

Fuzzy AHP-TOPSIS multi-criteria decision analysis applied to the Indus Reservoir system in Pakistan

Shahmir Janjua and Ishtiaq Hassan

ABSTRACT

The ranking of the reservoirs in Pakistan is an important decision and it has a vital impact on the sustainability of the region and the economic operation of the reservoir. The reservoirs ranking is a vital problem which involves multi-criteria decision-making. The framework proposed in this paper involves the fuzzy AHP-TOPSIS method for the ranking of reservoirs in Pakistan. Potential feasible locations are identified from the Water and Power Development Authority, Pakistan. Weight calculation for the criteria is done by the fuzzy AHP method, which is a multi-criteria decision-making method. In order to model the fuzziness, equivocacy, incomplete knowledge and ambiguity, the fuzzy AHP is used. Furthermore, in order to rank the selected reservoirs based on their performance, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied, which is a multicriteria decision making method. We demonstrate the application of the above-mentioned methods to the case study of the Indus Reservoir system in Pakistan. A decision support tool is provided for the decision makers in this paper to manage, evaluate and rank the planned reservoirs in the Indus River.

Key words | fuzzy AHP, Indus Reservoir system, multi-criteria decision making, sustainability, TOPSIS, WAPDA

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HIGHLIGHTS

- The ranking of the reservoirs in Pakistan.
- Ranking and selection of reservoir has a vital impact on the sustainability of the region and also the economic operation of the reservoir.
- Fuzzy AHP-TOPSIS method (multi-criteria decision-making method) for the ranking of reservoir.
- Helpful for the decision makers when conflicting criteria are involved.
- A decision support tool is provided for the decision makers to evaluate and rank the planned reservoirs having conflicting criteria.

INTRODUCTION

Conflicts arise over water resource projects and systems if they have diverse purposes and resource values. The main reason for the conflict is that the water resource projects are managed to optimize conflicting benefits for flood control, recreation, water supply and hydropower. The measurement of these benefits is usually easy because they are quantified in monetary value but the other resources, like environmental

and natural resources, are very difficult to measure and quantify in terms of economics. However, while analyzing the systems, specifically in optimization, it is most suitable if one quantitative measure is used to describe all the objectives for resource management (Flug *et al.* 2000).

The multi-criteria decision making (MCDM) methods, in recent years, have been used considerably in

environmental modelling (Zhou 2006). Apart from the economic criteria, as stated above, it is also essential to consider social, technical, environmental and political implications of water resource projects for ensuring the favourable and sustainable decisions. For this purpose, the stakeholders must be engaged at every step of the process that is necessary for decision making. This requires the use of both MCDM techniques and group decision making (Zarghami *et al.* 2008). The significant advantages of such MCDM techniques for water resources management are that these help to:

- deal with a limited quantity of water, manpower and financial resources;
- lower the costs of delays in decision making;
- allow for making decisions by considering different prominent criteria;
- provide information to resolve disputes among stakeholders;
- manage and administer the projects in a better and efficient way.

In order to construct an MCDM model, there is a need to establish the relative importance of criteria, their attributes as well as their hierarchy. In order to rank the water projects in Pakistan, a hierarchy of criteria and sub-criteria have been developed.

Due to their multi-objective, multi-layer and multi-period features, the management of the water resource projects becomes very difficult and a complicated task. Each stakeholder and decision maker may have a different level of satisfaction because for a given goal, many choices may exist; therefore, it is very difficult to point out which project is the best amongst them (Afshar *et al.* 2011).

Multi-criteria decision analysis (MCDA) has become an important tool for managing water resource projects because the policies of water are rarely defined by one objective. MCDA is a decision model which contains (Greco & Ehrgott 2016):

- ranking of the decision options by the decision makers,
- different units of criteria, and
- a set of performance measures.

When conflicting criteria are involved, MCDM is used for ranking alternatives (Larichev & Moshkovich 1995).

Some works related to MCDM are as follows: For River Basin Planning, multi-objective optimization was done by Gershon *et al.* (1982). The best wastewater management option was selected by using MCDA by Teclé (1988). Ranking of national water projects in Canada was done using MCDM by Simonovic (1989). Conflict management in water resource management and planning was done by Cai *et al.* (2004). Waste management problems were solved using a fuzzy approach by Tan *et al.* (2010).

There is a need for a reliable methodology for the ranking of water resource projects (Afshar *et al.* 2011). A framework is provided by the MCDA that helps the decision makers to find the main issues. These issues are assigned with the relative priorities and then an alternative is selected. This process facilitates a communication among the stakeholders and helps them to reach a decision (Hajkowicz & Collins 2007).

The Technique for Order Preference by Similarity of Ideal Solution (TOPSIS) was proposed by Hwang & Yoon (1981) for solving multi attribute decision making problems. Like fuzzy AHP, the fuzzy TOPSIS method has also been used for solving location selection problems. Ertuğrul & Karakaşoğlu (2008) applied fuzzy AHP and fuzzy TOPSIS to a facility location selection problem of a textile company. A fuzzy version of the TOPSIS method, based on fuzzy arithmetic operations, was proposed by Triantaphyllou & Chi-Tun (1996). Chen (2000) applied fuzzy TOPSIS for engineer's selection for a software company. A fuzzy TOPSIS model was also presented by Chu (2002) under group decisions for solving a facility location selection problem. Problems related to MCDM, with a given reference point, can be solved by defining the options or decisions that are nearest to the ideal point or reference point.

The pros and cons of MCDM approaches are shown in Table 1. Before setting up a large energy or hydropower project, its detriments and benefits to the society should be kept in perspective. According to Lior (2012), all large-scale projects should be implemented and designed sustainably keeping in view social, environmental and economic impacts.

The aim of this paper is to rank the water resource projects that are planned or ready for construction in Pakistan. The ranking of the reservoirs is among the decisions that are of importance in water supply management. The dam construction is very expensive, particularly

Table 1 | Comparison of multi-criteria decision-making methods

MCDM methods	Pros	Cons
ANP	<ul style="list-style-type: none"> • ANP is capable of handling feedbacks and interdependencies. • It depicts the dependence and influences of the factors involved to the goal or higher-level performance objective. 	<ul style="list-style-type: none"> • There are more pairwise comparison matrices in ANP than AHP. Hence, it is difficult to solve. • Specific software is required to solve it.
TOPSIS	<ul style="list-style-type: none"> • Measures the distance of the alternatives from the ideal solution • Used for selection of the one closest to the ideal solution • Easy to use and well understandable. • It can be solved using a spreadsheet. 	<ul style="list-style-type: none"> • Normalization is required to solve multi-dimensional problem. • Consistency check not possible.
ELECTRE	<ul style="list-style-type: none"> • Decision making by using thresholds of indifference and preference, and outranking method. • Applicable for quantitative and qualitative attributes. • Applicable even when there are incomparable alternatives. 	<ul style="list-style-type: none"> • It is difficult to conceptualize the problem in the absence of a hierarchical structure. • Comparatively more difficult to solve than AHP due to complex computational procedure. • May or may not figure out the preferred alternatives.
Multi-objective programming	<ul style="list-style-type: none"> • Model involves linear or nonlinear objective function and constraints. • It may have continuous or integer decision variables that can usually take on an infinite number of values. • It is used when there are large numbers of alternative choices. 	<ul style="list-style-type: none"> • Difficult to solve due to complex computational procedure. • Specific software or meta-heuristic approach is required to solve it • Applicable only for quantitative attributes. • Applicable only when exact data are available.
AHP	<ul style="list-style-type: none"> • Applicable for quantitative and qualitative attributes. • Use of hierarchical structure to present complex decision problem. • It can be solved using spreadsheet. • Consistency of the evaluation procedure can be measured 	<ul style="list-style-type: none"> • A large number of pairwise comparisons required as number of alternatives increase. • Due to aggregation, compensation between good scores on some criteria and bad scores on other criteria can occur.

for an underdeveloped country like Pakistan and it also has long-term environmental impacts. A large amount of Pakistan's national budget will be invested in the construction of these reservoirs. Therefore, to achieve greater efficiency in the allocation of water resources and funds, it is necessary to rank the projects and it is proposed that high ranked projects should be supported first in their construction. The low ranked projects will be constructed later due to the increasing stakeholders' conflicts and limited financial budget in Pakistan'.

An integrated multicriteria decision making framework has been proposed in this study for ranking the water projects in Pakistan in the presence of vague information and multiple factors. The ranking of water resource projects involves several conflicting criteria. The main criteria and sub-criteria are firstly identified using the experience of experts and available literature (Afshar *et al.* 2011; Zarghaami *et al.* 2007;

Minatour *et al.* 2015). The weights of the criteria are determined using the fuzzy AHP. The linguistic preferences of the experts are mapped with triangular fuzzy numbers (TFNs) to decide the importance and preference of one criterion over the another. TOPSIS is applied afterwards to rank the water projects based on their overall performance. The decision framework proposed in this paper provides useful insights for practicing managers in evaluating and selecting water projects.

The choice for an integrated fuzzy AHP-TOPSIS based framework proposed in this paper is justified by several reasons:

- A minimum number of feasible location choices are identified on the basis of social, technical, environmental, economic and political factors. This will not only make the task easier for decision makers to visualize the

situation and indicate their preferences, but also considers the viewpoint of many stakeholders. As a result, possible delays can be avoided.

- The linguistic preferences and incomplete knowledge of different interest groups are mapped to decide the preferences for both quantitative and qualitative criteria and to compare distinct alternatives. This is required for evaluating large-scale water projects, and fuzzy AHP allows it.
- TOPSIS can rank the alternative locations based on their overall performance, since it may identify the best solution that is closest to the positive ideal solution and farthest from the negative ideal solution.
- The proposed framework can be solved easily. The case study illustrated in this paper shows that it can be applied using a spreadsheet.

History of the Indus Basin

The Indus River (Figure 1) is a major source of life for Pakistan. It provides water for 90% of the food production in Pakistan and contributes towards 25% of the country's gross domestic product. Pakistan, being an agricultural country, could soon face a serious food and water shortage. It is projected that there will be 32% shortfall of water requirements and 70 million tons of food shortage in the country by 2025 (Qureshi 2011).

About 566,000 square kilometers (km²) of the area, which is about 70 percent of the country, is drained by the Indus Basin, comprising the four provinces, namely Punjab, Sindh Baluchistan and Khyber Pakhtunkhwa (KPK) (Yu *et al.* 2013). The basin is fed by the eastern rivers (Ravi and Sutlej) and western rivers (Jhelum,

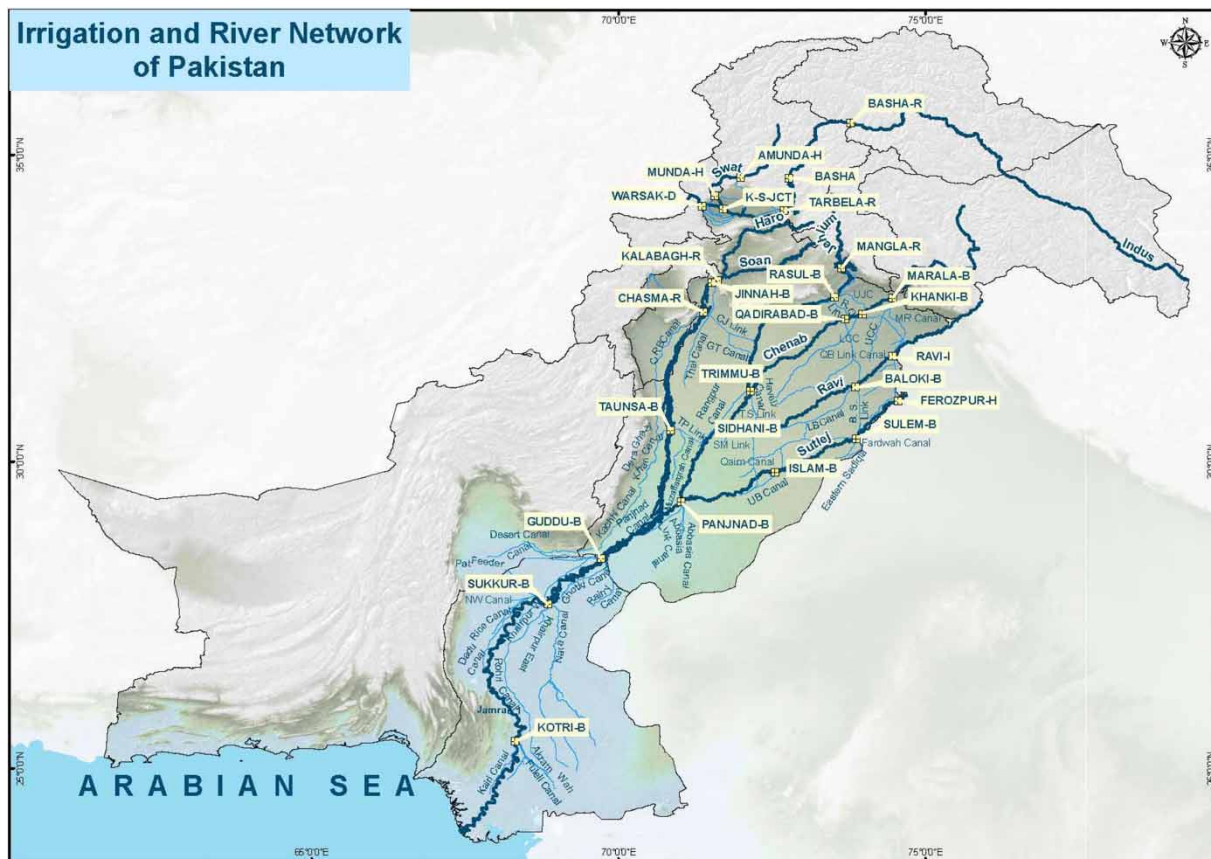


Figure 1 | Irrigation and River Network of Pakistan (This map was extracted from Indus River System Authority, IRSA). Available online: http://pakirsa.gov.pk/images/IrrigationNetwork_Pakistan.jpg.

Chenab and Kabul). The total length of the basin is about 2,900 km and an altitude of 18,000 ft from the top of the Himalayas to the low-lying areas of Sindh, where it flows into the Arabian Sea.

Although Indus Basin is the twelfth largest drainage basin in the world, it has the largest contiguous irrigation system in the world. About 150,000 km² of the cropland out of 190,000 km² is irrigated by the Indus Basin Irrigation System (Ahmad 2005). The Indus Basin is the home to seventh largest mangrove system and the fifth largest delta in the world. Due to lack of sustained minimum river flows, the delta ecosystem has deteriorated in recent years. The average precipitation in the basin is around 230 millimeters per year, which is very low. Sub-tropical climate exists in the basin with transpiration rates of 2,112 millimeters per year (Ullah *et al.* 2001). Most of the flow of the Indus River (around 40–70 percent) is from glaciers' melt and snow off the Himalayas. Most of the flow (about 85 percent) in the basin's catchment occurs from the months of May to September (National Research Council 2012). The Indus Basin in Pakistan has a mean annual flow of 176 billion cubic meter of which almost 90 percent is supplied for irrigation purposes. Despite this, there are high variations in demand and supply: for example, during the droughts of 2000–2002, the difference between supply and demand was 20 percent (Briscoe 2006). Due to factors such as urbanization and high population growth (Shahid *et al.* 2018), aggravated by evapotranspiration, canal and water course seepage, field application losses and field level irrigation inefficiency, the future deficits would be around 20 percent by 2025 (Briscoe 2006).

Problem statement

Storage capacity

As described above, in spite of the IBIS's massive distribution network, its storage capacity is very low – only about 30 days' worth of annual flow, contained mostly in two reservoirs – some 30 times less than that of the Murray-Darling and Colorado Basins. Such limited storage puts severe constraints on assuring that water supply will meet demand, especially as the majority of flow occurs during a three- to four-month period. Lack of storage also

limits the ability to provide the sustained minimum flow to the Indus delta necessary to maintain a healthy ecosystem of mangroves and fisheries. Although storage is urgently needed to alleviate droughts and attenuate flooding, the last new reservoir was constructed in 1976. Both the major reservoirs of Pakistan, Tarbela and Mangla, are plagued with siltation problems. Due to sediment deposition, both the reservoirs have lost 32 and 20 percent of their storage capacity respectively (Sattar *et al.* 2017). If no new storage is built soon, canal diversions will remain the same, and the shortfall will increase by 12% in the next decade. The Pakistan Water Sector Strategy estimates that Pakistan needs to raise its storage capacity by 22 BCM by 2025 to meet the projected requirements of 165 BCM. Therefore, it is of paramount importance that Pakistan gives serious attention to building new storage facilities. It is unfortunate that, even after completion of Tarbela Dam in 1976, no decision could be taken on the construction of new storage capacity (Rajput 2011).

Energy security: hydropower capacity

The electricity generation in Pakistan by hydropower is about 6,500 megawatts (MW) a year. This is far below the total hydropower generating potential of 60,000 MW (Trimble *et al.* 2011). The total electricity generation capacity in Pakistan was about 21,600 MW in the year 2010. This included all forms of power including hydropower, fossil fuel and nuclear. With the growing industry and population, the electricity demand of Pakistan is increasing by almost 7 percent annually, and the supply of electricity falls short of demand by 2,000–4,000 MW (Trimble *et al.* 2011). Due to poor transmission capability, generation deficits and increasing electricity demand, the country is facing extreme power shortages in the form of daily power rationing, also known as load shedding. Blackouts are frequent in the cities, which last about 8 to 10 hours a day during the summer season. In rural areas, these power outages are often double (Trimble *et al.* 2011).

Pakistan heavily relies on expensive imported oil for electricity generation despite its abundant access to hydropower. The oil-fired thermal generating plants produce about 39 percent of all the electricity in Pakistan (Trimble *et al.* 2011). The import of oil puts a considerable strain on

the economy as it raises the external current account deficit and worsens the country's balance of payments position (Trimble *et al.* 2011).

Development of the nation's available hydropower by building additional dams would lessen this financial burden while simultaneously providing much-needed supplementary capacity for irrigation storage and flood control.

Flood security: peak reduction and containment of floodwaters

For the millions of people living in the Indus Basin, flooding is a tragic fact of life. Floods in Pakistan have caused long term disruption of economic development and productive agriculture. More than seventeen major floods have occurred in Pakistan since 1950, which resulted in cumulative damage exceeding \$15 billion in the form of direct economic losses, 9,000 lives lost, and millions of acres of flooded land (Briscoe 2006). The 2010 flood was the worst in the history of Pakistan, which resulted in almost 2,000 deaths and 20 million displaced people. The economic damage done to the agricultural sector due to the flood was \$2.9 billion (Condon *et al.* 2014). Although, the threat of flooding is impossible to eliminate, it is important that more storage infrastructure should be built to attenuate dangerous high flows and harness water during times of excess to provide during times of drought.

METHODOLOGY

In order to evaluate, manage and rank the planned reservoirs in the Indus River, a three-phase methodology has been proposed (Figure 2).

Stage I: identification of potential locations

The water projects planned by Water and Power Development Authority (WAPDA) on the Indus River system have been considered in this study. Due to the high demand for irrigation water and high hydropower potential, numerous water projects have been planned by WAPDA. In this study, only large projects have been selected that have a high water storage potential and high power generation

capacity. After study and discussion with various experts, five projects were selected for the ranking (Appendix A).

Stage II: fuzzy AHP

Saaty proposed the analytic hierarchy process (AHP) in 1990. In the decision-making process, both the quantitative and qualitative factors are incorporated in AHP. As the discrete scale of 1 to 9 is used in AHP, this process is generally criticized as it does not incorporate the uncertainty in the process of decision-making.

In order to solve the multicriteria problems, the method of fuzzy AHP has been used in other fields as well. Haq & Kannan (2006) used this method to select the best vendor in a supply chain. Huang *et al.* (2008) used this for the selection of R & D projects. Pan (2008) used this methodology for selecting the appropriate method for bridge construction. Güngör *et al.* (2009) applied this methodology for a personnel selection problem.

As proposed by Zadeh, fuzzy set theory is a general form of classical set theory. It is a membership function and it allocates a grade between one and ten. If the letter represents a fuzzy set, a tilde '˜' is placed over it. A fuzzy event is denoted by (l, m, u) , where 'l' is the smallest value, 'm' is the most likely value and 'u' is the highest value. Some of the definitions related to Fuzzy AHP are discussed below.

Def 1. For a TFN \tilde{I} , the membership function is given by (l, m, u) and is defined as:

$$\mu_{\tilde{I}}(x) = \begin{cases} \frac{x-l}{m-l} & l \leq x \leq m, \\ \frac{m-x}{m-u} & m \leq x \leq u, \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

For the left and right-side representation, the degree of membership of a fuzzy number is given by:

$$\begin{aligned} \tilde{I} &= (A^{L(y)}, A^{R(y)}) \\ \tilde{I} &= (l + (m-l)y, u + (u-m)y), Y \in [0, 1] \end{aligned} \quad (2)$$

Def 2. Suppose that the two TFNs are $\tilde{I}_1 = (l_1, m_1, u_1)$ and $\tilde{I}_2 = (l_2, m_2, u_2)$. The operational laws of addition,

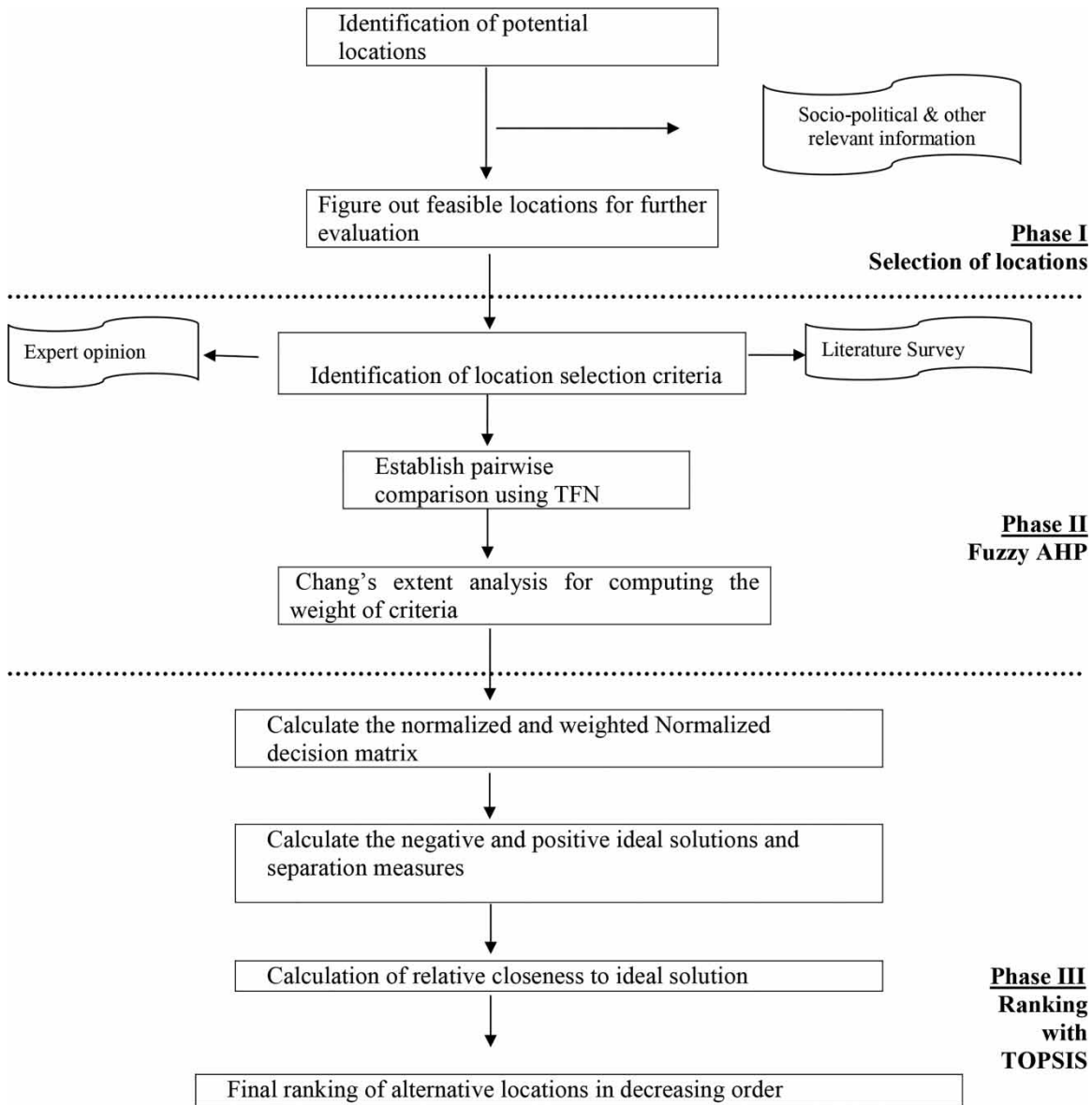


Figure 2 | The three-phase research methodology.

multiplication, subtraction, division and reciprocal are expressed as follows.

Their addition is given by

$$\tilde{I}_1 + \tilde{I}_2 = (l_1, m_1, u_1) + (l_2, m_2, u_2) = (l_1 + l_2, m_1 + m_2, u_1 + u_2) \quad (3)$$

Their multiplication is given by

$$\tilde{I}_1 \times \tilde{I}_2 = (l_1, m_1, u_1) \times (l_2, m_2, u_2) = (l_1 l_2, m_1 m_2, u_1 u_2) \quad (4)$$

$$\alpha \times \tilde{I}_2 = (\alpha l_2, \alpha m_2, \alpha u_2) \text{ where } \alpha > 0 \quad (5)$$

Their subtraction is given by

$$\tilde{I}_1 - \tilde{I}_2 = (l_1, m_1, u_1) - (l_2, m_2, u_2) = (l_1 - l_2, m_1 - m_2, u_1 - u_2) \quad (6)$$

Their division is given by

$$\tilde{I}_1 / \tilde{I}_2 = (l_1, m_1, u_1) / (l_2, m_2, u_2) = (l_1 / u_2, m_1 / m_2, u_1 / l_2) \quad (7)$$

Inverse is given by

$$\tilde{I}_1^{-1} = (l_1, m_1, u_1)^{-1} = \left(\frac{1}{u_1} + \frac{1}{m_1} + \frac{1}{l_1} \right) \tag{8}$$

For the interval judgements, the TFNs are used to give preference to one criterion over the other. A pairwise comparison is then done using extent analysis and finally the weights of the criteria are calculated. The general steps for this method are as follows.

Phase 1: synthetic extent calculation

Let $X = \{x_1, x_2, \dots, x_n\}$ be an object set and $U = \{u_1, u_2, \dots, u_m\}$ be the goal set. Extent analysis is performed using Chang's extent analysis (Chang 1996), which is given below.

$I_{gi}^1, I_{gi}^2, \dots, I_{gi}^m$, $i = 1, 2, \dots, n$, where all the I_{gi}^j ($j = 1, 2, \dots, m$) are TFNs. The fuzzy synthetic extent values with respect to the i th object is given by:

$$S_i = \sum_{j=1}^m I_{gi}^j \times \left[\sum_{i=1}^n \sum_{j=1}^m I_{gi}^j \right]^{-1} \tag{9}$$

Phase 2: fuzzy values comparison (Chang 1992), (Chang 1996)

The degree of possibility of $I_2 = (l_2, m_2, n_2) \geq I_1 = (l_1, m_1, n_1)$ is defined as:

$$V(I_2 \geq I_1) = \underset{X \geq y}{SUP} [\min(\mu_{I_1}(x), \mu_{I_2}(y))] \tag{10}$$

When a pair (x, y) exists such that $x \geq y$ and $\mu_{I_1}(x) = \mu_{I_2}(y) = 1$, then we have $V(I_2 \geq I_1) = 1$. Since I_1 and I_2 are convex fuzzy numbers, they are expressed as follows:

$$V(I_2 \geq I_1) = \text{hgt}(I_1 \cap I_2) = \mu_{I_2}(d) \tag{11}$$

'd' is the ordinate of the highest intersection point 'D' between μ_{A_1} and μ_{A_2} . When $I_1 = (l_1, m_1, u_1)$ and $I_2 = (l_2, m_2, u_2)$ then $\mu_{I_2}(d)$ is computed by:

$$\mu_{I_2}(d) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & l_1 \geq l_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - ((m_1 - l_1))}, & \text{otherwise} \end{cases} \tag{12}$$

Both the values of $V(I_2 \geq I_1)$ and $V(I_1 \geq I_2)$ are required for comparing I_1 and I_2 .

Phase 3: calculation of priority weight (Chang 1992), (Chang 1996) and (Gumus 2009)

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $I_i = (i = 1, 2, \dots, k)$ can be defined by:

$$V(I \geq I_1, I_2, \dots, I_k) = V(I \geq I_1) \text{ and } (I \geq I_2) \text{ and } \dots \text{ and } (I \geq I_k) \tag{13}$$

$$V(I \geq I_1, I_2, \dots, I_k) = \min V(I \geq I_i) \quad i = 1, 2, \dots, k \tag{14}$$

If

$$M(P_i) = \min V(S_i \geq S_k) \text{ for } k = 1, 2, \dots, n; \quad k \neq i. \tag{15}$$

Then, the weight vector is given by:

$$W_p = (m(P_1), m(P_2), \dots, m(P_n))^T \tag{16}$$

Here, P_i ($i = 1, 2, \dots, n$) are n elements.

Phase 4: calculation of normalized weight vector

After normalization of W_p , the normalized weight vectors are given by:

$$W_p = (w(P_1), w(P_2), \dots, w(P_n))^T \tag{17}$$

Here, W gives the priority weights of one alternative over another and it is a non-fuzzy number

Stage III: TOPSIS

Based on their performance, the projects are ranked using TOPSIS. The following three types of criteria or attributes are considered in this method:

- Cost criteria/attribute
- Qualitative benefit criteria/attribute
- Quantitative benefit

Two types of alternatives are considered in this study, as given below:

- Negative ideal solution
- Positive ideal solution

TOPSIS is based on the selection of the best alternative or project which is furthest from the negative ideal solution and closest to the positive ideal solution. The positive and the negative ideal solutions are the ones that have the highest benefits and lowest benefits, respectively. The final ranking of the projects is done on the basis of relative closeness to the ideal solution (Ilankumaran & Kumanan 2009).

The general TOPSIS process has the following steps (Gumus 2009; Joshi *et al.* 2011). In these steps, ‘m’ represents alternatives, ‘n’ represents the attributes, x_{ij} represents the score of the alternative i w.r.t criterion., ‘J’ represents the cost criteria and J represents the benefits criteria.

Step 1

Construct normalized decision matrix. The calculation of normalized value r_{ij} is done by:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, i = 1, \dots, m; j = 1, \dots, n \quad (18)$$

Step 2

Construct the weighted normalized decision matrix. Assume we have a set of weights for each criteria w_j for $j = 1 \dots, n$ and $\sum_{j=1}^n w_j = 1$. Each column of the normalized decision matrix is then multiplied by its weight. An element of the new matrix is:

$$\eta_{ij} = w_j r_{ij}, i = 1, \dots, m; j = 1, \dots, n \quad (19)$$

Step 3

Determination of positive ideal and negative ideal solutions.

For the positive ideal solution:

$$A^+ = \{\eta_1^+, \dots, \eta_n^+\}, \text{ where} \quad (20)$$

$$\eta_j^+ = \{\max(\eta_{ij}) \text{ if } j \in J; \min(\eta_{ij}) \text{ if } j \in J'\}, j = 1, \dots, n \quad (21)$$

and for the negative ideal solution:

$$A^- = \{\eta_1^-, \dots, \eta_n^-\}, \text{ where} \quad (22)$$

$$\eta_j^- = \{\min(\eta_{ij}) \text{ if } j \in J; \max(\eta_{ij}) \text{ if } j \in J'\}, j = 1, \dots, n \quad (23)$$

Step 4

Separation measures calculation.

From the positive ideal alternative, the separation measure is:

$$S_i^+ = \left\{ \sum_{j=1}^n (\eta_{ij} - \eta_j^+)^2 \right\}^{1/2} \quad i = 1, \dots, m \quad (24)$$

and from the negative ideal alternative, the separation measure is:

$$S_i^- = \left\{ \sum_{j=1}^n (\eta_{ij} - \eta_j^-)^2 \right\}^{1/2} \quad i = 1, \dots, m \quad (25)$$

Step 5

Calculation of relative closeness to the ideal solution:

$$C_i = \frac{S_i^-}{(S_i^+ + S_i^-)}, i = 1 \dots, m. C_i \in \{0,1\} \quad (26)$$

In the TOPSIS method, C_i will denote the final score.

Step 6

The alternatives should be ranked using the C_i value in increasing or decreasing order. The largest index value (C_i) will indicate that it has the shortest distance from the positive ideal solution, whereas the lowest index value (C_i) will indicate the shortest distance from the negative ideal solution.

CASE STUDY

Selection of feasible locations

There are numerous water resource projects that are planned by the WAPDA. The stakeholders; that is, the

provinces of Pakistan, would greatly benefit from the construction of these reservoirs. Ranking of the selected projects on the defined criteria is the main aim of this study. It will be proposed that the projects that are ranked high should be given priority in construction. The low-ranked projects will be constructed later due to the increasing stakeholders' conflicts and limited financial budget in Pakistan.

The three-phase methodology is adopted to rank the water projects in Pakistan. The five feasible locations were selected, which are given below. For the details of each alternative location, see Appendix A.

- Bunji Hydropower Project (P_1): Gilgit
- Diamer-Bhasha Dam (P_2): Gilgit
- Dasu (P_3): Kohistan District, KPK
- Kalabagh Dam (P_4): Mianwali District, Punjab
- Akhori Dam (P_5): Attock District, Punjab

Determination of the criteria weights using fuzzy AHP

Keeney & Raiffa (1993) stated that the hierarchy of the criteria should meet the following: completeness, non-redundancy, decomposable and minimum size. Certain compromises for some cases can be made. The 'time of construction', for example, can be combined with the calculation of financial attributes as the 'benefit to cost' ratio.

Criteria are defined in the fuzzy AHP to evaluate the alternative locations. To achieve this, the available literature was explored, and an intensive discussion was undertaken with the experts to determine the criteria and sub-criteria affecting the selection and ranking of the projects in Pakistan. The defined sub-criteria are further classified into six (as shown in Figure 3) criteria, which are:

- Cultural and social,
- Political, legal and security,
- Technical and executive,
- Environmental,
- Economic and financial,
- Comprehensive management.

The TFNs as defined by Gumus (2009) are used to compute the priority weights for each criteria. These TFN and their reciprocals are shown in Table 2. The questionnaires are used to prepare the fuzzy comparison matrices. The

questionnaire form is shown in Appendix-A. Description of potential locations for projects and criteria are shown in Table A-1 (Appendix A). The questionnaire form to calculate the weight of each criteria is given in Table A-2 (Appendix A).

Twelve experts from WAPDA were contacted to give their valuable input for further data analysis. They were asked to give their valuable opinion and input as per the questionnaire given in Appendix A. Out of 12, only 10 agreed to give their expert input and the remaining two excused giving their valuable input. These experts were related to these projects in the capacity of the execution and design team. As input/opinion of other people who had no detailed knowledge of these projects could have hampered both input and input-based output, only experts who belonged to the planning department of WAPDA were selected and contacted in this study, as they had all the relevant information related to these projects. Also, the feasibility reports for these projects were not available to anyone other than the personnel working in the planning department of WAPDA. Extensive literature reviews and interviews with various experts were conducted to define the criteria and sub-criteria, keeping in view the conditions in Pakistan. The importance rate of the criteria was determined by the experts using linguistic variables.

The linguistic variables were then adjusted with the TFNs in the next step. The data was then inserted in the Excel software. The first question of the questionnaire is shown in Table 3 as a sample, which compares the social and cultural criteria with the criteria of political, security and legality.

In a similar manner, a total of sixteen (16) such tables were developed and the other criteria were also compared. The dual comparison matrices were then prepared. Table 4 shows the fuzzy comparison matrices. Chang's extent analysis approach was used for the weight calculations. MS Excel is used for these calculations. The Excel template for the Ideal Solution using Chang's extent analysis approach is also shown in Appendix B.

Using Equation (9), the fuzzy synthetic extent values are:

$$S_1 = (0.05031004, 0.0710086, 0.10566663)$$

$$S_2 = (0.17226796, 0.2554786, 0.37200753)$$

$$S_3 = (0.172155363, 0.2597413, 0.38192277)$$

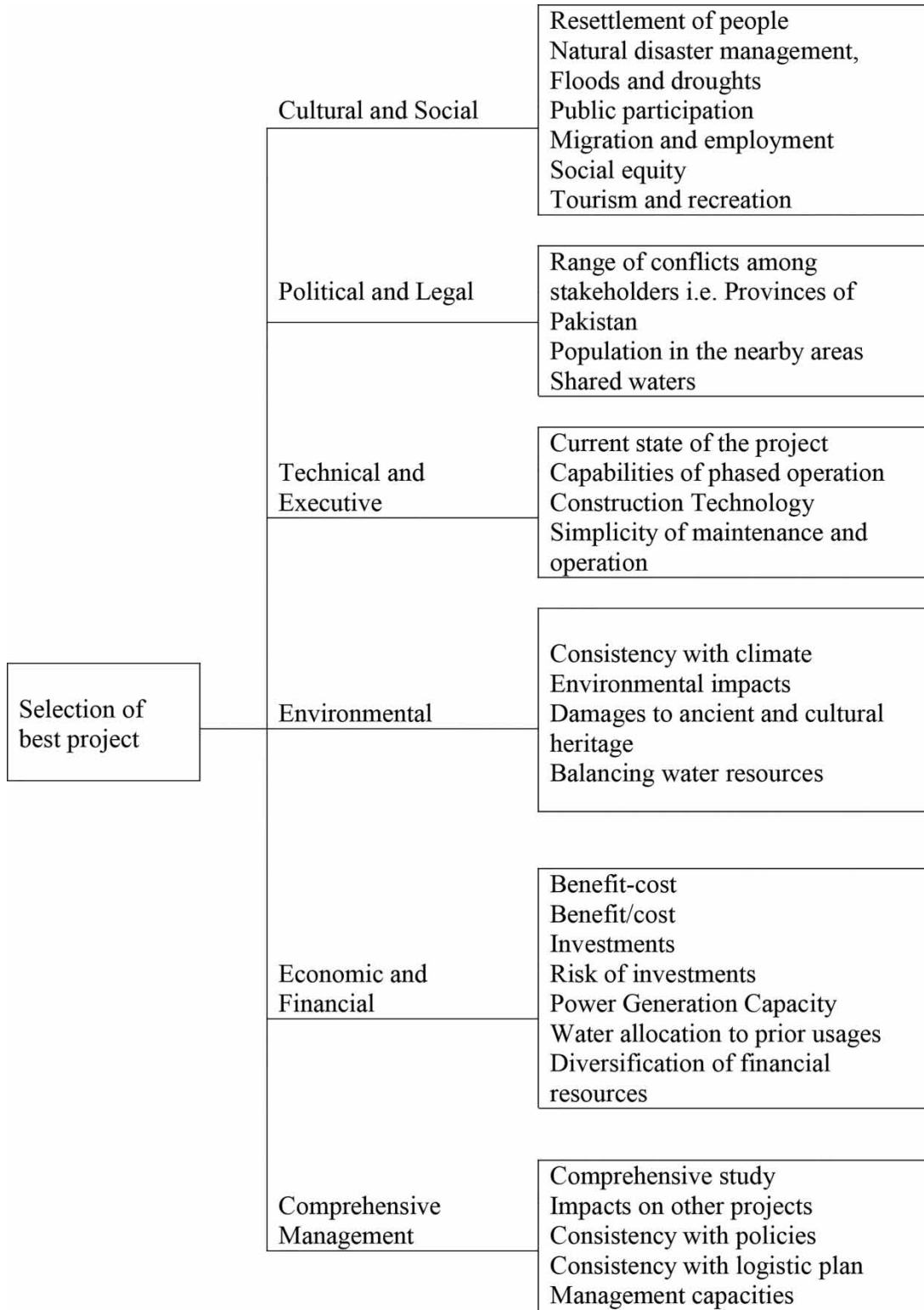


Figure 3 | The criteria and sub-criteria for ranking of water projects.

Table 2 | TFNs for linguistic comparison measures

Linguistic terms	Triangular fuzzy numbers (TFN)	Reciprocal of triangular fuzzy numbers (TFN Reciprocal)
Perfect	(8,9,10)	(0.1, 0.111, 0.125)
Absolute	(7,8,9)	(0.11, 0.125, 0.142)
Very good	(6,7,8)	(0.125, 0.142, 0.166)
Fairly good	(5,6,7)	(0.142, 0.166, 0.2)
Good	(4,5,6)	(0.166, 0.2, 0.25)
Preferable	(3,4,5)	(0.2, 0.25, 0.333)
Not bad	(2,3,4)	(0.25, 0.333, 0.5)
Weak advantage	(1,2,3)	(0.333, 0.5, 1)
Equal	(1,1,1)	(1, 1, 1)

Gumus (2009) and their reciprocals.

Table 3 | Social and cultural criteria in comparison with the criteria of political, security and legality

Social and cultural criteria compared with the criteria of political, security and legality

Triangular fuzzy number				
<i>l</i>	<i>m</i>	<i>u</i>	Linguistic variables	Expert
1	1	1	Equal advantage	1
1	1	1	Equal advantage	2
0.33	0.5	1	Weak advantage (reciprocal)	3
0.111	0.125	0.142	Absolute (reciprocal)	4
1	1	1	Equal advantage	5
0.2	0.25	0.333	Preferable (reciprocal)	6
1	1	1	Equal advantage	7
0.166	0.2	0.25	Good (reciprocal)	8
0.142	0.166	0.2	Fairly good (reciprocal)	9
0.25	0.333	0.5	Not bad (reciprocal)	10
0.5199	0.5574	0.6425	Average	

$$S_4 = (0.06849778, 0.0990314, 0.143689731)$$

$$S_5 = (0.13838967, 0.1990105, 0.28524759)$$

$$S_6 = (0.04868267, 0.0683579, 0.099802233)$$

$$S_7 = (0.03183454, 0.04387227, 0.06440454)$$

Equations (11) and (12) are used to calculate the values of V. After the calculation of V, Equation (15) is used for the

Table 4 | Paired comparison matrices of criteria

Criteria	Social and cultural			Legality, political and security			Executive and technical			Environmental			Economic and financial			Demand management			Comprehensive management		
	<i>l</i>	<i>m</i>	<i>u</i>	<i>l</i>	<i>m</i>	<i>u</i>	<i>l</i>	<i>m</i>	<i>u</i>	<i>l</i>	<i>m</i>	<i>u</i>	<i>l</i>	<i>m</i>	<i>u</i>	<i>l</i>	<i>m</i>	<i>u</i>			
Social and cultural	1	1	1	0.5199	0.5574	0.6425	0.1738	0.2202	0.3191	0.75	0.8974	1.1032	0.4403	0.4833	0.5783	0.829	1.0581	1.3384	1.2458	1.6642	
Political, security and legality	1.556	1.794	1.9234	1	1	1	2.5	3.1	3.7	2.6142	3.4166	4.22	1.4342	1.6416	1.8533	3.1	4.1	5.1	3.6	4.6	
Technical and executive	3.1338	4.5413	5.7537	0.27027	0.3225	0.4	1	1	1	4.6	5.6	6.6	1.225	1.433	1.65	1.765	2.2833	2.8166	3.8	4.8	
Environmental	0.9064	1.1143	1.3333	0.2369	0.2926	0.3825	0.1515	0.1785	0.2174	1	1	1	0.7377	0.9683	1.2173	1.1267	1.4308	1.7366	2.125	2.6333	
Economic and financial	1.7292	2.0691	2.2711	0.5397	0.6091	0.6972	0.606	0.6976	0.8163	0.8214	1.0327	1.3555	1	1	1	3.4	4.3	5.2	4.6	5.6	
Demand management	0.7472	0.9451	1.20627	0.196	0.2439	0.3225	0.355	0.4379	0.5665	0.5758	0.6989	0.8875	0.1923	0.2325	0.2941	1	1	1	1.4	1.7	
Comprehensive management	0.6008	0.80269	1.1079	0.1785	0.2174	0.2777	0.1724	0.2083	0.2631	0.3174	0.3797	0.4705	0.1515	0.1785	0.2174	0.5	0.5882	0.714	1	1	

Table 5 | The priority weights of alternative locations with respect to criteria

Location \ Criteria	Cultural and social			Legality, political and security			Executive and technical			Environmental			Economic and financial			Demand management			Comprehensive management		
Bunji Hydropower Project	0.2	1.1	2.8	6.2	8.1	9.4	5	7	8.7	2.4	4.4	6.4	5.2	7.2	8.9	7.2	8.9	9.8	6.2	8.1	9.3
Diamer-Bhasha Dam	1.7	3.4	5.4	5.8	7.8	9.3	6.8	8.6	9.6	6.6	8.3	9.5	8	9.4	9.9	5.8	7.7	9.2	4.4	6.4	8.3
Dasu Dam	4.4	6.4	8.2	7.4	9.1	9.9	4.4	6.4	8.2	5	7	8.5	4.8	6.8	8.5	4.8	6.7	8.4	3.6	5.6	7.6
Kalabagh Dam	2.8	4.5	6.3	2.1	3.2	4.6	5.6	7.5	9	5.6	7.5	9	7.6	9	9.6	5	6.9	8.6	3.6	5.6	7.5
Akhori Dam	1.9	3.5	5.4	6.2	8	9.2	5.6	7.6	9.2	5.6	7.6	9.2	4	6	7.8	5	6.9	8.6	3.6	5.6	7.4

Table 6 | The weighted normalized decision matrix

Location \ Criteria	Cultural and social			Legality, political and security			Executive and technical			Environmental			Financial and economic			Demand management			Comprehensive management		
Bunji Hydropower Project	0.0000	0.0000	0.0000	2.3064	3.0132	3.4968	1.9	2.66	3.306	0.0000	0.0000	0.0000	1.2844	1.7784	2.1983	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diamer-Bhasha Dam	0.0000	0.0000	0.0000	2.1576	2.9016	3.4596	2.584	3.268	3.648	0.0000	0.0000	0.0000	1.976	2.3218	2.4453	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Dasu Dam	0.0000	0.0000	0.0000	2.7528	3.3852	3.6828	1.672	2.432	3.116	0.0000	0.0000	0.0000	1.1856	1.6796	2.0995	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Kalabagh Dam	0.0000	0.0000	0.0000	0.7812	1.1904	1.7112	2.128	2.85	3.42	0.0000	0.0000	0.0000	1.8772	2.223	2.3712	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Akhori Dam	0.0000	0.0000	0.0000	2.3064	2.976	3.4224	2.128	2.888	3.496	0.0000	0.0000	0.0000	0.988	1.482	1.9266	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 7 | The final ranking and evaluation of the locations

Locations	S_i^+	S_i^-	C_i	Ranking
P ₁ : Bunji Hydropower Project	1.4438	2.2208	0.6060	3
P ₂ : Diamer-Bhasha Dam	0.4611	3.2045	0.8742	1
P ₃ : Dasu Dam	1.3984	2.2385	0.6155	2
P ₄ : Kalabagh Dam	2.5206	1.1138	0.3065	5
P ₅ : Akhori Dam	1.541	2.10975	0.5779	4

calculation of the minimum degree of possibility:

$$m(C_1) = 0, m(C_2) = 0.98, m(C_3) = 1.00, m(C_4) = 0.00, m(C_5) = 0.65, m(C_6) = 0.00 \text{ and } m(C_7) = 0.00$$

The weight vector is given by:

$$W = (0, 0.98, 1, 0, 0.65, 0, 0)$$

The normalized weight vectors are given by:

$$W = (0, 0.372, 0.38, 0, 0.247, 0, 0)$$

The weight vectors clearly show that experts do not consider the criterions C₁, C₄, C₆ and C₇ as important, therefore

the weighting of these criteria come out to be zero after applying Equations (11), (12) and (15).

RANKING OF ALTERNATIVES USING TOPSIS

Ranking of the alternative locations is done by using TOPSIS. As mentioned above, five locations are examined in this research, the projects are ranked by the experts using Table A-3 (Appendix A). This information is illustrated in Table 5 in the form of a decision matrix. The results after normalization are shown in Table 6. The final ranking of the projects and the evaluation of results are shown in Table 7.

RESULTS AND DISCUSSION

The value of C_i closest to 1 (unity) indicates the project to be more ideal. According to this study, which is entirely based on the input recorded from the 10 experts, P₂ is the most feasible option and P₅ is the least preferable option due to the collapse in terms of political, security and legality criteria. The studies conducted by various authors (Khalid & Begum (2013); Ghazanfar (2008); Nawaz Bhatti (2011); Khan (2014)) related to the Kalabagh Dam (P₅) also confirm

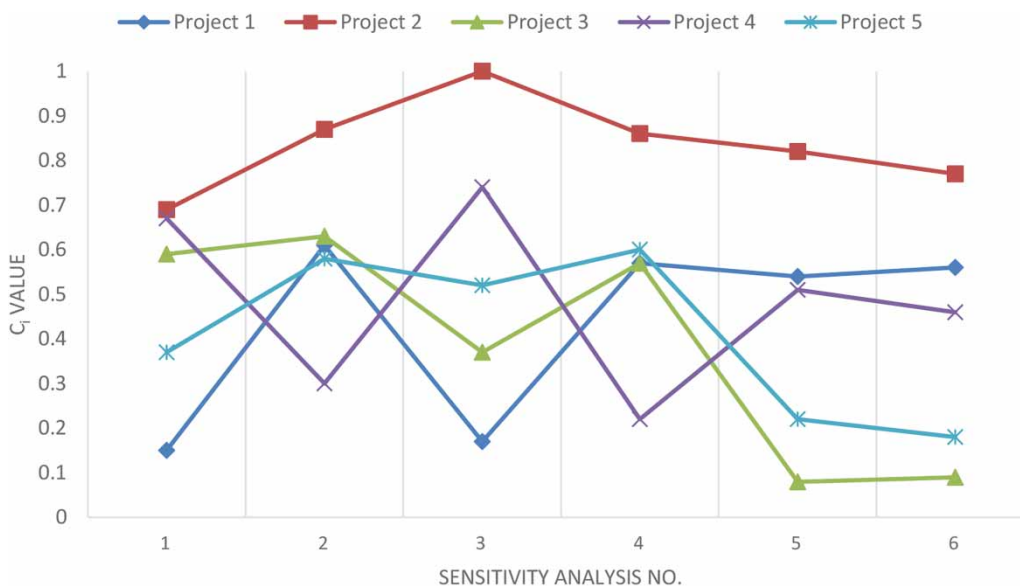


Figure 4 | Sensitivity analysis and its effect on ranking.

that this project is weak in terms of political, security and legality criteria.

In other words, the ranking of locations according to C_i values are Kalabagh Dam - Akhori Dam - Bunji Hydro-power Project - Dasu Dam - Diamer-Bhasha Dam from the least preferable to the most preferable one. Due to its highest C_i value, the Diamer-Bhasha Dam is the most preferable option. Sensitivity analysis can also be performed by the decision makers. To perform the sensitivity analysis, priority weights of the criteria are changed to reveal its outcome on the process of evaluation and the ranking of projects. To achieve this, the weights of the two criteria are exchanged while the others are kept constant. For example, in this study, the second criteria's weight is changed with C_1, C_3, C_4, C_5, C_6 and C_7 . The TOPSIS method is used to calculate the index values (C_i). The sensitivity analysis results are shown graphically in Figure 4 and are given in Table 8. It can be seen that the index values (C_i) and the ranking of the locations change as the priority weights of the criteria are mutually changed. If the priority weights of C_1 and C_2 are exchanged, the index value of P_4 (Kalabagh Dam) jumps from 0.34 to 0.67 and the ranking of P_4 changes from 5 to 2. The C_i value of P_2 remains the highest even with all the changes, which shows that this is the most feasible option. The weights can be changed in different manners and the sensitivity analysis can be further expanded to make the evaluation process easier for decision makers.

CONCLUSIONS

When water resources problems are encountered with conflicting criteria, MCDM can be a powerful tool to solve these conflicts. The fuzzy AHP is among the various methods for MCDM and is a combination of fuzzy numeric logic and AHP. The method is very appropriate for evaluating the alternatives if linguistic vagueness is involved. The main drawback to the fuzzy AHP is that it only involves subjectivity and relies on the experience and the opinion of the decision makers. Evaluation and judgement on the alternatives and the criteria require experience and knowledge but subjectivity may be displayed by the experts in making decisions. Ranking of alternatives is done by a systematic

Table 8 | Sensitivity analysis

Sensitivity analysis no.	Criteria weights	Calculation of (C_i)	Ranking of projects
1	$C_1 = 0$ $C_2 = 0.372$ $C_3 = 0.38$ $C_4 = 0$ $C_5 = 0.247$ $C_6 = 0$ $C_7 = 0$	$P_1 = 0.61$ $P_2 = 0.87$ $P_3 = 0.62$ $P_4 = 0.31$ $P_5 = 0.58$	$P_2 \rightarrow P_3 \rightarrow P_1 \rightarrow P_5 \rightarrow P_4$
2	$C_1 = 0.372$ $C_2 = 0$ $C_3 = 0.38$ $C_4 = 0$ $C_5 = 0.247$ $C_6 = 0$ $C_7 = 0$	$P_1 = 0.15$ $P_2 = 0.69$ $P_3 = 0.59$ $P_4 = 0.67$ $P_5 = 0.37$	$P_2 \rightarrow P_4 \rightarrow P_3 \rightarrow P_5 \rightarrow P_1$
3	$C_1 = 0$ $C_2 = 0.38$ $C_3 = 0.372$ $C_4 = 0$ $C_5 = 0.247$ $C_6 = 0$ $C_7 = 0$	$P_1 = 0.61$ $P_2 = 0.87$ $P_3 = 0.63$ $P_4 = 0.30$ $P_5 = 0.58$	$P_2 \rightarrow P_3 \rightarrow P_1 \rightarrow P_5 \rightarrow P_4$
4	$C_1 = 0$ $C_2 = 0$ $C_3 = 0.38$ $C_4 = 0.372$ $C_5 = 0.247$ $C_6 = 0$ $C_7 = 0$	$P_1 = 0.17$ $P_2 = 1.00$ $P_3 = 0.37$ $P_4 = 0.74$ $P_5 = 0.52$	$P_2 \rightarrow P_4 \rightarrow P_5 \rightarrow P_3 \rightarrow P_1$
5	$C_1 = 0$ $C_2 = 0$ $C_3 = 0.38$ $C_4 = 0$ $C_5 = 0.247$ $C_6 = 0.372$ $C_7 = 0$	$P_1 = 0.57$ $P_2 = 0.86$ $P_3 = 0.57$ $P_4 = 0.22$ $P_5 = 0.60$	$P_2 \rightarrow P_5 \rightarrow P_1 \rightarrow P_3 \rightarrow P_4$
6	$C_1 = 0$ $C_2 = 0$ $C_3 = 0.38$ $C_4 = 0$ $C_5 = 0.247$ $C_6 = 0$ $C_7 = 0.372$	$P_1 = 0.54$ $P_2 = 0.82$ $P_3 = 0.08$ $P_4 = 0.51$ $P_5 = 0.22$	$P_2 \rightarrow P_3 \rightarrow P_1 \rightarrow P_4 \rightarrow P_5$
7	$C_1 = 0$ $C_2 = 0$ $C_3 = 0.38$ $C_4 = 0$ $C_5 = 0.247$ $C_6 = 0$ $C_7 = 0.372$	$P_1 = 0.56$ $P_2 = 0.77$ $P_3 = 0.09$ $P_4 = 0.46$ $P_5 = 0.18$	$P_2 \rightarrow P_1 \rightarrow P_4 \rightarrow P_5 \rightarrow P_3$

method of TOPSIS. As compared with the other methods of multi-criteria analysis, TOPSIS and fuzzy AHP are quite simple in application and conception.

The ranking of reservoirs is generally subjugated by the political interests or by the traditional way of making decisions. Only the resource availability and the cost are considered in the traditional way of decision making and systematic and holistic approaches are not taken into consideration. The location decision is also influenced by the political interest of the political parties, which results in disputes among the provinces or states of the country. The process of ranking should, therefore, not only consider the technical problems but also the political, environmental, social and economic problems. In order to protect the interest of all the stakeholders; that is, the provinces of Pakistan, a systematic approach is required for the ranking of the water resources projects.

A fuzzy AHP-TOPSIS framework is used in this paper for the ranking and evaluation of the reservoirs planned by the WAPDA. Apart from this, few interviews were conducted, and the literature was explored. After this, the criteria and sub-criteria were defined for ranking of the projects. For the determination of criteria's relative weights and the location ranking, we integrated the fuzzy AHP and TOPSIS methods. The application of this framework is exhibited by the case study of the reservoirs ranking in Pakistan. In order to explain the results and discuss them in detail, a sensitivity analysis was also performed. An integrated approach is proposed in this paper, with the main objective of ranking the water projects in Pakistan despite the conflicting criteria. An efficient way for ranking the projects under conflict is proposed in this paper. The results show that Diamer-Bhasha Dam (P₂) is the most favorable option whereas the Kalabagh Dam (P₄) is the least favorable option (which laps mainly due to the political factor). We also observe that there are some interdependencies in the criteria that cannot be encountered by AHP method. Therefore, in order to consider the interdependencies among the decision attributes, the analytic network process (ANP) can be used.

CONFLICT OF INTEREST STATEMENT

Conflict of interest – none.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at <https://dx.doi.org/10.2166/ws.2020.103>.

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First received 22 January 2020; accepted in revised form 10 May 2020. Available online 22 May 2020