

Article

Assessment of Hydropower Potential in the Upper Indus Basin: A Geographic Information System-Based Multi-Criteria Decision Analysis for Sustainable Water Resources in Pakistan

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Abstract: The development of hydropower projects is crucial to addressing Pakistan's ongoing energy and financial crises. Despite the country's abundant hydropower resources, particularly in the northern regions, these have not been adequately explored, while energy consumption and supply issues have persisted for the past two decades. Focusing on Sustainable Development Goal (SDG-7): "Ensure access to affordable, reliable, sustainable, and modern energy", this study aimed to assess the hydropower potential at suitable sites in the Upper Indus Basin (Pakistan) by integrating Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDM). This study not only focused on estimating hydropower but also considered the environmental constraints at all sites by using the multi-criteria decision-making (MCDM) tool, which used the location and constraint criteria, along with benefit and cost criteria. The methodology combines technical evaluations (head and discharge) with environmental constraints to prioritize sustainable hydropower development. Key findings identify sites 17, 15, 16, 5, and 6 as the most promising locations, balancing energy generation with minimal environmental impact. This study provides a replicable framework for policymakers to harness hydropower resources responsibly, contributing to Pakistan's energy security and aligning with global Sustainable Development Goals. This approach not only bridges the gap between technical feasibility and environmental sustainability but also offers a model for other regions facing similar energy challenges.

Keywords: hydropower; SDG; ArcGIS; watershed delineation; MCDM



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1. Introduction

Pakistan is a developing nation with significant potential for sustainable and renewable energy resources, i.e., hydropower. According to the National Electric Power

Regulatory Authority (NEPRA), Pakistan's total installed power generation capacity stands at 45,888 MW as of June 2024, comprising 28,766 MW from thermal sources, 11,519 MW from hydroelectric sources, and significant contributions from nuclear, wind, and solar energy [1]. However, the country faces a significant gap between supply and demand, experiencing an energy crisis, with a power deficit ranging from 5000 MW to 8000 MW. This deficit underscores the urgent need to develop sustainable and reliable energy sources, such as hydropower, to bridge the gap and ensure energy security [2]. The strategic advancement of resources for hydropower in many nations has been hindered by financial circumstances and a shortage of data regarding topography, river flows, power grid infrastructure, environmentally vulnerable regions, and the potential energy for hydropower [3,4]. For sustainable energy consumption and usage, Pakistan's Ministry of Water and Power established its policy on energy in 2006, aiming to integrate hydropower development into the country's monetary plan. The energy policy prioritized examining various potential locations to establish Pakistan as a prominent player in renewable energy worldwide, with a particular focus on the northern regions of the country [5]. The country possesses considerable undeveloped hydropower capacity, primarily due to insufficient government investment in the energy sector, partially executed strategies, structural reforms, and inadequate analysis of the hydropower of various streams [6]. The Indus River possesses a potential of 60 GW, yet around 80% of this potential is still unidentified [7]. Despite facing a severe energy shortage, Pakistan's progress toward sustainability in the energy sector remains insufficient to meet its growing demands. Meanwhile, global hydropower installations continue to rise rapidly. In response to the ongoing energy crisis, the Ministry has initiated assessments of the hydroelectric potential across the country's rivers [8].

Hydropower, as a renewable energy source, is a clean, environmentally friendly, and cost-effective means of electricity production [9,10] that is beneficial for managing sustainable water resources [11]. Contemporary and efficient hydroelectric power facilities are expediting our shift toward renewable energy, supplying adequate electricity and reservoirs for agricultural irrigation, and contributing to climate change mitigation efforts. Hydropower produces minimal emissions of greenhouse gases, as it contributes 16% of overall energy consumption globally [12]. It is expected that the currently operational energy capacity of hydropower has the potential to exceed 1064 GW, although this would still fall short of the anticipated economically viable hydropower generation [13]. Hydropower development in various regions of the world is primarily hindered by economic constraints, increasing population, changes in hydrological systems, and limited assets. Approximately 70% of economically viable hydropower has not yet been developed, primarily in developing nations. Thus, sustainable hydropower may enable us to fulfill both the UN's (sustainable development) agenda and the climate change agreement in Paris [14].

Encouraging progress toward achieving SDG 7 highlights the growing accessibility and sustainability of energy. The hydropower sector is making significant advancements in renewable energy and efficiency, with electricity access accelerating in developing countries. This study aligns with SDG 7, particularly targets 7.1 and 7.2, which aim to ensure universal access to affordable, modern energy services and to significantly increase the share of renewable energy in the global mix by 2030 [15]. In 2016, Pakistan formally adopted the Sustainable Development Goals (SDGs) as its national development framework, becoming the first country to integrate them into its strategy through a unanimous National Assembly resolution. Significant investments have been made to address energy shortages, boost generation, and improve electricity access, contributing to progress toward SDG 7. Over the past decade, power accessibility has increased by 8%. Pakistan is now targeting a renewable energy share of 20% by 2025 and 30% by 2030 [16].

Numerous studies have assessed hydroelectric potential and identified suitable locations using various methods. Traditionally, most research relied on field investigations and conventional approaches. However, recent advancements have led to the growing use of modern tools like remote sensing (RS) and Geographic Information Systems (GIS) for more efficient and precise assessments [17–19]. The traditional approach of paper mapping incurs substantial costs and time requirements, restricting its use, particularly in remote areas characterized by complicated topography [20–24]. Furthermore, rational approximation involves utilizing the river's flow and elevation to estimate the potential for power generation. This estimation is performed through a site assessment conducted at a single point, two sites, or a very limited area [25]. Nevertheless, there are remote regions with challenging terrain where hydropower potential exists, rendering it impracticable to accurately evaluate power potential and identify significant sites using this technique. Furthermore, the presence of human error and the influence of subjective judgment impede the reliability of these approaches [26]. To address these challenges, GIS and RS techniques, along with Geospatial Information Systems (GSIS), are increasingly utilized for site analysis due to their efficient use of time and resources [27]. For example, Alashan et al. (2018) [25] utilized GIS to evaluate the feasibility of hydropower generation by employing a spatial decision support system. In addition, several studies have used GIS data to identify appropriate sites [28]. Similarly, a location analysis method was suggested by Belmonte et al. (2009) [29] for the exploration of potential hydropower sites using GSIS. Similarly, Fasipe et al. (2021) [30] utilized spatial tools and a hydrological model to analyze the Osse Sub-basin (OSB) and calculate the stream's peak discharge (Q_p). This method quantifies potential locations for small hydropower (SHP) by evaluating catchment parameters along the drainage network in run-of-river projects, thereby overcoming the limitations of traditional survey methods. Similarly, many studies have advanced location analysis systems using GIS and RS for spatially optimized hydropower assessments [31]. A hydropower potential assessment was carried out at the White Bandama Watershed in West Africa by Kouadio et al. (2022) [32] and at the Samar River System in the Philippines by Uy et al. (2023) [33]. Both studies integrated a hydrological model with GIS, specifically the Soil and Water Assessment Tool (SWAT). Similarly, Akande et al. (2023) [34] employed a GIS-based methodology to evaluate the potential for small hydropower generation along the River Ogun in Nigeria. This approach aimed to identify suitable locations for small hydropower projects that could benefit rural communities along the river. The capacity for run-of-river hydropower generation along the Gumara River was evaluated by Ayele (2020) [35], utilizing geospatial data and techniques. The utilization of GIS involves the manipulation of satellite images, demarcating watershed and stream networks, and identifying viable sites for hydropower projects, resulting in the discovery of 20 suitable sites with hydropower potential.

Multi-criteria decision-making (MCDM) methods offer a practical solution for these analyses, enabling the evaluation and prioritization of alternatives based on multiple measures [36,37]. It is also used for hydropower assessments in some cases. For example, it can help locate appropriate potential locations for the construction of small-scale hydropower facilities to generate electricity along the Awata River in Ethiopia. Areri and Bibi (2009) [38] examined the identified suitable sites by prioritizing the sites using an analytical hierarchy process (AHP). The utilization of MCDM methodologies, such as TOPSIS, AHP, and ANP, has witnessed a significant rise in recent years [39–41]. These approaches are particularly prevalent in the field of water resource engineering and management, where they are employed to tackle complex problems [42,43].

While hydropower offers significant potential as a clean energy source, it also has notable negative impacts that must be carefully considered. The construction of dams

disrupts natural ecosystems and alters the flow of rivers, potentially harming aquatic and terrestrial habitats [44]. Dams can block the migration of fish species, which is a critical concern in many regions. For example, the dams on the Snake River in the U.S. have significantly reduced the survival of juvenile salmon, impacting biodiversity and local communities that rely on these species for their livelihoods [45]. Environmental concerns also include sediment accumulation, which reduces the storage capacity of reservoirs over time, threatening water quality and availability downstream. As reservoirs fill with sediment, they can lose up to 25% of their storage capacity by 2050, exacerbating water shortages and compromising hydropower efficiency [46]. Moreover, the flooding of large areas for dam construction can displace local populations, often leading to social conflicts, as seen with Indigenous communities whose ancestral lands are submerged [47,48].

Hence, considering the positive and negative factors for developing hydropower projects, this study is based on assessing the suitable and environmentally friendly locations for potential hydropower projects to fulfill the nation's energy requirements. While Pakistan possesses significant hydropower potential, particularly in the Upper Indus Basin, in existing studies, there is a lack of integrated approaches that combine Geographic Information Systems (GIS) with multi-criteria decision-making (MCDM) tools to evaluate and prioritize hydropower sites in a holistic manner. This gap limits policymakers' ability to make informed decisions that balance energy generation with environmental sustainability. Hence, concentrating on Sustainable Development Goal (SDG) 7, "Ensure access to affordable, reliable, sustainable and modern energy" [49], and the exploration of hydropower potential in the Upper Indus Basin and the identification of promising locations along the Indus, Gilgit, and Hunza Rivers, this study employed a location analysis methodology integrating GIS and a multi-criteria decision-making (MCDM) approach. The significance of this study stands out because it combines technical and environmental evaluations to prioritize hydropower sites in Pakistan's northern regions. By bridging the gap between technical feasibility and environmental sustainability, this study provides a valuable resource for policymakers and stakeholders seeking to harness Pakistan's hydropower resources responsibly. This study addresses these gaps by employing a novel, integrated methodology that combines GIS-based spatial analysis with an MCDM approach to assess hydropower potential in the Upper Indus Basin. Specifically, this study can achieve the following goals:

- Introduce a framework for prioritizing sites while identifying and evaluating potential hydropower sites along the Indus, Gilgit, and Hunza Rivers, considering both technical factors (e.g., head, discharge) and environmental criteria.
- Provide actionable insights for policymakers by identifying the most promising sites and demonstrating how environmental constraints can be integrated into the decision-making process.
- Offer a replicable methodology that can be applied to other regions with similar hydropower potential, thereby contributing to global efforts in sustainable energy development.

This article is organized into six sections. Section 2 provides a detailed description of the study area, including the geographical and hydrological characteristics of the Upper Indus Basin, and outlines the adopted methodology, which includes the use of GIS for watershed delineation, the area ratio method for discharge estimation, and the multi-criteria decision-making (MCDM) framework for site prioritization and suitability. Section 3 presents the results, highlighting the hydropower potential of the identified sites and the environmental constraints considered and their role in the selection and prioritization of suitable sites. Section 4 discusses the implications of the findings, emphasizing the balance between energy generation and environmental sustainability. Section 5 concludes this study

by summarizing the key findings and their relevance for policymakers. Finally, Section 6 summarizes the assumptions and limitations of this study and offers recommendations for future research.

2. Material and Methods

2.1. Study Area

Pakistan, as a prominent nation in the Global South, possesses extensive and varied surface topography, encompassing both undulating terrain and vast plains [50]. It is endowed with abundant natural resources and has experienced rapid population growth. These factors underscore the importance of gathering sufficient data on environmental and socioeconomic conditions to work toward achieving Sustainable Development Goals (SDGs) [51]. Pakistan spans 61–76° E longitude and 24–37° N latitude, covering an area of 796,095 km². It borders India, Afghanistan, China, Iran, and the Arabian Sea. The Upper Indus Basin in northern Pakistan features a rugged landscape shaped by the upward thrust of the Hindu Kush, Karakoram, and Himalayas along the tectonic boundary of the Indian and Eurasian Plates. The Indus River's main tributary originates in the Tibetan Plateau, one of Earth's most erosive landforms, situated over 5 km above sea level [52]. The Tibetan Plateau encompasses a watershed spanning 970,000 km², with a mountainous catchment area of 264,000 square kilometers. In the northern region of Pakistan, upstream of the Tarbela Dam, approximately 75,000 km² falls within this boundary [53]. The Indus River enters northern Pakistan from the Indian-administered Jammu Kashmir and merges with the Shyok and Shigar Rivers in the Skardu Basin. After the Gilgit River confluence, the river reaches the Tarbela Reservoir and flows through the Bisham and Chilas regions before eventually joining the Arabian Sea, 3020 km from its source [54].

Regarding social and economic factors, there has been a noticeable rise in the region's population over the past few decades, with an average annual growth rate of 1.8%. The region is susceptible to future changes due to heightened climate variability, extensive disasters, rapid population growth, and accompanying land modifications [55]. Consequently, accurate environmental impact assessment techniques are required to ensure sustainable development. Figure 1 shows the study area, the Upper Indus Basin (UIB), selected for study, highlighting the proposed sites with hydropower potential. Therefore, keeping the potential for hydropower in mind, the present study focused on identifying appropriate locations within the Upper Indus Basin, specifically in the Indus, Hunza, and Gilgit Rivers. To identify possible sites, discharge data were collected from the Water and Power Development Authority (WAPDA) of Pakistan.

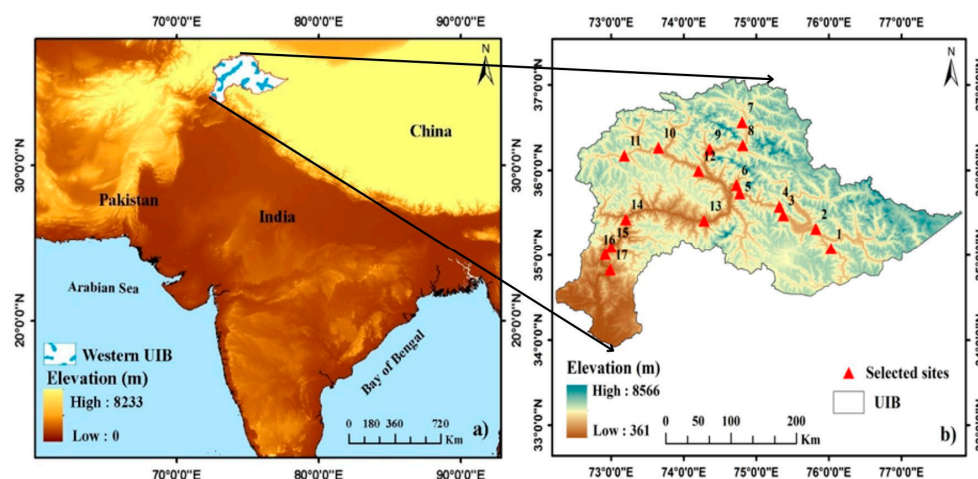


Figure 1. (a) Study area, i.e., Upper Indus Basin (Pakistan). (b) Seventeen proposed sites in the Upper Indus Basin (Pakistan).

2.2. Data Collection and Framework for DEM

The data were collected at Besham for the Indus River (1985–2022), at Gilgit Bridge for the Gilgit River (1960–2016), and at Daniyori Bridge for the Hunza River (1966–2016) and Shimshal and Passo tributaries. Additionally, a high-resolution DEM was created using the Sentinel-1 SLC dataset by adopting the procedure outlined in Figure 2. This study utilized Sentinel-1 SLC images to generate a high-resolution digital elevation model (DEM) through Interferometric Synthetic Aperture Radar (InSAR) processing. This dataset was selected due to its superior temporal coverage, which minimizes temporal decorrelation and ensures reliable elevation extraction for hydropower site assessment. Both Sentinel-1 (C-band SAR) and the generated DEM have a 10 m spatial resolution, ensuring high accuracy in elevation modeling. Sentinel-1 images acquired between 2015 and 2023 were used to cover a range of hydrological conditions and capture seasonal variations in river inflow. A total of 36 Sentinel-1 SLC images were processed to ensure sufficient temporal representation and enhance the accuracy of elevation estimation. Sentinel offers superior temporal coverage compared to earlier sensors, significantly reducing temporal decorrelation. The Sentinel-1 InSAR processing began with co-registering the interferogram, TOPS Deburst, and phase filtering. Subsequent steps involved creating subsets and opening the interferogram in S1TBX, followed by phase unwrapping using the SNAPHU algorithm. SNAPHU, a phase unwrapping statistical-cost, network-flow algorithm, was used to unwrap the interferograms and was then re-imported into S1TBX. The interferometric phase was transformed into a digital elevation model (DEM) using the radar tool in S1TBX by converting phase data to elevation. Finally, geocoding and Range Doppler terrain correction generated the geocoded terrain-corrected DEM. This DEM was employed in GIS to identify suitable sites and determine elevation and watershed areas at potential locations. To further support the hydropower potential assessment, river discharge data from the Water and Power Development Authority (WAPDA), Pakistan, were integrated. Additionally, the Shuttle Radar Topography Mission (SRTM) 30 m DEM was utilized for validation, ensuring consistency in terrain elevation measurements.

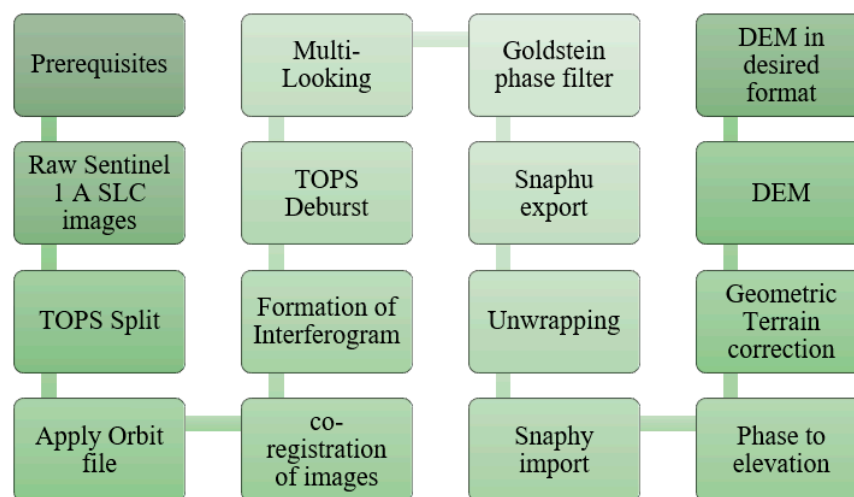


Figure 2. Steps involved in creating DEM using Sentinel-1.

2.3. Adopted Procedure for Analysis

This study utilized a methodology that employed GIS and MCDM approaches to determine the most optimal location for hydropower generation. This process is illustrated in the flowchart (Figure 3) for a comprehensive description.

2.4. Head Determination at Proposed Sites

Seventeen potential sites for hydropower were identified along the river's centerline to indicate the projected sites for hydropower, as shown in Figure 1. The site selection process involved a multi-stage GIS analysis that integrated hydrological, topographical, and environmental factors, ensuring that spatial variability and hydrological feasibility were adequately considered. The selection relied on freely available satellite-based datasets (Sentinel-1, SRTM DEM, and Google Earth Pro). The Indus River, Hunza River, and Gilgit River are sustained by tributaries and rivers fed by glaciers. For each proposed site, an appropriate narrow segment of the river and a turn in the river flow were considered suitable factors. All seventeen sites were selected by choosing search points immediately before a new tributary. To analyze the suitability of each site, base coordinates were selected. Locations for proposed plant/turbine sites and intake sites were chosen on a GIS map based on the rivers' centerline. The designated sites were identified using the ArcGIS Editor Toolbar. The elevation at each suggested site was obtained using Google Earth Pro. Subsequently, the head for each of the seventeen search points/sites was determined by calculating the difference between the elevation head and the tailwater level. The head was determined by subtracting the assumed elevation of the intake point from the elevation of the assumed turbine position.

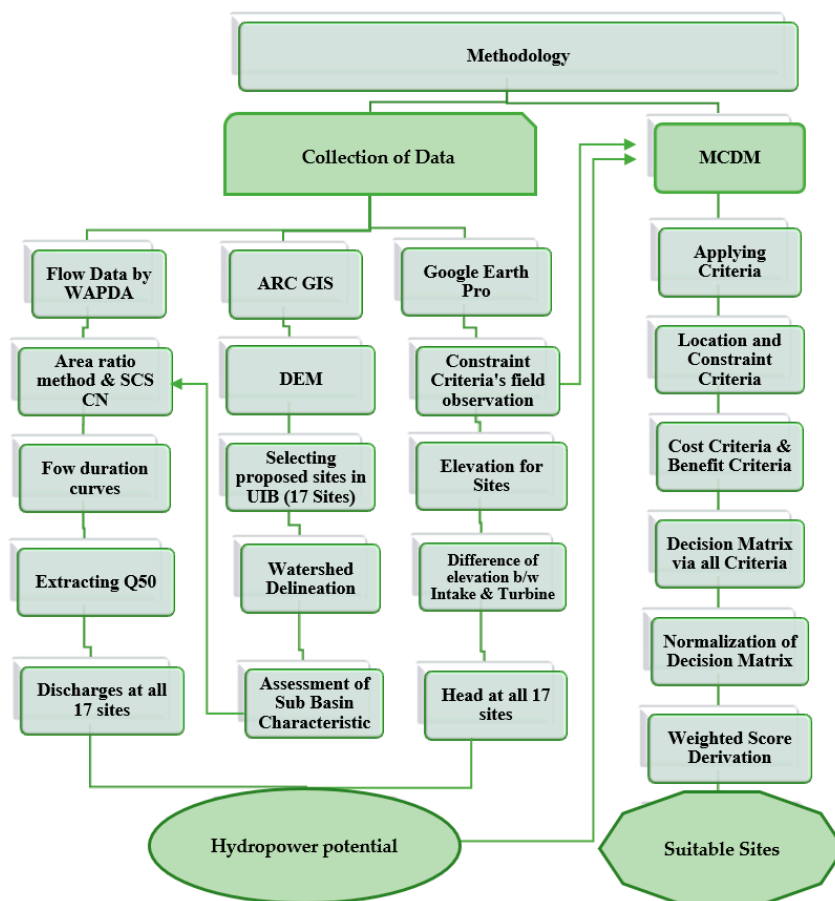


Figure 3. Methodology adopted to complete this study.

2.5. Discharge Determination at Ungauged Sites

The data were acquired utilizing the area ratio method for ungauged stations due to the absence of discharge data at different locations, supported by the Soil Conservation Service Curve Number (SCS-CN) methodology. The Soil Conservation Service Curve Number (SCS-CN) method is a widely used empirical model for estimating surface runoff

based on land use, soil type, and antecedent moisture conditions. The SCS-CN approach was employed to estimate the discharge of sub-basins with meteorological stations, while the area ratio method was utilized to synthesize the data for the remaining points. In addition, the delineation of watersheds was conducted at all seventeen locations to split the Upper Indus Basin into seventeen smaller basins. The characteristics of each catchment, such as area, length, and CN, were estimated using GIS. Below are the specifics of the SCS-CN method and the area ratio method. The SCS-CN method is extensively employed for estimating runoff in ungauged basins and is designed to consider hydrologic abstraction and land characteristics of CN. The curve number (CN) primarily depends on soil type, land use, and antecedent moisture conditions (AMCs) [56–58]. The runoff (Q) is estimated using rainfall (P), curve number (CN), and initial abstraction (Ia) using the SCS-CN method, as shown below in Equations (1) and (2).

$$\frac{P - Ia - Q}{S} = \frac{Q}{P - Ia} \quad (1)$$

$$Q = \frac{(P - \lambda S)^2}{P + (1 - \lambda)S} \quad P > \lambda S \text{ else } Q = 0 \quad (2)$$

Here, S is the maximum potential retention and can be determined as follows: $S = \left(\frac{1000}{CN} - 10\right)$ if P is in inches, while $S = \left(\frac{2540}{CN} - 25.4\right)$ if P is in cm, $\lambda = 0.2$. CN is the dimensionless index used in tabular form and ranges from 0 to 100. The area ratio method is a commonly used regionalization approach for estimating streamflow at ungauged sites by scaling discharge values from gauged locations based on watershed areas. The area ratio approach can be employed to estimate discharge at specific sites in cases in which flow data are insufficient by leveraging existing data obtained from one or more adjacent gauging stations on streams that possess comparable attributes [59]. The discharge per unit area in the targeted ungauged watershed is assumed to be equal to that in the known basin when using the area ratio technique applied using Equation (3). This method requires the runoff of the gauged site (Q_g), and the area of the target ungauged sub-basin derived from watershed delineation (A_u), the area of the whole basin (A_g) for estimating the runoff of the targeted ungauged basin (Q_u). The area ratio approach has been used in several studies [60,61], which have found that it works very well in areas with few gauging networks [62].

$$Q_u = K \left(\frac{A_u}{A_g} \right)^\phi \times Q_g \quad (3)$$

Here, ϕ is the factor valued by the area of the gauged basin and the regression analysis of flow and is considered to be 1.0, and K is a bias correction aspect = 1.0 [59,62].

After estimating and gathering discharge data at each of the seventeen sites, a flow duration curve (FDC) was generated for each selected site. The discharge from each proposed site was individually organized in descending order to generate the FDC. The corresponding percentiles were computed utilizing the Weibull plotting algorithm. For the present study, Q_{100} , Q_{90} , Q_{80} , Q_{70} , Q_{60} , and Q_{50} were obtained from the FDC of each site. Q_{100} denotes the flow rate equal to or exceeding 100% of the time. Q_{50} denotes the discharge equal to or exceeding 50% of the time.

2.6. Estimation of Hydropower Potential

Before assessing the most promising sites using the MCDM approach, the hydropower potential was determined using Equation (4) for all suggested sites in the Upper Indus Basin, assuming a global efficiency rate of 81% [63].

$$P = \frac{\eta \rho g H Q}{1000} \quad (4)$$

In Equation (4), H denotes the estimated head for each site in meters, Q denotes the discharge in m³/s, and P refers to the mean annual electric power in kW. The density of water (ρ) is taken as 1000 (kg/m³), while g refers to the gravitational acceleration in m/s². η denotes the turbine efficiency, which usually ranges from 75 to 88 (%). Q_{50} is considered for hydropower estimation, as Q_{50} represents the flow that is equaled or exceeded 50% of the time [64]. According to [65], The discharge in Q_{50} is almost perennial for the whole year, although it is lower than in Q_{75} and Q_{90} . Therefore, Q_{50} was used in this study.

2.7. Multi-Criteria Decision-Making (MCDM)

Multi-criteria decision-making (MCDM) is employed to evaluate, prioritize, choose, or rank alternatives based on a limited set of options, using various competing criteria. The process of MCDM includes making a decision matrix based on location and constraint criteria, normalizing the decision matrix based on cost and benefit criteria, applying relative weights, and obtaining a final score.

2.7.1. Step 1: Criterion Selection

Several hydrologic, topographic, environmental, and socioeconomic criteria and water resource-related factors were used, based on the literature, to assess the circumstances of the study region. For this study, the criteria were divided into constraint criteria and location criteria, as indicated in Table 1. Discharge and head were utilized for power calculations. The location criteria incorporated both head and discharge. The sustainability of hydropower sites is influenced by various criteria rather than just the head and discharge. In addition, these constraint criteria were further categorized based on their positive aspect (where a higher value indicates a benefit) or negative aspect (where a higher value indicates a cost) [66]. Table 1 displays the constraint criteria and power criteria (obtained after estimating hydropower potential using head and discharge) for MCDM processing.

Table 1. Criteria considered for the MCDM.

Major Criteria	Sub-Criteria	Criterion Type (Benefit or Cost)
Location Criteria (Power)	Head Discharge	Benefit Benefit
Constraint Criteria (Environmental)	Site Access	Benefit
	Agricultural Areas	Cost
	Residential Areas	Cost
	Interaction with existing HPPs	Cost

2.7.2. Step 2: Making a Decision Matrix

The intangible criteria were quantified on a scale of zero to ten using benefit and cost criteria analysis. This allowed for the creation of a decision matrix for each site, as illustrated in Table 2. If the proposed site encompasses a substantial agricultural region, evaluating its environmental impact is necessary, and the possibility of resettlement arises in the event of constructing a hydropower project at that specific location. Therefore, it will be assigned a value of 1 based on the scale. Conversely, if the chosen proposed site has a

significantly reduced agricultural area, it implies that there would be no concerns regarding environmental impact assessment. Therefore, it is assigned a value of 9. Similarly, a site that has excellent accessibility is assigned a value of 9 on the scale, whereas a site with challenging or no accessibility is given a value of up to 1.

Table 2. Range of values that could be assigned to the constraint criteria considering site constraints using benefit and cost criteria.

Cost Criteria	Assigned Value	Benefit Criteria
	0	
Very high	1	Very low
High	3	Low
Normal	5	Normal
Low	7	High
Very low	9	Very high
	10	

2.7.3. Step 3: Normalization of the Decision Matrix Using Constraint Criteria and Location Criteria

Evaluating location criteria, i.e., power criteria, and converting constraint criteria into numerical values, a comprehensive decision matrix was created for each proposed site. The decision matrix was subsequently standardized according to the benefit and cost criteria using Equations (5) and (6).

$$\text{For benefit criteria, } n_{ij} = \frac{b_{ij} - b_{\max}}{b_{\min_{\max}}} \quad (5)$$

$$\text{For cost criteria, } n_{ij} = \frac{c_{ij_{\max}}}{c_{\min_{\max}}} \quad (6)$$

Here, b_{ij} characterizes the i th value of j th benefit criteria, c_{ij} represents the i th value of j th cost criteria, min and max in subscript characterize the respective minimum and maximum value of benefit criteria and cost criteria, respectively, and n_{ij} is the normalized value.

2.7.4. Step 4: Conveying the Weights to Each Criterion

The rank-sum weighted method was employed to normalize the decision matrix and allocate weights to each criterion. The weights in the rank-sum (RS) method are calculated by normalizing the individuals' rankings using Equation (7). This is achieved by dividing their combined ranks by the sum of all ranks [67].

$$W_j = \frac{2(n+1-r_j)}{n(n+1)} \quad (7)$$

Here, $j = 1, 2, 3, \dots, n$, and r_j is the ranking of j th criterion.

2.7.5. Step 5: Ultimate Standing of Sites Considering the Weighted Result

Once the relative weights for all criteria were established, each criterion was multiplied by its corresponding weight. The resulting values were then added together to obtain a total score, which was used to rank the suitable sites.

3. Results

3.1. Head Determination

The elevations of the selected sites were determined using Google Earth Pro to assess the head at the seventeen marked sites. To determine the starting point of the river, specific

sites were selected on a geographic information system (GIS) map of the Upper Indus Basin. These sites were chosen along the centerline of the river and were meant to indicate potential sites for plants/turbines and intake points. The ArcGIS Editor Toolbar was utilized to designate the intended positions. The disparity in elevation between the head and tail waters is subsequently employed to compute the head for each of the seventeen search points/sites. Head determination of all seventeen sites in the Upper Indus Basin is shown in Figure 3.

Table 3 demonstrates the utilization of the first point as the intake point and the second point as the powerhouse/turbine position to calculate the elevation difference/head. According to the findings, sites 8, 5, and 7 exhibit the three highest heads, i.e., 193.902 m, 100.304 m, and 81.707 m, respectively.

Table 3. Head determination of all seventeen sites in the Upper Indus Basin.

UIB Sites	Latitude	Longitude	River	Elevation at Headrace (ft)	Elevation at Tailrace (ft)	Head (ft)	Head (m)
1	35.09024581	76.03007488	Indus River	7734	7713	21	6.402
2	35.32856256	75.84508775	Indus River	7465	7372	93	28.353
3	35.46771954	75.37402412	Indus River	6925	6842	83	25.305
4	35.58937774	75.31262481	Indus River	6661	6445	216	65.853
5	35.71520232	74.77516221	Indus River	5209	4880	329	100.304
6	35.83186087	74.7384981	Indus River	4687	4520	167	50.915
7	36.56014352	74.79766065	Hunza river	8831	8563	268	81.707
8	36.30682781	74.80682667	Hunza river	8321	7685	636	193.902
9	36.25099837	74.36602402	Hunza river	5887	5817	70	21.341
10	36.26599732	73.65190705	Gilgit river	6560	6406	154	46.951
11	36.17492298	73.18099361	Gilgit river	7957	7892	65	19.817
12	35.99434956	74.20603515	Gilgit river	5203	5128	75	22.866
13	35.42022285	74.29436234	Indus River	3478	3404	74	22.560
14	35.42795033	73.20348386	Indus River	2781	2704	77	23.476
15	35.10399255	73.00655144	Indus River	2214	2155	59	17.987
16	35.0027519	72.91029199	Indus River	2079	1960	119	36.280
17	34.82609753	73.00278555	Indus River	1818	1722	96	29.268

3.2. Discharge Determination

3.2.1. Watershed Delineation

The geographic information system (GIS) and CN-Tables were used to determine the catchment features, such as the watershed area size and the curve number (CN). These attributes were then used to calculate the discharge using the area ratio (AR) and Soil Conservation Service Curve Number (SCS-CN) techniques. Figure 4 depicts the process of demarcating the watershed, starting from the upper reaches and extending to the lower reaches, utilizing the GIS extension Arc-hydro tool.

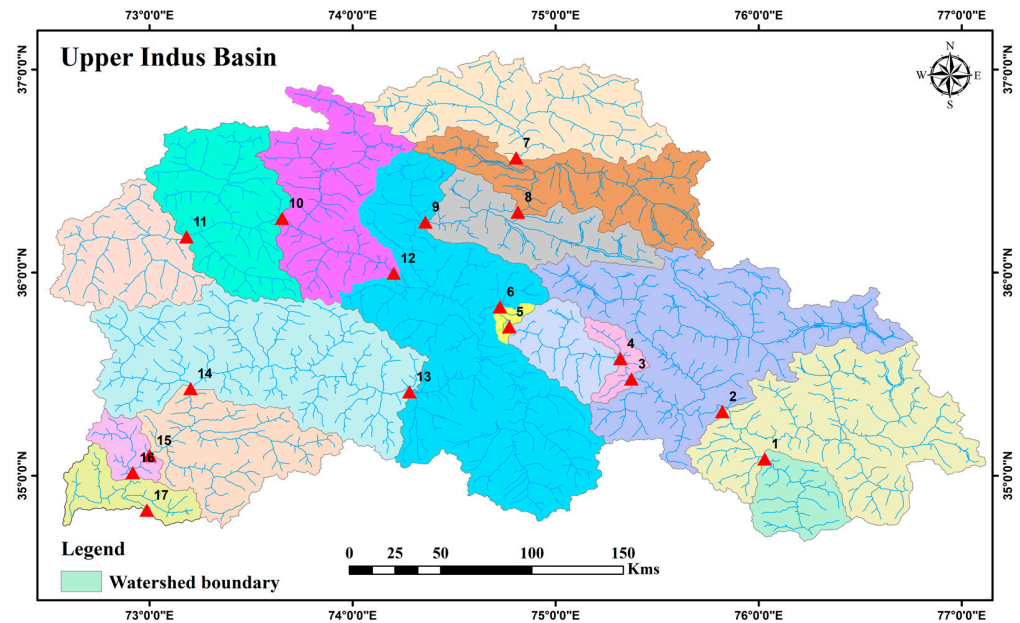


Figure 4. Watershed delineation of Upper Indus River at all 17 proposed alternatives. Numbers denote the Watershed delineated area. i.e., Number 1 denotes the Watershed delineated area for Site 1, and so on.

3.2.2. Flow Duration Curves (FDC)

Figure 5 shows the flow duration curves for the Indus, Hunza, and Gilgit Rivers. The flow duration curve (FDC) for three designated locations in the Upper Indus Basin—site 6 on the Indus River, site 8 on the Hunza River, and site 12 on the Gilgit River—illustrates the diversity of hydrological regimes in the Upper Indus Basin, emphasizing the disparate potential for hydropower generation at each site. The selected sites were derived from 17 prospective hydropower locations to offer a representative and comprehensive understanding of the basin’s hydrological parameters. FDCs demonstrate the UIB’s substantial flow capacity, with discharge values consistently high across most exceedance probabilities, signifying a reliable and considerable flow regime suitable for high-capacity hydropower production.

Coefficient to check the accuracy of the model:

The Nash–Sutcliffe efficiency (NSE) [68] is a normalized statistical metric that quantifies the proportion of residual variance relative to the variance of the measured data. The Nash–Sutcliffe efficiency assesses the degree to which the observed data align with the simulated data along the 1:1 line. The Nash–Sutcliffe efficiency is calculated using Equation (8) as follows:

$$E = 1 - \frac{\left\{ \sum_{i=1}^n (O_i - P_i)^2 \right\}}{\left\{ \sum_{i=1}^n (O_i - \bar{O})^2 \right\}} \quad (8)$$

In Equation (8), O_i represents the observed flow, P_i represents the simulated flow, and $\bar{O}$ represents the average of the observed data. Following Equation (8), the Nash–Sutcliffe efficiency calculated for the observed flow vs. simulated flow in 2012 is 0.987 at the Gilgit River, 0.98 at the Hunza River, and 0.97 at the Indus River, which shows the accuracy of the simulation produced using this method.

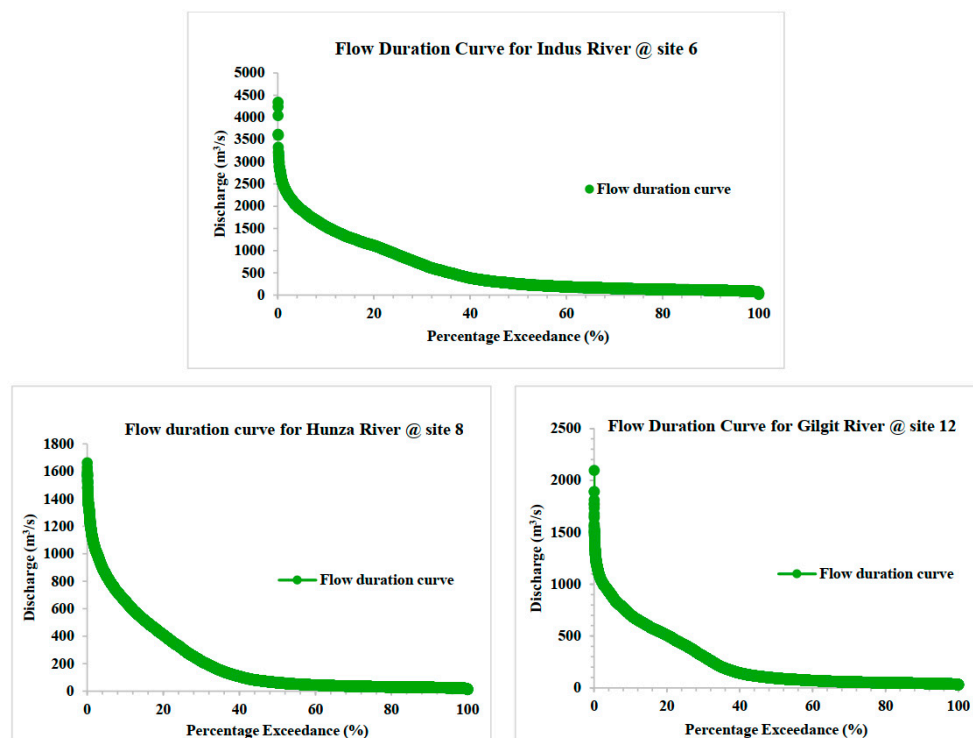


Figure 5. Flow duration curves showing discharges at selective sites i.e., Indus, Hunza, and Gilgit Rivers.

Willmott [69] introduced an agreement index (d) as a standardized metric to quantify the level of model prediction error, ranging from 0 to 1. The index of agreement is the ratio of the mean square error to the potential error. A value of 1 signifies a complete match in agreement, while a value of 0 shows no agreement at all. The index of agreement can identify both additive and proportional discrepancies in the observed and simulated means and variances. However, the index of agreement is highly responsive to extreme values because it involves squared differences [70]. The agreement index is determined as follows:

$$\text{ioa} = 1 - \left(\frac{\left\{ \sum_{i=1}^n (O_i - e_i)^2 \right\}}{\left\{ \sum_{i=1}^n \left(|O_i - \bar{O}| + |e_i - \bar{e}| \right)^2 \right\}} \right) \quad (9)$$

In Equation (9), O_i represents the observed power, e_i represents the simulated power, $\bar{O}$ represents the average of the observed data, and $\bar{e}$ represents the average of the simulated data. The index of agreement produced satisfactory results. After the application of the abovementioned equation, the index of agreement value for the observed flow vs. simulated flow for the year 2012 is 0.94 at the Gilgit River, 0.95 at the Hunza River, and 0.98 at the Indus River, which shows the accuracy of the simulation produced using this method.

The R^2 score quantifies the degree of correlation between the simulated and observed values [71]. The R^2 coefficient is estimated using Equation (10) as follows:

$$R^2 = \frac{\left\{ \sum \left(Q_{\{obs\}} - \overline{Q_{\{obs\}}} \right) \times \left(Q_{\{sim\}} - \overline{Q_{\{sim\}}} \right) \right\}}{\left\{ \sqrt{\left\{ \sum \left(Q_{\{obs\}} - \overline{Q_{\{obs\}}} \right)^2 \times \left(Q_{\{sim\}} - \overline{Q_{\{sim\}}} \right)^2 \right\}} \right\}} \quad (10)$$

In Equation (10), Q_{obs} is the observed value, Q_{sim} is the simulated value, $\bar{Q}_{obs}$ is the average observed value, and $\bar{Q}_{sim}$ is the average simulated value. The permissible values for R^2 range from 1.0 (indicating the best fit) to 0.0 (indicating an inadequate fit). The correlation coefficient (R^2) also produced satisfactory results. After the application of the abovementioned equation, the correlation coefficient (R^2) value for the observed flow vs. simulated flow for the year 2012 is 0.98 at the Gilgit River, 0.94 at the Hunza River, and 0.96 at the Indus River, which shows the accuracy of the simulation produced using this method. The model calibration results are indicated in Figure 6 for the Gilgit, Hunza, and Indus Rivers.

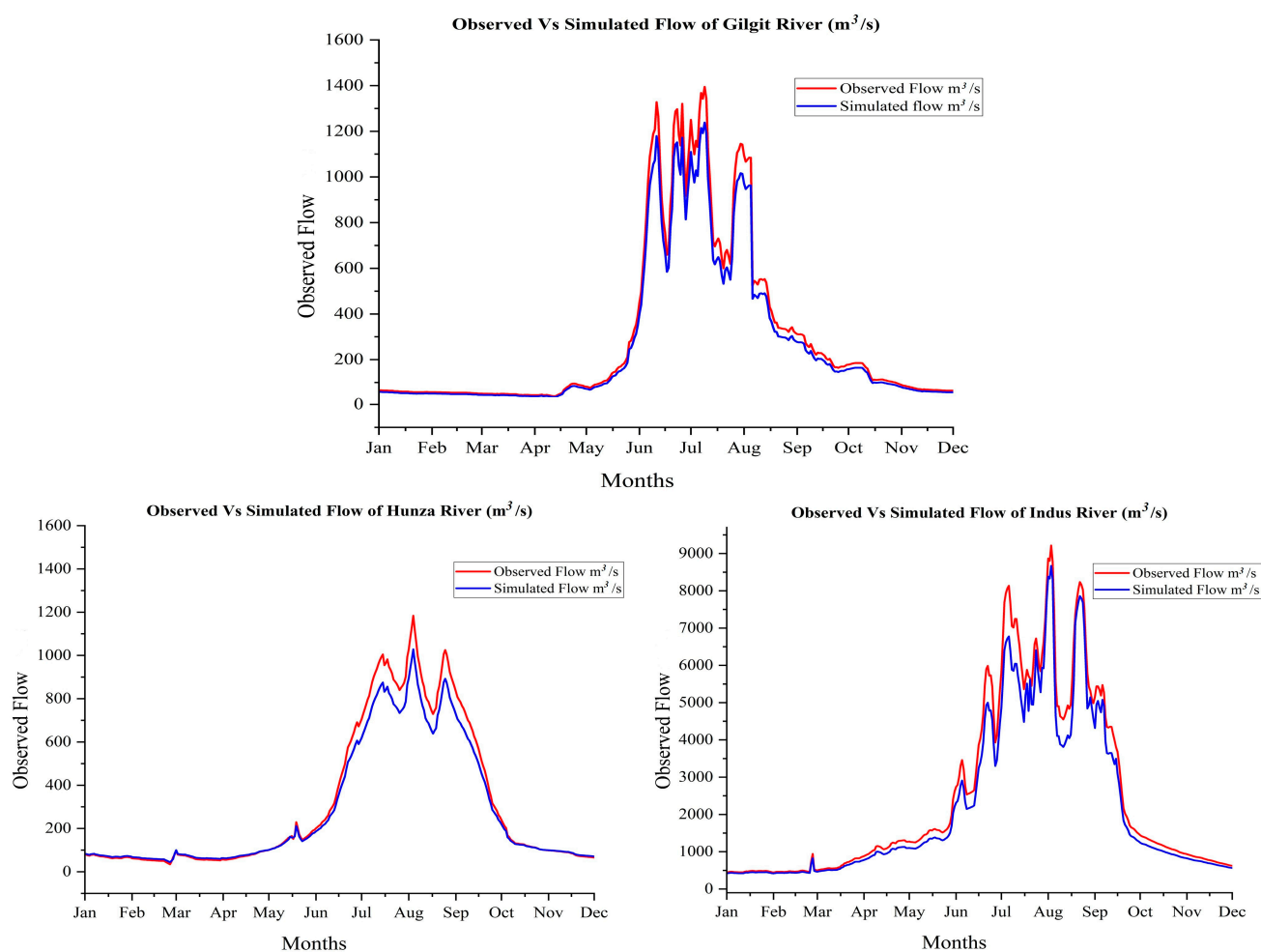


Figure 6. Calibration of results for observed vs. simulated flow at Gilgit, Hunza, and Indus Rivers.

As shown in Figure 6, the calibration of the area ratio method yields satisfactory results. Therefore, it is recommended that further steps be taken.

3.3. Hydropower Potential

Estimating hydropower availability at all seventeen selected sites was conducted using Equation (4), as illustrated in Table 4. The hydropower potential of the 17 proposed sites in the Upper Indus Basin (UIB) reveals significant variations in power generation capacity, ranging from small-scale to large-scale potential. The discharge values at these sites vary widely, with site 17 showing the highest discharge ($861.64 \text{ m}^3/\text{s}$) and site 11 the lowest ($24.79 \text{ m}^3/\text{s}$). Similarly, head values range from 6.4 m at site 1 to 100.3 m at site 5, influencing the power output at each site. The power generated at these sites also spans a broad range, with the lowest estimated at 3.9 kW (site 11) and the highest at

243.66 MW (site 16). Sites 5, 6, 15, 16, and 17 are the most promising locations due to their high discharge rates and favorable head conditions, suggesting substantial hydropower potential. While the hydropower potential values estimated for the proposed sites in the Upper Indus Basin provide a strong foundation for identifying viable energy generation locations, it is crucial to incorporate a multi-criteria decision-making (MCDM) analysis to prioritize these sites based on environmental constraints, thereby minimizing the negative impacts of the construction of hydropower projects.

Table 4. Estimation of hydropower for all seventeen proposed sites.

UIB Sites	Discharge Q50 (m ³ /s)	Head (m)	Density (kg/m ³)	Turbine Efficiency	Gravitational Acceleration (ms ^{−2})	Power (KW)	Power (MW)
1	19.153	6.402439	1000	0.81	9.81	974.3978	0.974398
2	110.406	28.35366	1000	0.81	9.81	24,874.58	24.87458
3	220.472	25.30488	1000	0.81	9.81	44,331.43	44.33143
4	227.435	65.85366	1000	0.81	9.81	119,012.1	119.0121
5	246.942	100.3049	1000	0.81	9.81	196,820.8	196.8208
6	249.312	50.91463	1000	0.81	9.81	100,864.8	100.8648
7	34.169	81.70732	1000	0.81	9.81	22,184.38	22.18438
8	61.794	193.9024	1000	0.81	9.81	95,210.23	95.21023
9	81.405	21.34146	1000	0.81	9.81	13,804.77	13.80477
10	57.953	46.95122	1000	0.81	9.81	21,621.05	21.62105
11	24.792	19.81707	1000	0.81	9.81	3903.958	3.903958
12	93.132	22.86585	1000	0.81	9.81	16,921.56	16.92156
13	682.726	22.56098	1000	0.81	9.81	122,393.5	122.3935
14	788.72	23.47561	1000	0.81	9.81	147,127.5	147.1275
15	835.559	17.9878	1000	0.81	9.81	119,428.9	119.4289
16	845.2	36.28049	1000	0.81	9.81	243,661.3	243.6613
17	861.643	29.26829	1000	0.81	9.81	200,391.3	200.3913

By integrating these considerations, the analysis will support a more sustainable decision-making process, helping to avoid irreversible environmental damage and ensuring that hydropower projects align with the broader goals of environmental conservation and sustainable development.

3.4. MCDM

The constraint parameters were assigned quantitative values, as illustrated in Table 5, through the utilization of opinions from experts and field analysis. Table 5 presents the comprehensive decision matrix, showcasing a numerical illustration of the constraint and location criteria for each proposed site. The decision matrix was further standardized based on cost and benefit criteria using Equations (5) and (6).

Once the decision matrix was compiled with numerical values, it was normalized to ensure that the influence of a single larger criterion does not outweigh that of the other criteria. To achieve this objective, the benefit criteria (Site Accessibility and Power) were standardized by dividing the values of each proposed site by the highest value among all proposed sites for each specific criterion. This process ensures that the highest value is assigned a score of 1.0.

According to Table 5, the highest value for the benefit criteria is 243.661, corresponding to site 16. To normalize the power values, each was divided by 243.661. For instance, for site 16, dividing 243.661 by 243.661 results in 1.0. Similarly, for site 2, dividing 24.8746 by 243.661 gives 0.1021. For the cost criteria—including residential area, agricultural area, and interaction with other HPPs—normalization was performed by dividing each site's value by the smallest value among all sites for each criterion. This ensures that the lowest value

receives a normalized score of 1.0. As shown in Table 5, the smallest observed value is 1 for the agricultural area. This value was used to normalize the proposed sites for criterion 3. For example, for site 16, the agricultural area value was calculated as 1 divided by 3, resulting in 0.3333. Meanwhile, the minimum value of 1 divided by 1 yields 1.0. After applying the numerical scale to the intangible criteria, the normalized decision matrix is elaborated in Table 6.

Table 5. Decision matrix wherein the intangible criteria (benefit and cost) are assigned numerical values.

Site No.	Power (MW)	Site Access	Agricultural Area	Residential Area	Interaction with Existing HPPs
1	0.9744	7	9	9	9
2	24.8746	7	9	7	9
3	44.3314	7	3	3	9
4	119.012	7	7	7	9
5	196.821	7	9	9	9
6	100.865	7	3	3	9
7	22.1844	7	7	7	9
8	95.2102	7	9	9	9
9	13.8048	7	3	3	9
10	21.6211	7	3	3	9
11	3.90396	7	7	7	9
12	16.9216	7	7	7	9
13	122.393	7	5	5	9
14	147.127	7	7	7	9
15	119.429	7	1	1	9
16	243.661	7	3	3	9
17	200.391	7	1	1	9

Table 6. Normalized decision matrix after applying the numerical scale to the intangible criteria (cost and benefit).

Site No.	Power (MW)	Site Access	Agricultural Area	Residential Area	Interaction with Existing HPP
1	0.0039	1	0.1111	0.1111	1
2	0.1021	1	0.1111	0.1428	1
3	0.1819	1	0.3333	0.3333	1
4	0.4884	1	0.1428	0.1428	1
5	0.8078	1	0.1111	0.1111	1
6	0.4139	1	0.3333	0.3333	1
7	0.0910	1	0.1428	0.1428	1
8	0.3907	1	0.1111	0.1111	1
9	0.0566	1	0.3333	0.3333	1
10	0.0887	1	0.3333	0.3333	1
11	0.0160	1	0.1428	0.1428	1
12	0.0694	1	0.1428	0.1428	1
13	0.5023	1	0.2	0.2	1
14	0.6038	1	0.1428	0.1428	1
15	0.4901	1	1	1	1
16	1	1	0.3333	0.3333	1
17	0.8224	1	1	1	1

Additionally, as shown in Table 7, the relative weights were obtained using Equation (7).

Table 7. Weights of criteria based on their relative preferences.

Criterion	Preference	Relative Weight
Power	1	0.333
Site Access	2	0.267
Agricultural areas	3	0.200
Residential areas	4	0.133
Interaction with existing HPP	5	0.067

Table 7 presents the relative weights assigned to different criteria based on their importance in hydropower site selection. Power generation potential is given the highest priority (weight: 0.333), followed by site access (0.267) and agricultural land (0.200), which impacts land use considerations. Residential areas (0.133) and interaction with existing HPPs (0.067) are weighted lower due to their relatively lesser influence on site feasibility. These weights reflect a balanced approach, prioritizing power output and accessibility while minimizing environmental and social impacts. The relative weights for each site were multiplied by the corresponding criteria, as shown in Table 8, and the sum of all the criteria was used to determine the final score for the suggested sites.

Table 8. Weighted decision matrix obtained by multiplication of the relative weights with values of the normalized decision matrix.

Site No.	Outcome Accomplished by the Multiplication of Criteria by Their Respective Relative Weights					Summation of Criteria Weightage
	Power	Site Access	Agricultural Area	Residential Area	Interaction with Existing HPP	
1	0.00133	0.2667	0.02222	0.01481	0.0667	0.371
2	0.03399	0.2667	0.02222	0.01904	0.0667	0.408
3	0.06058	0.2667	0.06667	0.04443	0.0667	0.505
4	0.16264	0.2667	0.02857	0.01904	0.0667	0.544
5	0.26898	0.2667	0.02222	0.01481	0.0667	0.639
6	0.13784	0.2667	0.06667	0.04443	0.0667	0.5823
7	0.03031	0.2667	0.02857	0.01904	0.0667	0.411
8	0.13011	0.2667	0.02222	0.01481	0.0667	0.501
9	0.01886	0.2667	0.06667	0.04443	0.0667	0.463
10	0.02954	0.2667	0.06667	0.04443	0.0667	0.474
11	0.00533	0.2667	0.02857	0.01904	0.0667	0.386
12	0.02312	0.2667	0.02857	0.01904	0.0667	0.404
13	0.16726	0.2667	0.04	0.02666	0.0667	0.567
14	0.20107	0.2667	0.02857	0.01904	0.0667	0.5821
15	0.16321	0.2667	0.2	0.1333	0.0667	0.829
16	0.333	0.2667	0.06667	0.04443	0.0667	0.777
17	0.27386	0.2667	0.2	0.1333	0.0667	0.941

Table 8 shows the weighted decision matrix, where each site's attributes are multiplied by the corresponding relative weights from Table 7. The final column sums these weighted values to rank the suitability of potential sites. Sites with higher scores indicate better feasibility based on the chosen criteria. For instance, site 17 (0.941) and site 15 (0.829) rank the highest, suggesting they offer the most favorable conditions for hydropower development. This matrix aids in making informed decisions by systematically evaluating multiple factors affecting site selection. Table 9 displays the ultimate rankings of the suggested sites, determined by the total weightings of all criteria for the proposed hydropower sites in the Upper Indus Basin. After applying the multi-criteria decision-making (MCDM) analysis, a significant shift in priorities is observed when environmental constraints are considered.

Table 9. Ordering of each proposed site according to the final score.

Site No.	Longitude	Latitude	Sum of All Criteria Weightage (from Table 8)	Final Rankings
1	35.09024581	76.03007488	0.371	17
2	35.32856256	75.84508775	0.408	14
3	35.46771954	75.37402412	0.505	9
4	35.58937774	75.31262481	0.544	8
5	35.71520232	74.77516221	0.639	4
6	35.83186087	74.7384981	0.5823	5
7	36.56014352	74.79766065	0.411	13
8	36.30682781	74.80682667	0.501	10
9	36.25099837	74.36602402	0.463	12
10	36.26599732	73.65190705	0.474	11
11	36.17492298	73.18099361	0.386	16
12	35.99434956	74.20603515	0.404	15
13	35.42022285	74.29436234	0.567	7
14	35.42795033	73.20348386	0.5821	6
15	35.10399255	73.00655144	0.829	2
16	35.0027519	72.91029199	0.777	3
17	34.82609753	73.00278555	0.941	1

While sites 16, 17, 5, 14, and 15 initially had high hydropower potential based on their discharge and head values, their rankings are altered when environmental and socioeconomic factors are incorporated into the decision-making process. Site 17, with the highest environmental score (0.941), emerges as the most optimal choice for development, despite not being the top contender based on hydropower generation alone. Similarly, site 16, which had more promising hydropower outputs than site 15, now ranks lower than site 15 after considering their environmental impacts. This shift in rankings emphasizes the importance of adopting a holistic approach to hydropower site selection.

By integrating environmental considerations, the methodology ensures that potential sites are evaluated not only based on technical feasibility but also on their sustainability and impact on local ecosystems. These results underscore the role of MCDM in prioritizing sites that minimize negative environmental consequences, such as habitat destruction, sedimentation, and water quality degradation, which are commonly associated with hydropower development. The final rankings indicate that while high hydropower potential is crucial, addressing environmental challenges is essential for sustainable development. The prioritization of sites based on their total weighted score ensures that the proposed projects align with global sustainability goals, such as SDG 7, by providing clean energy while protecting ecosystems and local communities. This integrated approach paves the way for informed decision-making that balances energy needs with environmental preservation.

4. Discussion

The growing need for sustainable and renewable energy has encouraged the advancement of small run-of-river plants. Initial investigations are necessary to evaluate the technical and economic viability of these plants. After conducting an analysis and calculating the final score using the MCDM method, it has been determined that site 17, site 15, site 16, site 5, and site 6 are the most promising sites among the seventeen alternatives proposed (Table 9), yielding estimated hydropower of 200.39, 119.45, 243.66, 196.82, and 100.86 MW, respectively (Table 4). The assessment of hydropower potential in the Upper Indus River Basin revealed that this area has significant opportunities for hydropower development, including the Indus River, Hunza River, and Gilgit River. Furthermore,

the MCDM analysis of each site showed that site 16 possesses the highest hydropower potential, i.e., 243.66 MW, yet ranks third rank because of the impacts of constraint criteria compared to the first and second ranked sites.

Previous research is also discussed here to place the findings in the broader context of the existing literature, highlighting the consistencies and discrepancies and providing a comprehensive perspective on how the current study's results fit within the wider scientific discourse. This analytical hierarchy process has been utilized by various researchers in the assessment of hydropower development, e.g., [72,73], and yielded reasonable results when it was used. In one study, Ali et al. (2023) [74] analyzed the possible sites for small-scale run-of-river hydropower projects in Thailand's Songkhla Lake Basin (SLB) using the analytical hierarchy process (AHP), geographic information system (GIS), and other tools, considering environmental, economic, and technical factors during the selection process. The same methodology was adopted in another study, where MCDM was used by Vassoney et al. (2021) [75] in Aosta Valley, Italy, to determine the best environmental flow scenario for releasing water from hydroelectric power. The study considered four criteria: energy, environment and fishing, landscape, and economy.

Thus, it was determined that the presence of significant favorable location criteria alone does not make the site the most suitable. Other factors, such as constraint criteria, also have a crucial impact on the overall suitability of the environment. Therefore, this study conducted an initial evaluation and comprehensive examination to facilitate the advancement of hydropower initiatives in the designated region.

5. Conclusions

This study demonstrates the significant hydropower potential in the Upper Indus Basin of Pakistan, highlighting its capacity to sustainably meet the country's growing energy demands. Multi-criteria decision-making (MCDM) and Geographic Information Systems (GIS) allowed for a thorough evaluation of seventeen proposed hydropower sites, considering both technical and environmental factors. This study successfully identified optimal sites that balance energy potential and environmental sustainability. The final rankings, which prioritize sites based on environmental sustainability, revealed that sites 17, 15, 16, 5, and 6 were selected as the most promising sites for hydropower projects in the study region. The findings emphasize the importance of integrating environmental constraints into hydropower site selection, ensuring that the benefits of hydropower are realized without compromising the integrity of local ecosystems and communities. While it is not a substitute for detailed field investigations, the methodology presented here provides a valuable framework for policymakers and developers to conduct initial assessments of hydropower potential. By leveraging GIS and MCDM tools, this approach efficiently identifies the most promising sites for future hydropower projects while minimizing negative environmental consequences. In short, this study lays the groundwork for sustainable hydropower development in Pakistan, contributing to the achievement of Sustainable Development Goal 7 (SDG-7) by ensuring access to affordable, reliable, and sustainable energy. The methodology provides a replicable model that can be applied globally, offering a balanced approach to hydropower development that respects environmental limits while addressing energy security needs.

6. Limitations and Future Research Directions

While this study focused on assessing conventional hydropower potential in the Upper Indus Basin, future research could explore the feasibility of pumped-hydro storage (PHS) systems at the identified sites. PHS offers significant potential for energy storage and grid stability, particularly in regions with variable energy demand and increasing renewable

energy integration. A detailed assessment of PHS feasibility, including site suitability, environmental impacts, and economic viability, would provide valuable insights for policy-makers and stakeholders. This could further enhance the sustainability and reliability of Pakistan's energy system. Incorporating PHS units in the UIB could significantly enhance Pakistan's energy storage capabilities and contribute to a more resilient and sustainable power grid. Additionally, this study did not consider the economic and political challenges associated with hydropower development, such as funding availability, regulatory hurdles, or geopolitical issues in the region. The elevation data used for head calculations (e.g., from DEMs/Google Earth Pro) were assumed to be accurate and representative of the actual terrain. The impact of climate change on future water availability and hydropower potential was not considered.

Future research should expand on this methodology by incorporating additional indices and more precise location criteria, particularly for small-scale hydropower projects. The lack of geological, seismic, and riverbed studies, as well as electricity transmission infrastructure and cost assessments in this analysis, presents an opportunity for further exploration in future studies, which could refine the understanding of potential sites. Additionally, incorporating more advanced engineering techniques, such as headrace tunnels, would allow for a more comprehensive evaluation of the sites. Future research directions can also focus on the need for ground-based hydro-meteorological and geological data collection to improve model precision, the integration of economic feasibility assessments, such as Levelized Cost of Energy (LCOE) analysis and financial risk assessment, to refine hydropower project planning, and the potential of public–private partnerships and policy frameworks to support the implementation of GIS-based site selection methods for practical decision-making.

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