

Research

Evaluating the socioeconomic and environmental sustainability of barrages using analytical hierarchy process with a rating approach

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Abstract

Assessing the environmental sustainability and economic viability of barrage infrastructure is a critical challenge in water resource management. To address this, the analytical hierarchy process (AHP) approach was applied to develop a novel model for three barrages in Punjab, Pakistan: Jinnah, Khanki, and Rasul. The model incorporates three impacts, nine parameters, and twenty-seven sub-parameters within a structured decision tree to rank the three alternatives (Barrages). Quantitative weights were assigned using pairwise comparisons to impacts, parameters, and sub-parameters. As a result, socio-economic impacts received the highest priority (64.10%), followed by environmental (28%) and other impacts (7.41%). Jinnah Barrage ranked first among alternatives with a sustainability score of 0.426, due to superior performance in irrigation potential, renewable energy generation, water quality, low carbon emissions, and recreational value. The proposed model provides a structured framework for the future design of barrages to enhance their environmental resilience and optimize socio-economic benefits.

Keywords Decision tree · Sustainability development · Barrages · Analytical hierarchy process · Socioeconomic impacts · Environmental impacts

1 Introduction

A barrage is a man-made structure built across rivers to redirect water into major canals. These structures play a key role in generating carbon-free electricity, managing floods, and replenishing groundwater [1]. Globally, barrages serve as lifelines for agricultural societies by ensuring a steady water supply for irrigation and sustaining livelihoods in regions prone to water scarcity [2]. Pakistan has one of the largest irrigation systems, which consists of 37,014 km of irrigation canals [3]. Pakistan's barrages are well-known for their wildlife reserves, such as the Chashma Barrage, which

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covers 34,099 hectares along the Indus River [4]. The Taunsa barrage supports a variety of flora, including vegetation, aquatic plants, and river forests [5]. In addition to their practical functions, barrages are also used for recreational activities such as boating, fishing, and hunting [6]. Despite these numerous benefits, the sustainability of barrages in terms of their socio-economic and environmental resilience remains difficult to evaluate comprehensively. To address this challenge, a multi-disciplinary criterion known as the analytical hierarchy process (AHP) technique was used in the study to assess the qualitative and quantitative aspects of a barrage. The AHP was established by Prof. Thomas L. Saaty in the 1980s. The AHP is a widely used decision support tool that helps to tackle multidimensional selection issues. Through its hierarchical structure, AHP provides a consistent framework for evaluating different aspects of complex systems by considering both the goals and parameters of a given project [7]. In recent years, AHP has been applied to a variety of civil engineering projects, such as risk safety assessments, water resources management, and the evaluation of agricultural water management practices [8].

In 2010, severe water issues arose due to groundwater contamination from mining activities, soil salinization, and petroleum oil leakage into Lake Poopó, Bolivia. These problems not only polluted the local water but also forced the relocation of residents. Calizaya et al. used the AHP approach to address this water pollution crisis. They developed an Integrated Water Resources Management (IWRM) model, considering environmental, social, and economic factors to support the affected population. The IWRM model was broken down into categories of factors, conflicts, instruments, and actors to evaluate the best water resources management alternative for the Lake Poopó Basin. Saaty's scale was used to assess each criterion, conflict, instrument, and actor. They concluded that the AHP method was highly effective and efficient in implementing the IWRM strategy [9].

In 2012, Anane et al. applied the AHP combined with Geographic Information Systems (GIS) to evaluate irrigation suitability in the Nabeul-Hammamet aquifer region of Tunisia, North Africa. Five primary factors were assessed: land suitability, resource availability, cost efficiency, social acceptance, and environmental impact. It was concluded that the most suitable sites were located near existing irrigated areas, emphasizing the need for community collaboration to promote the use of treated wastewater as a reliable irrigation source. The AHP-GIS approach proved effective for site selection, offering potential for replication in other regions and applications, such as aquifer recharge or urban green space irrigation planning [10]. In 2014, Gudienė et al. applied the AHP method to evaluate key factors influencing construction projects in Lithuania, Europe. The study involved two surveys, ranking 71 project factors divided into seven groups, with insights from 27 experienced professionals. The results highlighted the AHP method's usefulness in identifying critical factors and specific groups for construction projects, offering valuable guidance for future studies in Lithuania [11].

In 2017, Sun et al. evaluated agricultural water management systems in three irrigation districts of the Huang-Huai-Hai River basin in northern China using the AHP approach. The agricultural water management system was assessed using five parameters: technological, engineering, management, environmental, and economic aspects. Saaty's scale was used to assign weights to each of these parameters. The engineering and management factors are identified as the most influential in the agricultural water management system [12]. Kubicz et al. used the AHP approach to determine the variants for hydraulic structures located on multiple rivers. The model was divided into distinct stages to achieve the desired outcomes. At the first level of the AHP model, the primary objective was defined, while the alternatives were placed at the final level. The evaluation of each alternative was conducted through a questionnaire survey filled with highly qualified specialists. The study concluded that the AHP method is effective in quantifying the environmental impacts of hydraulic structures [13].

Hachoł et al. applied the AHP method to compare five lowland watercourses in Lower Silesia. They concluded that the AHP method is a valuable tool for the linear ranking of watercourses, as it systematically identifies the most feasible solution aligned with sustainable development goals [14]. In 2021, Yu et al. performed a comprehensive bibliometric analysis of AHP and ANP (Analytical network process) literature, based on 9859 publications sourced from the Web of Science database. Their findings showed that China leads in publication volume, while the USA excels in producing high-impact publications. In addition to mapping global research trends and collaboration patterns, the study reaffirms the significance of AHP as a robust decision-making tool, particularly suited for addressing complex problems where benefits are intangible and difficult to quantify [15]. Recently, Grošelj et al. evaluated the application of the AHP in sustainable forest management through a structured SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis based on inputs from 16 European experts. Their study highlights AHP's key strengths, such as its intuitive structure, ease of use, and ability to integrate qualitative and quantitative criteria, making it particularly effective in complex, multicriteria forestry contexts. The SWOT analysis further supports AHP's favorable positioning over other multi-criteria decision-making tools in terms of design and calculation capacities. Their findings confirm

that AHP is most valuable when used to structure complex decisions hierarchically and facilitate stakeholder participation in forest management planning [16].

Given the inherent complexity in evaluating both tangible (e.g., structural efficiency, economic returns) and intangible (e.g., environmental degradation, social displacement) impacts of water resource structures, especially barrages, it is imperative to employ a comprehensive and structured decision-making framework capable of accommodating multiple trade-offs [17]. Traditional evaluation methods often overlook the integrated nature of these systems, leading to fragmented assessments. This study is motivated by the pressing need to align the performance of hydraulic infrastructure with the principles of sustainability, particularly in the context of pre-construction planning. A critical review of existing literature reveals a significant research gap i.e. the absence of integrated, multi-criteria frameworks that holistically assess engineering, environmental, and socio-economic parameters.

To address this gap, the primary objective of this research is to develop a model with the help of the Analytic Hierarchy Process (AHP) approach, to evaluate and rank key parameters influencing the sustainability of barrage infrastructure. Specifically, the study aims to: (i) assess the relative importance of three major impacts: environmental impacts, socio-economic impacts, and other impacts; (ii) identify and prioritize sub-parameters within each impact through expert judgment; and (iii) apply the model to three real-world barrage scenarios (Khanki, Rasul, and Jinnah) to evaluate their sustainability performance and support evidence-based prioritization. The outcomes from this study will provide stakeholders with a robust decision support tool for sustainable barrage management, ensuring a balance between developmental needs and ecological preservation.

To the best of our knowledge, this study is the first to employ the Analytic Hierarchy Process (AHP) to evaluate the sustainability of barrage infrastructure by integrating environmental, socioeconomic, and engineering criteria within a unified framework, and validating the model through real-world case scenarios. In addition to addressing the identified research gap, this study makes several important contributions. First, it introduces a novel application of the AHP specifically tailored to assess the sustainability of barrage infrastructure. Second, the proposed model is validated using three real-world case studies: Khanki, Rasul, and Jinnah barrages, demonstrating its practical utility for comparative sustainability assessments. Finally, the study offers a structured and replicable methodology that enables decision-makers to systematically prioritize alternatives during the pre-construction phase of hydraulic infrastructure projects. This integrated approach provides a more holistic and actionable tool for sustainable water resource planning.

2 Material and methods

The study was conducted following the institutional guidelines and regulations. The study was approved by the synopsis approval committee of the National University of Computer & Emerging (NUCES), Lahore Pakistan. Informed consents were taken from all participants before data collection.

To conduct a comprehensive analysis, the impacts, parameters, and sub-parameters of the barrages were selected based on an extensive literature review [18–23] and input from industry professionals. Three barrages located on different rivers in Pakistan were selected for case studies such as the Khanki barrage on the Chenab River, the Jinnah barrage on the Indus River, and the Rasul barrage on the Jehlum River (Fig. 1a). Detailed descriptions of these barrages are provided in subsequent sections.

2.1 Scenarios

2.1.1 Scenario 1: Rasul barrage

The Rasul barrage is situated on the Jhelum River in the Mandi-Bahauddin district of Punjab Province, Pakistan (Fig. 1c). The Rasul barrage is 3201 feet long and has a discharge capacity of 850,000 Cusecs. According to the Punjab Irrigation and Power Department, the Lower Jhelum Canal (LJC), which originates on the left side of the Rasul barrage, irrigates 6870 square kilometers of agricultural land through five branch canals, four distributary channels, one minor, and one sub-minor channel. The Rasul hydropower plant is located upstream of the Rasul barrage and has a total generation capacity of 22 MW [24]. The ponding area of Rasul Barrage provides shelter to different species of fish like Gulfam, Rohu, Takla, and Tilapia [25].

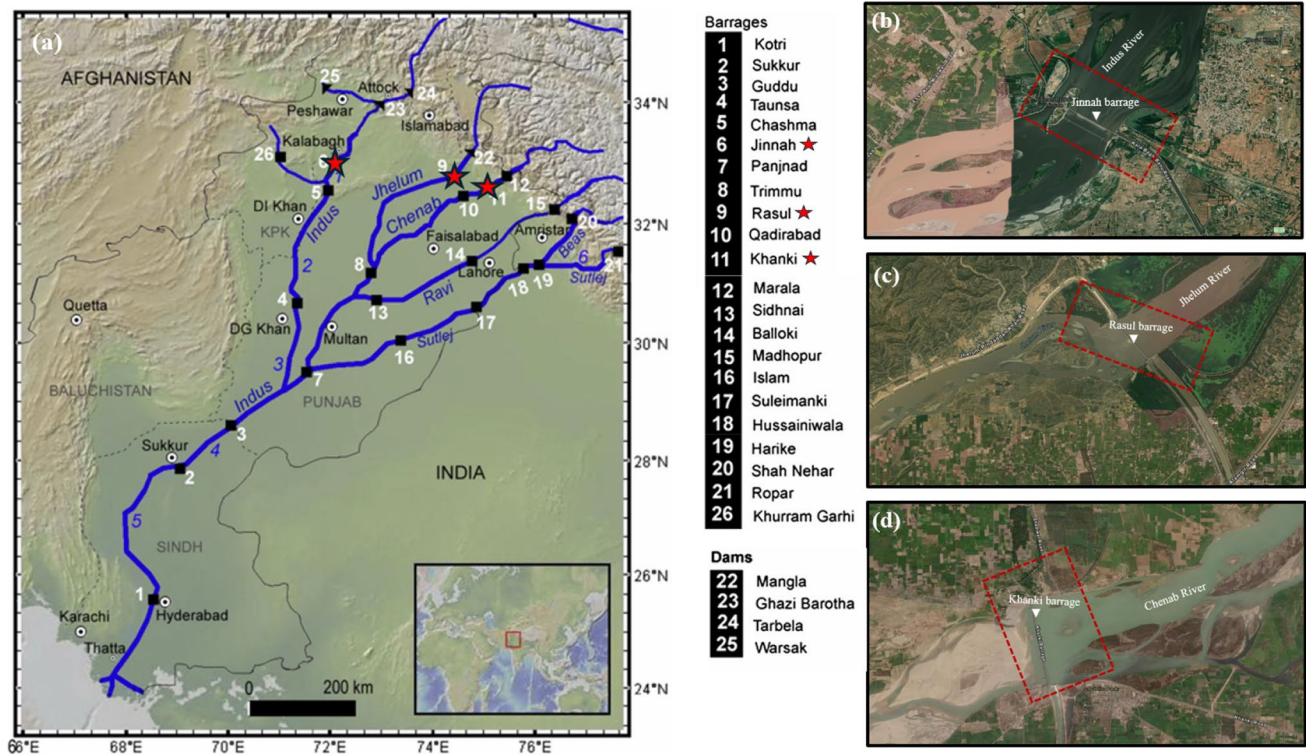


Fig. 1 a Location of barrage and dams in Pakistan; b satellite view of the Jinnah barrage on the Indus River; c satellite view of the Rasul barrage on the Jhelum River; d satellite view of the Khanki barrage on the Chenab River

2.1.2 Scenario 2: Khanki barrage

The Khanki Barrage is located on the Chenab River in the Gujrat district of Punjab Province, Pakistan (Fig. 1d). The Khanki Barrage is 4384 feet long in total, has a discharge capacity of 1,100,000 Cusecs, and irrigates around 3 million acres of rich land in eight districts of Punjab through the lower Chenab canal. The barrage features 65 gates in all, which will help to release peak flow during flood conditions. It also includes a big fish pass that allows a variety of species to swim upstream and downstream. There is no hydroelectric plant on the Khanki Barrage [26]. The region near the Khanki Barrage is ideal for many types of birds to stage and winter, while the pounding area beyond the barrier gives sanctuary to a variety of fish, including Ruho, Dumbra, Takla, Mori, and others [27].

2.1.3 Scenario 3: Jinnah barrage

The Jinnah Barrage is located on the Indus River in the district of Mianwali in Punjab Province, Pakistan (Fig. 1b). The Jinnah barrage is 3780 feet long and has a design capacity of 950,000 cusecs. Two branch canals, thirteen distributary channels, six minor channels, and one sub-minor channel supply water to 23,000 km² of rich areas via the Thal canal, which began on the left side of the Jinnah barrier [25]. The Jinnah hydropower plant is located on the right side of the Jinnah barrage. The Jinnah has a total generation capacity of 96 MW [24]. The Punjab Irrigation and Power Department has documented that Jinnah barrage is home to various fish species such as Indus trout, Soul, Singhara, Maha sheer, Gulfaam, Raho, Malei, and Cherda [21].

2.2 Procedure for analytical hierarchy process (AHP) using rating method

The first step in the AHP was to create a decision tree for the model. At the top level of the tree, the research objective, significant variants of barrages, was placed. The second level defined the impacts of barrages i.e., environmental, socio-economic, and other impacts. On the third level, these impacts were further classified into parameters (Fig. 2). For instance,

the socio-economic impacts were subdivided into categories such as flood control and protection, irrigation and water supply, and hydropower. The environmental impacts were divided into groundwater recharge patterns, greenhouse gases, and ecosystems. The other impacts were categorized into water quality parameters, accessibility, and recreational activities.

At the fourth level of the model, the parameters were further divided into sub-parameters to achieve the model's objectives such as flood control and protection were classified into sub-parameters like high flood, very high flood, and exceptional high flood [21]. Irrigation and water supply were divided into sub-parameters such as minor project, medium project, and major project [3], while hydropower was divided into medium hydropower plant, small hydropower plant, and mini hydropower plant [23] (Table 1). At the final level of the decision tree, three alternatives: Khanki barrage, Jinnah barrage, and Rasul barrage were ranked (Fig. 2).

In the second step of the AHP method, a relative comparison approach was used to compare each impact, parameter, and sub-parameter based on their common aspects. After comparison, they were rated using Saaty's nine-point scale, which ranges from 1 (equal importance) to 9 (extreme importance) to reflect the intensity of relative importance [28].

A homogeneous matrix was constructed based on paired comparison judgments to check the consistency of matrixes. For instance, the pairwise comparison matrix (A) was constructed for impact (Fig. 3). Each element was multiplied by its corresponding impact to form a matrix (B). The row-wise sums of the matrix (B) were divided by the respective priority weights. The average of these values was used to calculate the consistency index (CI), which was subsequently used to determine the consistency ratio (CR) as follows:

$$\text{Consistency ratio (CR)} = \text{Consistency index (CI)} / \text{Random index (RI)} \tag{1}$$

Here; the random index (RI) is the consistency index of the paired-wise generated matrix obtained through experiments using samples with large quantities [29].

The third step of the AHP method was the most important, as it was directly related to the research objective. The three alternatives were ranked based on the sub-parameters score to determine which contributes most towards environmental resilience.

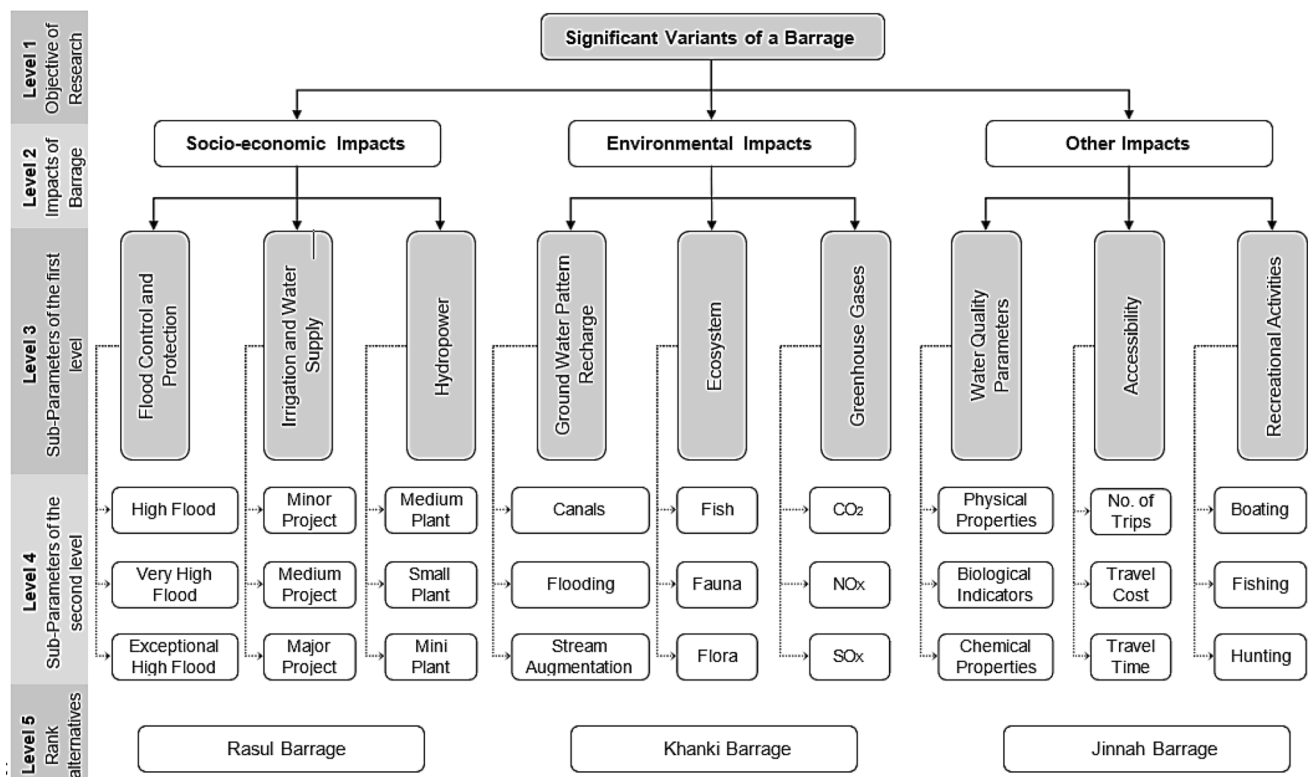


Fig. 2 Level of AHP Decision Tree

Table 1 Selected impacts, parameters, and sub-parameters of barrages

Impacts	Parameters	Sub-parameters
Environmental impacts	Greenhouse gases	Carbon dioxide (CO ₂) Nitrogen oxides (NO _x) Sulfur oxides (SO _x)
	Groundwater pattern recharge	Canals Flooding Stream augmentation
	Ecosystem	Fish Fauna Flora
Socio-economic impacts	Flood control and protection	High flood Very high flood Exceptionally high flood
	Irrigation and water supply	Minor project Medium project Major project
	Hydropower	Medium plant Small plant Mini plant
Other impacts	Recreation activities	Boating Fishing Hunting
	Accessibility	Number of trips Travel cost Travel
	Water quality parameters	Physical properties Biological indicators Chemical properties

Fig. 3 3×3 Matrix (A) of impacts of the barrage

<u>Environmental Impacts</u>	<u>Environmental Impacts</u>	<u>Environmental Impacts</u>
<u>Environmental Impacts</u>	<u>Socio – Economic Impacts</u>	<u>Other Impacts</u>
<u>Socio – Economic Impacts</u>	<u>Socio – Economic Impacts</u>	<u>Socio – Economic Impacts</u>
<u>Environmental Impacts</u>	<u>Socio – Economic Impacts</u>	<u>Other Impacts</u>
<u>Other Impacts</u>	<u>Other Impacts</u>	<u>Other Impacts</u>
<u>Environmental Impacts</u>	<u>Socio – Economic Impacts</u>	<u>Other Impacts</u>

2.3 Design of survey proforma and sample size

The scenarios were evaluated using a questionnaire survey completed by highly qualified specialists. The survey form consisted of 7 pages and was organized into five sections: Demographic Information, which defined key terms [20–22]. Explanation of Terms, which included the Saaty’s Scale for pairwise comparisons [7]. The third, fourth, and fifth sections included questions related to the impact of barrages, parameters, and sub-parameters (Appendix I).

The sample size was estimated using the standard method for an unknown population [30]:

$$\text{Sample Size} = \frac{[(Z\text{-Score value})^2 * \text{Standard Deviation} * (1 + \text{Standard Deviation})]}{\text{Margin of error}^2} \tag{2}$$

Here the Z-Score value taken was 90% with a confidence level of 1.645. The sample size estimated through the standard method for an unknown population was 68. It is noteworthy that the total number of responses collected (150) exceeded the estimated sample size (68).

2.4 Data collection

The evaluation of the socioeconomic and environmental impact of the barrage was a challenging task. After the completion of the survey proforma, interviews were conducted with 150 respondents from water resources departments such as the Water and Power Development Authority (WAPDA), National Engineering Services Pakistan (NESPAK), and the Press Information Department (PID). The respondents included director generals, subdivision officers, and senior engineers with over 2 years of experience in their respective fields. These professionals were asked to assign scores to each impact and its associated parameters and sub-parameters using the Saaty nine-point scale. These scores were then converted into percentages and ranked using the AHP method.

Although the AHP method provided a structured and systematic framework for evaluating the sustainability of barrages, it is important to acknowledge certain limitations associated with its application in this study such as confidence in expert judgment introduces biases, which may affect the consistency of the results. Additionally, the use of only three case study alternatives (Khanki, Jinnah, and Rasul barrage) may limit the generalizability of the findings. The model's static nature also restricts its ability to account for dynamic or time-dependent changes in socioeconomic conditions. Finally, while Saaty's nine-point scale is widely used, respondents may interpret the scale differently, leading to variability in scoring. These factors should be considered when interpreting the study outcomes and applying the model to broader contexts.

3 Results and discussion

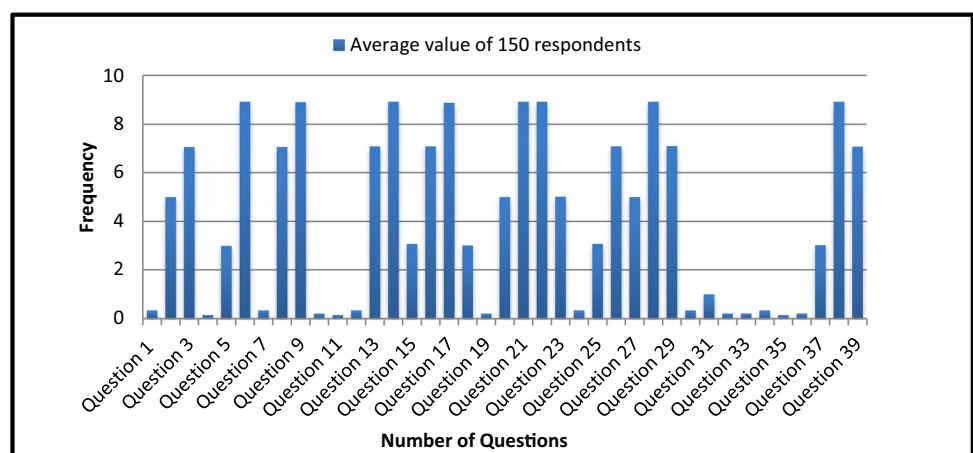
3.1 Statistical analysis and reliability analysis

This study presents a decision-support model developed using the Analytic Hierarchy Process (AHP) to evaluate the sustainability of three barrages: Jinnah, Khanki, and Rasul. To support this model, data were collected from 150 professionals in civil and environmental engineering through structured surveys (Fig. 4). Reliability analysis of the responses yielded a Cronbach's Alpha of 0.714, indicating acceptable internal consistency [31]. The survey data were analyzed using IBM SPSS, and pairwise comparison matrices were constructed to assess the relative importance of impacts, parameters, and sub-parameters. The consistency ratios (CR) of all matrices were below 0.10, confirming that the judgments provided by respondents were reliable and logically coherent.

3.2 Weights of impacts, parameters, and sub-parameters

The final values of 39 questions from the descriptive analysis were used for pairwise comparison matrices of impacts, parameters, and sub-parameters. Saaty's nine-point scale was used to rank the selected impacts, parameters, and sub-parameters. The results revealed that socio-economic impacts were considered the most influential, with a local

Fig. 4 Average values of 150 Respondents regarding 39 Questions



weight of 0.644. Within this category, the “irrigation and water supply” parameter received the highest weight (0.784 local weight; 0.505 global weight), and the sub-parameter “major irrigation projects” (0.785 local weight; 0.396 global weight) emerged as the most significant individual factor. These findings underscore the critical role of irrigation infrastructure in supporting agricultural productivity, particularly in regions dependent on canal-based irrigation (Table 2). This result aligns with Purohit and Bakalár et al. who emphasized that effective irrigation networks are vital for food security and rural economic development in water-scarce areas [32, 33].

The second-highest parameter under socio-economic impacts was “Flood Control and Protection,” with the sub-parameter “exceptional high flood” (0.780 local weight; 0.075 global weight) ranked highest in its group. This indicates the need for barrages to withstand extreme floods exceeding 800,000 Cusecs. This threshold is consistent with findings from Khan et al. [21]. Moreover, these results also reflect Sharma et al. suggestions that flood resilience should be a central consideration in infrastructure design, especially in flood-prone regions [34].

Under the “hydropower” parameter, the sub-parameter “small hydropower plants” (0.670 local weight; 0.029 global weight) was identified as the most sustainable energy alternative. These systems are typically rated between 1 and 100 MW and are considered environmentally favorable and economically feasible for localized energy production (Table 2). Similar conclusions were reached by Darmawi and Troldborg et al. study which highlighted that small-scale hydropower strikes an optimal balance between clean energy generation and minimal ecological disruption [35, 36].

In the environmental impact category (0.282 local weight), the parameter “ecosystem” carried the most significance (0.665 local weight; 0.188 global weight), with “fish species” (0.649 local weight; 0.122 global weight) rated as the most important sub-parameter. This finding highlights the ecological value of barrages in sustaining aquatic biodiversity and supports earlier work by Muhammad study reported high fish diversity near the Taunsa barrage [37]. The “groundwater pattern recharge” parameter also received considerable weight (0.290 local weight; 0.082 global weight), with “Canals” (0.751 local weight; 0.061 global weight) being the dominant sub-parameter. This emphasizes the role of canals in naturally replenishing groundwater tables as previously observed by Alam et al. in their analysis of canal seepage impacts in South Asia [38]. Additionally, under the “greenhouse gases” parameter, “carbon dioxide” was the most influential (0.786 local weight; 0.012 global weight), highlighting the environmental benefit of hydro-power as a low-emission energy source validating studies by Morimoto and Ashofteh et al. [39, 40].

Although “other impacts” carried the smallest overall weight (0.074), several sub-parameters within this category were still deemed important. Under “water quality parameters,” “chemical properties” (0.714 local weight; 0.004 global weight) emerged as a priority, due to concerns over heavy metal contamination, an issue emphasized in Javed et al. work [41]. The “accessibility” parameter identified “travel time” (0.731 local weight; 0.015 global weight) as a key benefit, underscoring the dual function of barrages as bridges that reduce local travel distances (Table 2). These results are supported by Rangari et al. who highlighted the social and logistical value of multipurpose barrage infrastructure [42]. “Recreational

Table 2 Local weights and global weights of impacts, parameters, and sub-parameters

Level 1: Research Objective	Level 2: Impacts	Local Weight	Level 3: Parameters	Local Weight	Global Weight	Level 4 Sub-parameters	Local Weight	Global Weight				
1	2	3	4	5	6	7	8	9				
Evaluation of Significant Variants of Barrage	Socio-Economic Impacts	0.644	Flood Control and Protection	0.150	0.096	High Flood	0.07	0.007				
						Very High Flood	0.150	0.014				
			Irrigation and Water Supply	0.784	0.505	Exceptional High Flood	0.780	0.075				
						Major Irrigation Project	0.785	0.396				
						Medium Irrigation Project	0.149	0.075				
						Minor Irrigation Project	0.066	0.033				
						Mini Hydropower Plant	0.064	0.003				
						Small Hydropower Plant	0.670	0.029				
			Hydropower	0.066	0.043	Medium Hydropower Plant	0.266	0.011				
						Canals	0.751	0.061				
	Environmental Impacts	0.282	0.282	Groundwater Pattern Recharge	0.290	0.082	Flooding	0.071	0.006			
							Stream Augmentation	0.178	0.015			
							Ecosystem	0.665	0.188			
				Fish	0.649	0.122	Flora	0.279	0.052			
							Fauna	0.072	0.014			
							Greenhouse Gases	0.055	0.0155			
				Carbon Dioxide	0.786	0.012	Nitrogen Oxides	0.066	0.001			
							Sulfur Oxides	0.149	0.002			
							Other Impacts	0.074	0.074	Water Quality Parameters	0.072	0.005
										Accessibility	0.279	0.020
	Biological Indicators	0.143	0.0007									
	Chemical Properties	0.714	0.004									
	Number of Trips	0.081	0.002									
	Travel Cost	0.188	0.004									
	Travel Time	0.731	0.015									
	Recreation Activities	0.649	0.048	Boating	0.655	0.031						
				Fishing	0.290	0.014						
Hunting				0.055	0.003							

Key: Grey color The Impact of greater weight; Green color Parameter of greater weights; Blue color Sub-Parameters of greater weights

activities” also received recognition, with “boating” (0.031) noted as a leading sub-parameter, contributing to social well-being and local economic activity—a theme also addressed by Hooper and Austen [43].

3.3 Ranking of alternatives

By combining local and global weights, the analysis identified nine sub-parameters as the most critical to barrage sustainability (Table 3): exceptional high flood (7.50%), major irrigation projects (3.96%), small hydropower plants (2.90%), canals (6.10%), fish species (12.20%), carbon dioxide (1.20%), chemical properties (0.40%), travel time (1.50%), and boating (3.10%). These sub-parameters were then used to score and rank the three barrages (Table 4). Jinnah Barrage received the highest overall score (0.426) due to its balanced contribution across multiple domains particularly a 96 MW small hydropower plant, a major irrigation network spanning 23,000 km², and facilities supporting cargo and recreational uses. Khanki Barrage, with a score of 0.234, excelled in managing exceptionally high floods and maintaining aquatic biodiversity due to its larger design capacity and habitat diversity. Rasul Barrage, while ranking third (0.171), offered a significant improvement in travel time for nearby communities and thus retained socio-spatial importance. These global weights were used to rank scenarios providing a clear understanding of the relative importance of various sub-parameters in determining the viability and sustainability of barrage projects. The score of scenarios (Khanki barrage, Jinnah barrage, and Rasul barrage), was determined by multiplying the global weights of the parameter with the respective weights (Table 4).

The AHP-based model successfully captured the complex trade-offs between socioeconomic and environmental considerations in barrage infrastructure planning. Jinnah Barrage’s high score illustrates the advantage of a multipurpose structure that performs well across both economic and ecological dimensions. Khanki Barrage’s strengths lie in hydrological performance and biodiversity support, while Rasul Barrage’s value is rooted in regional connectivity. These findings validate the utility of multi-criteria approaches like AHP in making informed, sustainable infrastructure decisions. The close alignment of the model’s outcomes with previously published studies across Asia and other global contexts [44–49] further reinforces its reliability and relevance to future water resource planning.

Table 3 Ranking of Impacts, Parameters and Sub-Parameters

Level 1: Research objective	Level 2: Impacts	Ranking	Level 3: Parameters	Ranking	Level 4: Sub-parameters	Ranking		
1	2	3	4	5	7	8		
Evaluation of Significant Variants of Barrage	Socio-Economic Impacts	I	Flood Control and Protection	II	High Flood	III		
					Very High Flood	II		
					Exceptional High Flood	I		
			Irrigation and Water Supply	I	Major Irrigation Project	I		
					Medium Irrigation Project	II		
					Minor Irrigation Project	III		
					Hydropower	III		
			Environmental Impacts	II	Groundwater Pattern Recharge	II	Canals	I
							Flooding	III
							Stream Augmentation	II
	Ecosystem	I			Fish	I		
					Flora	II		
					Fauna	III		
	Other Impacts	III	Water Quality Parameters	III	Carbon Dioxide	I		
					Nitrogen Oxides	III		
					Sulfur Oxides	II		
			Accessibility	II	Physical Properties	II		
					Biological Indicators	II		
					Chemical Properties	I		
					Recreation Activities	I		
				Number of Trips	III			
				Travel Cost	II			
				Travel Time	I			
				Boating	I			
				Fishing	II			
				Hunting	III			

Key: Grey color The Impact of greater weight; Green color Parameter of greater weights; Blue color Sub-Parameters of greater weights

Table 4 Overall score of scenarios based on the selected nine sub-parameters

Scenarios	Sub-parameters									Overall score
	Alternatives	Exceptional high flood	Major project	Small hydro plant	Canals	Fish species	Carbon dioxide	Chemical properties	Travel time	
Khanki barrage	0.056	0.071	-	0.020	0.079	-	0.0010	0.003	0.004	0.234
Jinnah barrage	0.014	0.297	0.024	0.020	0.034	0.011	0.0030	0.001	0.022	0.426
Rasul barrage	0.005	0.028	0.005	0.020	0.098	0.001	0.0003	0.010	0.004	0.171

4 Conclusion

This study applied the Analytic Hierarchy Process (AHP) to evaluate the sustainability of barrage infrastructure through an integrated assessment of socioeconomic, environmental, and other key impact categories. Among the evaluated impacts, socioeconomic impacts were found to be the most influential, with Irrigation and Water Supply ranked highest among the parameters. In the environmental and other impact domains, Ecosystem and Recreational Activities were identified as the most significant, respectively. Based on the global weights derived from expert judgment, the Jinnah Barrage emerged as the most socio-economically and environmentally sustainable option among the three alternatives studied (Khanki, Rasul, and Jinnah Barrages).

The proposed model for barrages based on AHP provides a structured and replicable framework for sustainability assessment. The use of this model enables planners to identify and prioritize critical parameters during the pre-construction phase, thereby supporting more informed and balanced infrastructure decisions. The sub-parameters defined in this study offer a transferable foundation that can be adapted for future barrage projects across different river systems.

Future research may focus on integrating climate change projections into the model to evaluate the long-term environmental resilience of barrage projects. Additionally, exploring trade-offs between socioeconomic gains and ecological risks using hybrid decision-making techniques such as Fuzzy AHP or Analytic Network Process (ANP) can improve the current framework. As AHP requires extensive pair-wise comparisons, especially for large-scale projects, there is scope to develop automated tools or digital platforms to streamline the process. Lastly, the approach outlined in this study can be extended beyond barrage infrastructure to other civil engineering applications, including green buildings, canal fall structures, dams, and urban water management systems.

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Data availability Data can be provided via email to corresponding authors upon request.

Declarations

Ethics approval and consent to participate Not applicable.

Informed consent Informed consent was obtained by the participants who participated in the survey questionnaires.

Consent for publication Not applicable.

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