equation,

$$\left(\prod_{i=1}^{n} a_i\right)^{1/n} = \sqrt[n]{a_1\, a_2\, a_3\, \ldots .\, a_n} \quad (2)$$

TABLE 6 PAIRWISE COMPARISON MATRIX (A1)

Criteria	Land cover type	The proximity of nearest settlement	Sanctuary buffer distance	Project cost	Heritage	Population density	Nearest transmission line distance
Land cover type	1.000	1.739	0.207	0.339	0.253	1.716	0.787
Proximity of nearest settlement	0.575	1.000	0.257	0.388	0.395	1.469	0.512
Sanctuary buffer	4.839	3.896	1.000	3.061	1.030	4.531	3.774
Project cost	2.948	2.580	0.327	1.000	0.245	2.433	3.248
Heritage	3.950	2.534	0.971	4.083	1.000	3.704	3.945
Population density	0.583	0.681	0.221	0.411	0.270	1.000	0.754
Nearest transmission line distance	1.270	1.954	0.265	0.308	0.254	1.326	1.000

Checking for consistency of weights obtained

A pairwise comparison matrix formed through the judgments of experts was taken to check for consistency. Since these numeric values are derived from the subjective preferences of individuals, some inconsistencies in the final judgment are inevitable. After all, a consistency ratio of 10% indicating the consistency of weights, and the Consistency Ratio (CR) is given by equation (3).

$$CR = \frac{CI}{RI} \quad (3)$$

where CI represents Consistency Index and RI represents Randomness Index,Randomness Index (RI) depends on the number of criteria (dimension of pairwise comparison matrix). The value of the Randomness Index was given by Saaty (1980) as shown in table7.

TABLE 7 RANDOMNESS INDEX (SAATY, 1980)

n		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI		0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Finally, for the Suitability Ranking, the total weighted score is calculated using equation (4) to find suitability. The percentage of total weightage can be adopted to determine the degree of suitability for establishing a small hydropower plant. Hence, the prospective locations can be ranked based on the suitability score where a higher score indicates higher suitability.

$$Suitability\ (S) = (R_1 x W_1) + (R_2 x W_2) + \ldots. + (R_n x W_n) \quad (4)$$

ISSN: 2249-7137 Vol. 11, Issue 7, July 2021 Impact Factor: SJIF 2021 = 7.492

where R is the score of each parameter and W is the weight of each criterion.

4. RESULT AND DISCUSSION

4.1.Consistency Inspection

Initially, the samples of expert judgments collected were 20 but after individual consistency inspection, only 15 were found out to be consistent. Therefore, only consistent data were used for carrying out the AHP. **Consistency Factor (CF)**is determined based on the geometric mean of elements in a row in pairwise comparison matrix gives consistency factor of that row as given by equation (5).

$$CF = (C1\ x\ C2\ x\ C3\ x\ C4\ x\ C5\ x\ C6\ x\ C7)^{\frac{1}{7}}$$
(5)

a. For calculating the Principal Eigen value (λ_{max}), the following processes were adopted.

$$CF = \begin{bmatrix} 0.635 \\ 0.559 \\ 2.689 \\ 1.251 \\ 2.482 \\ 0.495 \\ 0.681 \end{bmatrix}; \quad A2 = \begin{bmatrix} 0.635/8.739 \\ 0.559/8.739 \\ 2.689/8.739 \\ 1.251/8.739 \\ 2.482/8.739 \\ 0.495/8.739 \\ 0.681/8.739 \end{bmatrix} = \begin{bmatrix} 0.072 \\ 0.064 \\ 0.306 \\ 0.142 \\ 0.282 \\ 0.056 \\ 0.077 \end{bmatrix}$$

$\sum CF = 8.793$

$$A3 = A1\ X\ A2 = \begin{bmatrix} 0.523 \\ 0.473 \\ 2.177 \\ 1.077 \\ 2.121 \\ 0.402 \\ 0.564 \end{bmatrix}; \quad A4 = A3/A2 = \begin{bmatrix} 7.245 \\ 7.438 \\ 7.119 \\ 7.566 \\ 7.515 \\ 7.140 \\ 7.286 \end{bmatrix}$$

$\bar{X} = \lambda_{max} = (7.245+7.438+7.119+7.556+7.515+7.140+7.286)/7 = 7.330$

Matrix A4 gives Eigenvalues for each criterion and the average of matrix A4 gives the Principal Eigenvalue (λ_{max}).

b. To determine the Consistency Index (CI), Randomness index (RI), and Consistency Ratio (CR), the following equations were adopted:

$$CI = \frac{(\lambda_{max}\text{-}n)}{(n\text{-}1)} \quad (6)$$

$CI = \frac{(7.330-7)}{(7-1)} = 0.05497$For a 7x7 matrix, the RI = 1.32

$$CR = \frac{CI}{RI} \quad (7)$$

$CR = \frac{0.05497}{1.32} = 0.04164 < 0.1$ (Acceptable)

The inconsistency in the data collected is less than 10% which is an acceptable limit for proceeding further with the AHP.

Weights and alternative rankings

TABLE 8 WEIGHTAGE OF EACH CRITERION

Criteria	**The weightage (%)**
Land cover type	7.947
The proximity of nearest settlement	6.043
Sanctuary buffer	29.108
Project cost	16.809
Heritage	26.552
Population density	5.155
Nearest transmission line distance	8.387

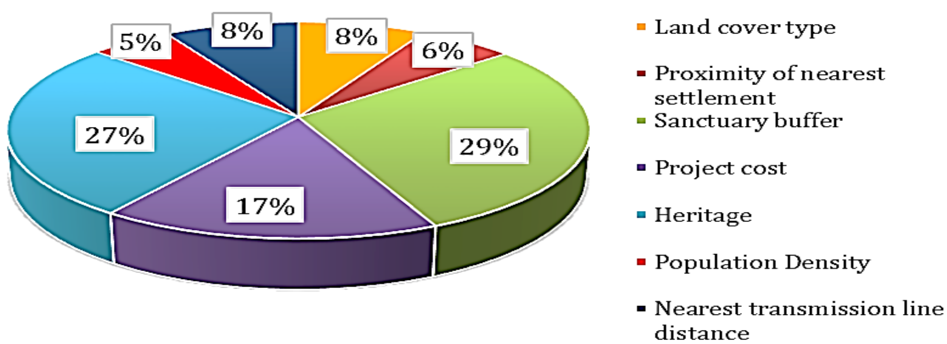


Fig.6 Weight age of criteria

After determining the weights of each criterion (table 8), the criteria with the highest weight age are Sanctuary buffer with 29% followed by heritage with 27%, and then project cost with 17%.

TABLE 9 APPLYING WEIGHTS TO SCORE FOR EACH ALTERNATIVE

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
Weights	**0.0795**	**0.0604**	**0.2910**	**0.1681**	**0.2655**	**0.0515**	**0.0839**
1	0.333	1.000	0.580	0.639	0.800	1.000	1.000
2	0.333	0.248	0.469	0.599	1.000	0.940	0.801
3	0.333	0.367	0.415	0.514	1.000	0.940	0.768
4	0.333	0.330	0.320	1.000	1.000	0.940	0.757
5	0.333	0.139	0.527	0.298	1.000	0.940	0.853
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7	0.333	0.224	1.000	0.438	1.000	0.940	0.785
8	0.333	0.135	0.678	0.683	1.000	0.452	0.772
9	1.000	0.120	0.222	0.788	1.000	0.929	0.957
10	1.000	0.013	0.266	0.471	0.800	0.479	0.771

TABLE 10 SUITABILITY MATRIX AND CORRESPONDING RANKINGS

Possible Locations	Suitability score	Suitability score percentage	Rank
1	0.7109	71.09	3
2	0.6597	65.97	7
3	0.6345	63.45	8
4	0.6852	68.52	5
5	0.6239	62.39	9
6	0.7161	71.61	2
7	**0.7844**	**78.44**	**1**
8	0.7003	70.03	4
9	0.6773	67.73	6
10	0.5385	53.85	10

Location 7 as in table 10, was found to be the most suitable as rank 1 based on the matrixfor the run-of-river small hydropower project. It is followed by location 6, the second most suitable, and the next one location 3. It has been notable, these locations are more economic benefits having fewer impacts on the environment as well the heritage comparison to others. It has been indicated for the outcomes that the highest prioritized is given to the Sanctuary buffer distance (Environmental aspect) - 29% and the Distance from Heritage Sites (Social Aspect) - 27%; followed by the Project Cost (Economic Aspect) - 17%. The result concurs with the fundamental pillars of Gross National Happiness which is the guiding philosophy of the country. It states that the economic growth of the country should progress sustainably through preserving the environment and cultural heritage.

5. CONCLUSIONS AND RECOMMENDATIONS

The primary focus of this study was to assist in prioritizing criteria and factors affecting site selection for the upcoming small hydropower plants in Bhutan. Hydropower development being a multidisciplinary approach involves various processes, complexities and expertise though, it is bound to integrate the political, environmental, andsocio-economic aspects that for the multicriteria decision-making approaches.

The study revealed environmental factors to play a vital role in hydropower development in Bhutan followed by cultural heritage and the project cost as well. These results will guide any planners in aligning with environmental acts and regulations to prevent form the detrimental effects on its environment and heritage. The protected areas that constitute national parks, a nature reserve, wildlife sanctuaries, and biological corridors cover 43% or 16,396 km² of Bhutan’s total landmass which is taken care of in this study. It is also been noticed that the preservation and promotion of heritage sites have been a top priority in a country for its unique culture and heritage. Bhutan has been reliant on external funds especially India for its hydropower development which has resulted in a whopping amount of money as debt to the country for the large hydropower, hence this paper may help to focus on the small development of hydropower projects.

Such prioritization would differ with the state/national interest and regulations in place, which becomes evident through expert weightage calculations. The criteria adopted based on site specifications and AHP can serve as a reference for researchers venturing into small-scale

ISSN: 2249-7137 Vol. 11, Issue 7, July 2021 Impact Factor: SJIF 2021 = 7.492

hydropower plant developments. However, the criteria can differ based on the location of the study area, and the site studies which were a limitation in this study can further assist in refining the criteria. Furthermore, other multicriteria decision-making approaches like ANP, TOPSIS, FUZZY decision making, and other advanced methods can be adopted to validate the results.

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