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Multi-Criteria Decision Making Approach for Flood Risk and Sediment Management in Koshi Alluvial Fan, Nepal

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Abstract

This paper presents the results of multi-criteria decision-making (MCDM) approach for flood risk and sediment management in dynamic alluvial fan. The study is based on real problems of Koshi River, Nepal. Criteria weighting for each measure were estimated using Entropy, AHP and AHP-Entropy techniques. Preference ranking of alternatives was prioritized using MCDM methods—ELECTRE, TOPSIS and SAW. Five alternate measures for flood risk management and eight alternate measures for sediment control with seven evaluation criteria comprising economic, social, environmental and political aspects were taken into account. The Spearman's rank correlation coefficient between the criteria weighting techniques AHP and AHP-Entropy, Entropy and AHP-Entropy and AHP with Entropy were 0.964, 0.429 and 0.321 respectively. Preference ranks were determined using nine combinations of criteria weighting techniques and preference ranking methods. In the case of flood risk management, using of old Koshi channel was recommended as the highest prioritized solution. Similarly, for sediment control, reduction of upstream sediment supply was recommended as the top prioritized measures. The Euclidean distance test for each pairs of criteria weighting and prioritization methods showed all three MCDM methods of preference ranking were sensitive to weighting. On implementation of the recommended measures, local people of Sunsari, Saptari and Morang districts of Nepal will be highly benefited.

Keywords

Flood, Sediment, Prioritization, MCDM, Entropy, AHP, ELECTRE, TOPSIS, SAW

1. Introduction

Nepal is one of the worst flood-affected countries and frequently suffers from different kinds of water-induced disasters like landslides, debris flow, flooding and sedimentation. Most of the major rivers, which flow through Nepalese territory, are of snow fed characteristics and trans-boundary type. They originate from the Himalayas; flows through Siwaliks and Terai plain before crossing the Nepal-India border and are taken as the boon to these areas. However, during the monsoon season these rivers suffering from flash flooding become devastatingly hostile, cause damages to the infrastructures, farmland, settlements, and lives, and thereby become curse to these regions at the same time. Flood control in Nepal especially in the Terai region (Southern flat plain of Nepal) is a relatively recent issue. Until the middle of the past century natural forests covered the Terai and population was limited, also because of the malaria risks. After the eradication of malaria and the related deforestation the population density of the Terai increased substantially, amongst by the migration from hill tribes into the Terai. The forests were cut to allow for amongst others indigo plantations [1]. The increased rate of deforestation put the pressure for additional flood control measures.

The Koshi River is one of the major rivers in South Asia having snow fed characteristics. The Koshibasin is roughly located between 85˚ to 89˚ east longitude and 25˚ to 29˚ north latitude. The Koshi is a trans-boundary river, originating in Tibet, flowing through the Himalaya, through the eastern part of Nepal and the flat plain of Indian north territory [2]. The Koshi River, located on one of the most active alluvial fans in the world, poses major challenges in flood management and in coping with the excessive quantities of sediment entering the alluvial plain. The river formed an inland delta, a huge alluvial fan [3]. After 2008 disaster [3], sustainable flood risk management and sediment control in Koshi alluvial fan have been challenging issues.

Multi-criteria decision making (MCDM) is a decision support tool that describes a set of methods for structuring and evaluating alternatives on the basis of multiple criteria and objectives [4]. Three separate steps are utilized in MCDM models to obtain the ranking of alternatives: determine the relevant criteria and alternatives, attach weights to the criteria and numerical measures to the impacts of the alternatives on these criteria and finally process the numerical values to determine a ranking score of each alternative [5]. In the multi-criteria models the weights of criteria play a very significant role and they have different interpretations depending on context of decision making, on multi-criteria analysis methods [6]. Due to knowledge induced from the participation of several actors MCDM techniques can handle the inherent complexity and uncertainty of problems [7]. Mateo (2012a) describes MCDM as an advanced tool that can enhance the quality of decisions by making the process more explicitly rational and efficient leading to justifiable and explainable choices. Moreover, MCDM provides an adequate platform for stakeholders to communicate their personal preferences facilitates compromise and group decisions and promotes the role of participants in decision process as well [8]. The combinations of these characteristics enable the development of real participatory processes, which are crucial for the implementation of successful and long lasting flood management programs [9]. Since 1990s, MCDM has been successfully applied for the selection of best strategies of flood risk mitigation thus supporting for the optimization and allocation of available resources [10] [11] [12]. Recently, MCDM has also been applied to access the flood risk and coping capacity [13] [14] [15].

Since 1960s, dozens of MCDM techniques have been developed [16]. All the MCDM techniques are divided into concordance sub-group, compromising sub-group and scoring sub-group. Despite large number of MCDM methods, none is perfect and applicable to all decision problems. The selection of an appropriate tool will depend on the problem type and decision maker's objectives. Chistaz and Banihabib (2015) compared seven MCDM tools and concluded that ELECTRE III stood superior to select flood management options. Chung and Lee (2009) employed five methods and uncovered no clear methodological advantages to any of them. Apart from comparative studies, several researchers have combined two MCDM approaches to complement each other [17] [18] [19]. From the analysis of 128 peer-reviewed papers on multi-criteria decision making for flood risk management published from 1995 to 2015, Evers *et al.* (2016) concluded that AHP was the most popular method followed by TOPSIS and SAW. Based on the previous applications, objectives of the study and specific problems of the study area as well, Entropy, AHP and AHP-Entropy techniques are used for criteria weighting. Moreover, for preference ranking of alternatives, one method from each sub-group of MCDM methods is chosen. The selective methods include ELECTRE from the concordance sub-group; TOPSIS from compromising sub-group and SAW from the scoring sub-group. This paper aims to develop a methodology to prioritize alternative measures for flood risk management and sediment control in a dynamic alluvial fan with the MCDM approach.

The rest of this paper is structured in the following manner. A description of the study area is presented in Section 2. In Section 3, a brief review of materials and methods is provided. Section 4 summaries results. Analysis of results and discussion are dealt in Section 5. Finally, the conclusion is reported in section 7 followed by sensitivity analysis in Section 6.

2. The Koshi Alluvial Fan and Study Area

The Koshi River is a trans-boundary river flowing through Tibet (China), Nepal and India. It is one of the largest tributaries of the Ganges River. The entire Koshi river basin has an area of 69,300 km^2 up to its confluence with Ganges in India, out of which 29,400 km^2 lies in China, 30,700 km^2 in Nepal and 9200 km^2 in India. The Koshi basin occupies eastern part of Nepal (**Figure 1**).

Koshi River in Nepal has seven major tributaries: Sunkoshi, Tamakoshi, Dudhkoshi, Indrawati, Likhu, Arun and Tamor. At Barahkshetra in Nepal it emerges from mountains and becomes the Koshi River. After flowing another 58 km it crosses into Bihar (India) near Bhimnagar and after another 260 km joins

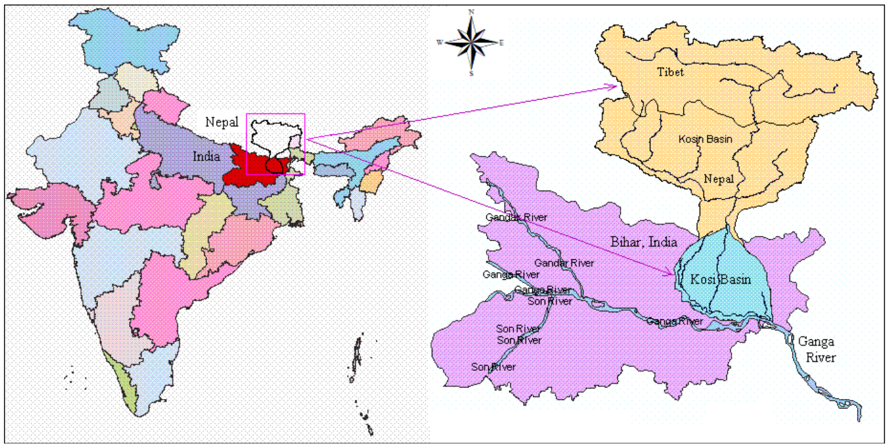

Figure 1. Index map of Koshi basin (Meera 2012).

the Ganges near Kursela. The river has a total length of 729 km. The study area (Figure 2) is the Koshi alluvial fan in Nepal extending from Chatara to Koshi barrage having a stretch of around 50 km.

The stretch between Chatara to Bhimnagar is steeply sloped. Downstream of Bhimnagar, the fan spreads out laterally with decreased slope having a radius of approximate 100 km. The Koshi fan covers both Nepal and Indian territory (North Bihar) extending to an area of about 11,000 km^2. The Koshi alluvial fan is flat country like any other floodplain with its apex at Chatara (Nepal). Over 200 years, as the result of avulsions, the river has shifted its course over 120 km from east to west (Figure 3). At present, the main channel of Koshi river is located at west of the fan. The river channel over the alluvial fan is highly unstable resulting strike of flood with little warning. Due to unstable characteristics of alluvial fan the flood can travel at high speeds carrying large amounts of sediments and debris. The process of dying and emerging new channels within the alluvial fan is active. The study reach can be described as a braided channel containing many islands both large and small. On the alluvial fan, the Koshi shows different channel patterns. The first 100 km downstream from Chatara the river is braided. The river is meandering for last around 160 km at toe of the fan.

Annual rainfall in the Koshi plains is spatially distributed ranging from 1000 mm to 1600 mm. The average annual discharge at Chatara hydrological station (station no. 695) is recorded 1800 m^3/s. At Chatara, total annual sediment load is estimated 100 million m^3, out of which 60 million m^3 is bed load and suspended load and rest 40 million m^3 is considered wash load. Approximately 30 - 40 million m^3 of sediment load is presumed to be deposited annually between Chatara to Kursela [20].

3. Materials and Methods

3.1. Alternative Measures

Long-term visions of flood management strategies are the starting point to reduce the problems of Koshi River system. Both structural and non-structural

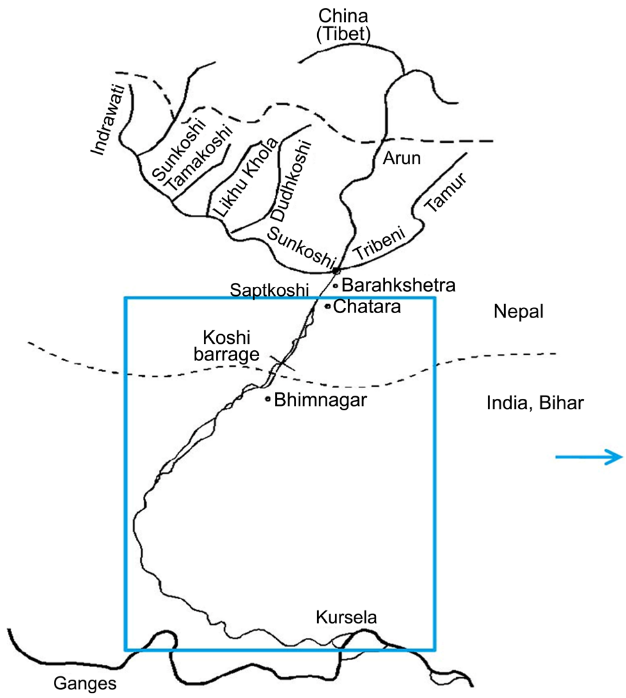

Figure 2. Koshi alluvial fan (Hooning 2011).

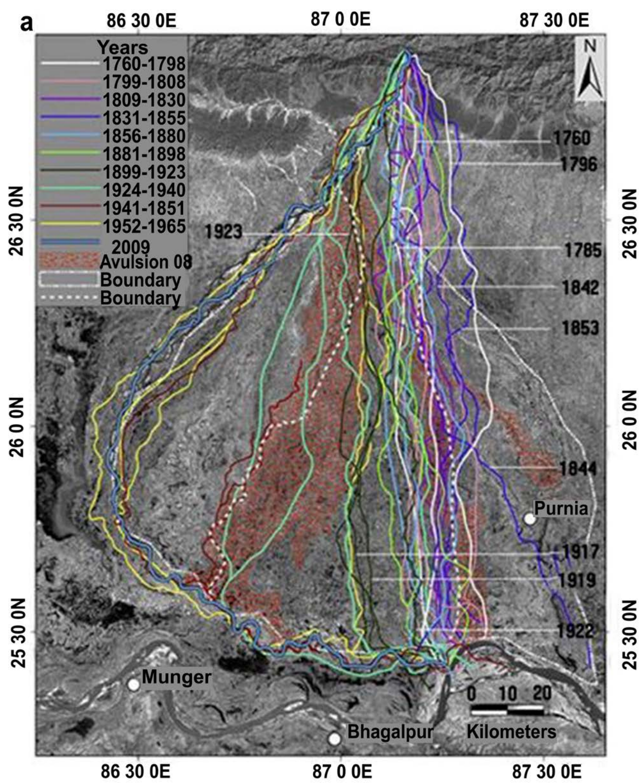

Figure 3. Different courses of Koshi River over time (Chakraborty *et al.* 2009).

flood risk management are the part of these management strategies. This study focuses on solutions of flood risk management incorporating both permanent and recurrent measures. The solutions are based on previous studies [3] focused on hydraulic and morphological processes and sediment management as well. Some alternatives are common for both measures. The alternatives on hydraulic measures and sediment control measures are presented in tabular form (Table 1).

3.2. Hydraulic Measures

3.2.1. Increasing the Height of Embankments over Time (Q1)

In this measure, the height of the embankments is designed to increase over time, following the increase of bed level and flood levels of the Koshi River as in Yelow River in China (Figure 4). However, this process will continue over the years, resulting in an elevated river; the riverbed is a couple of metres higher than the surrounding area. This measure requires only small extra area; just increasing heights and width of the embankments. Development of forest might strengthen existing channels. This measure doesn't impact adversely in Nepal/India cooperation. However, there is very large risk of consequences of flooding on breaching the embankments.

3.2.2. Sleeper Dikes (Q2)

In this measure, a second line of defence (dark black line) is constructed as sleeper dikes (Figure 5). The existing red line along the bank represent existing embankment and blue colour represents the water body in river channel in low flow season. If an embankment breaches, the second dike ring prevents large flooding. The merits of this intended solution are: limited inundation area and creation of more space for sediment deposition. However, this measure requires expropriation of land at both sides over a width of around 200 m. In addition, it takes many years for the completion of construction resulting the displacement of bridges and other existing structures.

Table 1. List of alternative measures.

Alternatives		
Hydraulic measures	S.N	Sediment control measures
Increasing the height of embankments over time (Q1)	1	Reduction of supply of sediments (S1)
Sleeper dikes (Q2)	2	Koshi high dam (S2)
The use of an old Koshi course (Q3)	3	Narrowing of the river with permanent structures (S3)
Controlled flooding, flood storage (Q4)	4	Narrowing of the river with recurrent measures (S4)
Koshi high dam (Q5)	5	Dredging (S5)
	6	Controlled flooding using old course (S5)
	7	Controlled flooding with storage areas (S6)
	8	Removing embankments and Koshi barrage (S7)

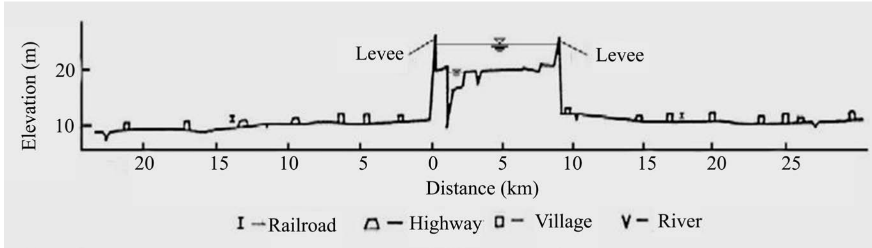

Figure 4. Raising embankments of the Yellow River (Baosheng Wu 2007).

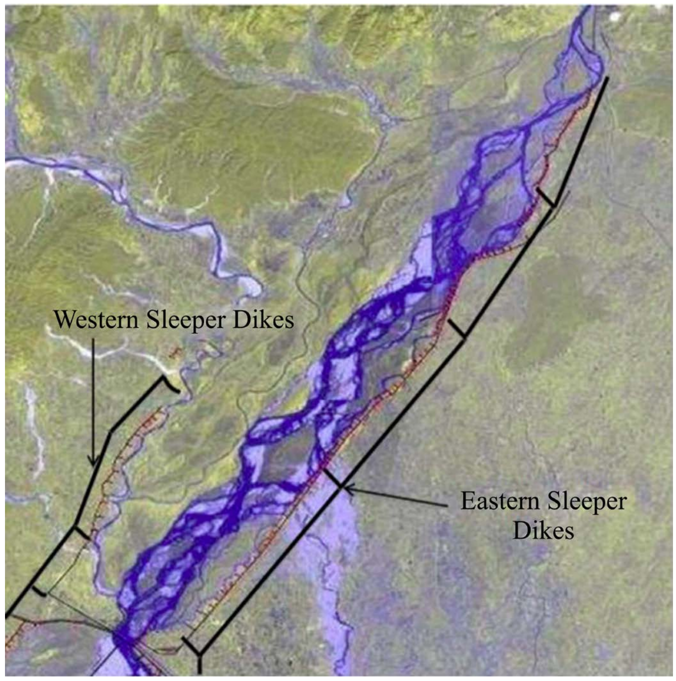

Figure 5. Proposed Sleeper dikes.

3.2.3. Use of an Old Koshi Course (Q3)

In this intended solution, the flood peak is lowered by extracting discharge by the use of an old course during the flood (Figure 6). Construction of hydraulic structure is required to regulate this process. The courses of former channels define the possible location for this regulating structure. This measure reduces discharge in downstream resulting smaller loads in embankments. This helps people to be prepared and location of inundation is known. The demerits of this measure are: requirement of hydraulic structure of around 250 m - 300 m wide to open bifurcation channel, additional construction of bridges along highway, additional construction of embankments along the old course, acquirement of large agriculture land, protection of bank erosion and deposition of large sediment between embankments along the old course.

3.2.4. Controlled Flooding, Flood Storage (Q4)

In this measure, the flood peak is supposed to be lowered by extracting discharge using selected and prepared inundation areas (Figure 7). Construction of new hydraulic structure is needed or a part of the embankment needs to be destroyed

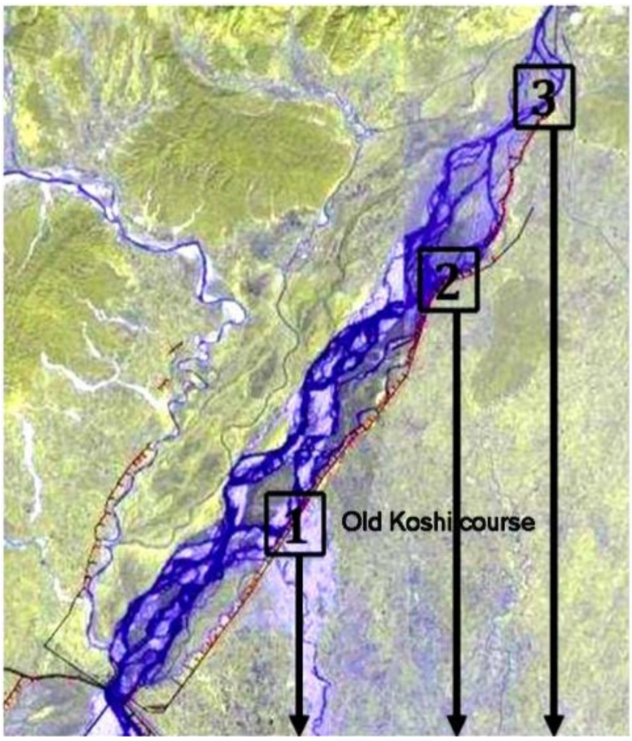

Figure 6. Possible locations of using old Koshi course.

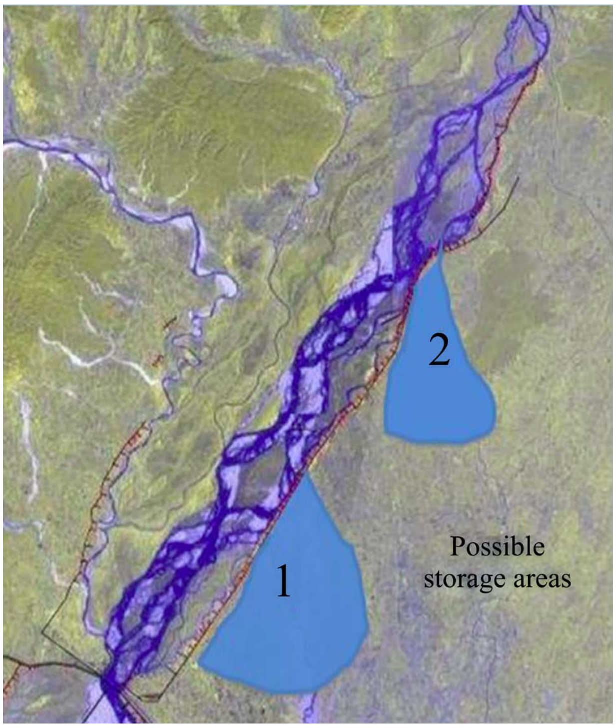

Figure 7. Proposed flood storage areas.

and rebuilt later on. Merits of this intended solution are the reduction of discharge downstream, which results in smaller loads on the embankments, and people are prepared with known location of inundation. However, it requires construction of levees around villages and there is risk to destroy other levee by people to protect their own land.

3.2.5. Koshi High Dam (Q5)

In this measure, a high dam is constructed, located somewhere between Tribeni and Chatara, to control the floods (Figure 8). The discharge of the river is controlled; flood peak can be lowered. Such a dam can be used for hydropower as well. This solution works fast after the dam is constructed. However, it is supposed of taking long time before the project can be realized. People around 75 thousand who live upstream the dam have to be resettled due to reservoir inundation. In the downstream side, the ground water level drops, which may cause problems for the farmers. Existing Sunsari-Morang irrigation facilities gets less water. It is very expensive solution.

3.3. Sediment Control Measures

3.3.1. Reduction of Upstream Supply of Sediments (S1)

The different regions including the high Himalaya, Mountains, Siwaliks and Terai which the Koshi River passes (Figure 9) contribute to the high sediment load. In the high Himalaya region, moraine dammed glacier lakes are common and can result in catastrophic floods when moraines are breached. In the High Mountains region, the rocks are resistant to weathering. All valleys in this region were glaciated. Active river cutting enhanced by high river gradients has resulted in very deep canyons being carved since glaciations. The Middle Mountains are present north of the Siwaliks. The Koshi River is down-cutting this area. Mass wasting (rock falls and landslides) is present. The Siwaliksregions possess steep

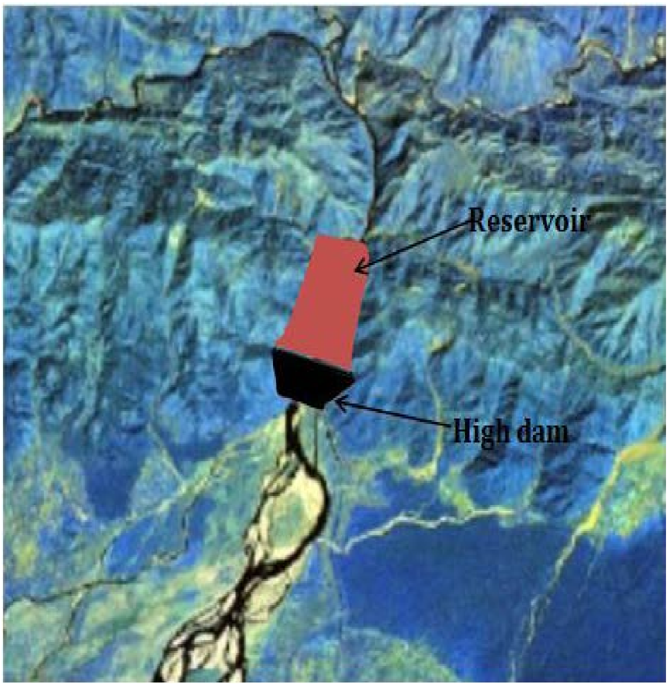

Figure 8. Proposed high dam.

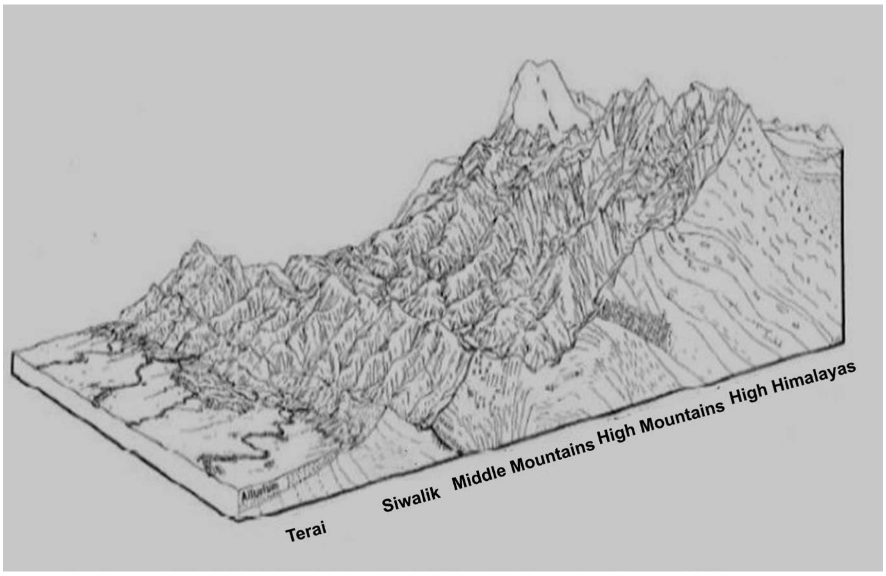

Figure 9. The physiographic regions of Nepal (Galay 1987).

slopes and weakly consolidated layers of bedrock, subject to severe surface erosion. High intensity rainfall produces high erosion and torrent flows. Mass wasting is exceptionally high throughout the Siwalik. The Terai region is the flat land as in **Figure 9**. It consists of gently sloping recently deposited alluvium. The soil is sandy. In the Terai, there is primarily sediment deposition.

Possible measures to reduce such sediment supply are bottom or bank protection; check dams and reforestation to decrease the supply of sediment at its origin. The processes which are responsible for the high sediment load of the river *i.e.* landslides, bank and bottom erosion and GLOFs, have to be reduced.

3.3.2. Koshi High Dam (S2)

This alternative is common to hydraulic measures (**Figure 8**). The high dam traps the sediment transported by the Koshi. Downstream of the dam, the aggrading riverbed changes into a degrading one.

3.3.3. Narrowing of the River with Permanent Structures (S3)

In this measure, permanent structures are constructed narrowing the river to close off channels (**Figure 10**). The higher flow velocities resulted from reducing the flow area by narrowing the river the sediment load is transported over longer distances. In Nepal side, this solution may provide more spaces for people and more agriculture land may be reclaimed. However, problems are moved further downstream to India side. It is costlier and lots of maintenance work is needed. It may be temporary solution because of downstream sedimentation. Indian side may be reluctant to implement this solution.

3.3.4. Narrowing of the River, but with Recurrent Measures (S4)

In this measure, certain channels are closed off and the river is narrowed by recurrent river training measures (**Figure 11**). The narrowing will induce higher

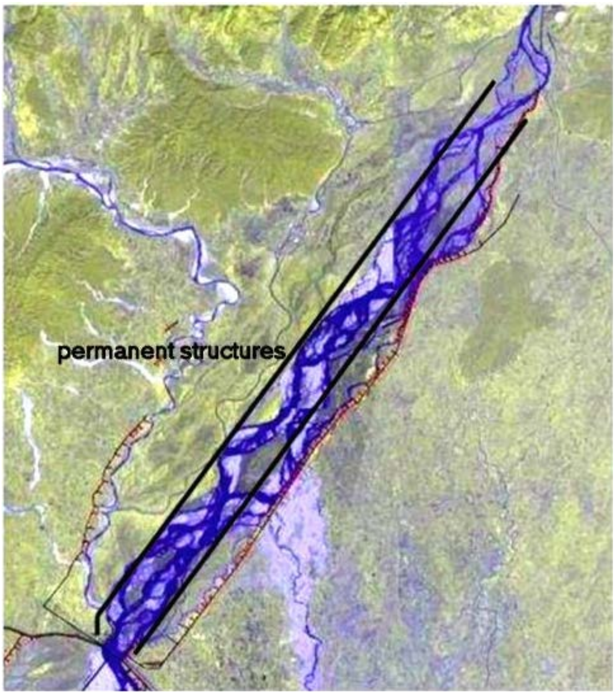

Figure 10. Proposed permanent structures narrowing the river.

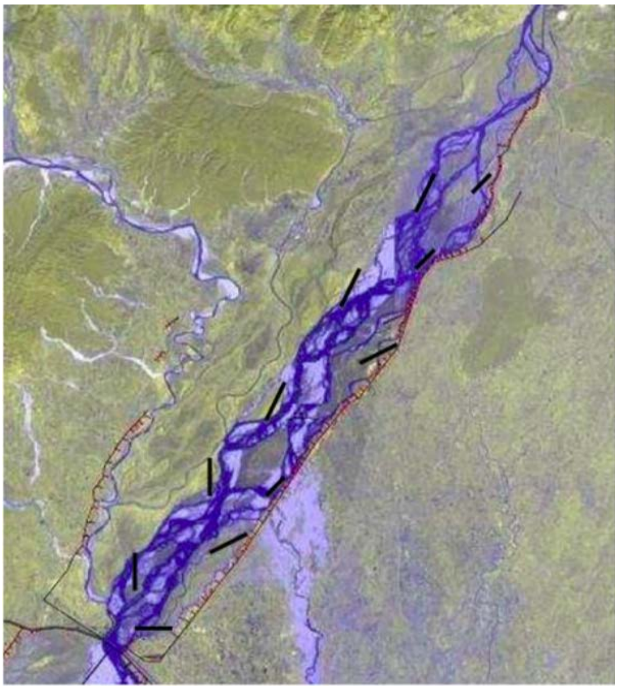

Figure 11. Proposed recurrent measures narrowing the river.

flow velocities and the sediment load is transported over longer distances. The channels are also diverted away from the embankments. This solution isn't so expensive. It's a flexible application, learning by doing. There may uncertainty about effectiveness and may be risk of bypassing. Experienced people are needed for effective implementation.

3.3.5. Dredging (S5)

In this measure, annual deposited sediment between Chatara to the Koshi barrage is dredged and deposited elsewhere thus maintaining the riverbed at a constant level. The merit of this measure is that it is workable and has no impact on nature. Only the deposited sediments of around 20 million m^3 have to be dredged annually. Managing the space to store the dredged sand is a big challenge. It is expensive and spending huge amount annually may be difficult for local authority.

3.3.6. Controlled Flooding, Using Old Course (S6)

In this measure, discharge and sediment are extracted out of the embanked system and flushed away by the use of an old course in high discharge (**Figure 6**). A hydraulic structure is proposed to regulate this process. The location of this measure should be just upstream of the barrage, to flush as much sand as possible.

3.3.7. Controlled Flooding with Storage Areas (S7)

In this measure, water and sediment are temporarily stored with regulating system in low areas (**Figure 7**). Hydraulic structures, such as an inlet with levees, compartmentalization with levees, have to be built. A warning system is needed and consensus with the local people has to be reached for effective implementation.

3.3.8. Removing Embankments and the Koshi Barrage (S8)

In this measure, embankments and the Koshi barrage are supposed to be removed without regulation of the Koshi River. Additional measures should be taken to build shelter areas, raising villages or construct embankments around villages thus marking valuable or less valuable areas and to sacrifice the less valuable areas in case of a flooding or an avulsion. This solution provides a lot of space for sediment deposition resulting the formation of inland delta. No disaster on the scale of 2008 flood is envisaged. However, many smaller floods over the alluvial fan may cause big damage. Removing of embankments will cause instant flooding. Indian government may also be reluctant to implement this measure as Koshi barrage has helped to flood control during monsoon reducing the damage due to flood in northern Bihar, India.

3.4. Evaluation Criteria

Flood imposes destruction effects on social, ecological and economic environment and threatens sustainable development of flood prone areas. Flood management can be an integrated solution if social, environmental and economical instabilities of the region due to destruction of floods are controlled. So, each alternative should be evaluated with economic, technical, social and environmental aspects. In addition, in this particular case being a trans-boundary river and treaty between two sovereign government authorities, political cooperation is also considered a criterion. Based on stakeholder's opinion, the considered criteria are discussed briefly as below:

1) Costs: It includes design, construction, maintenance and expropriating of land costs as well.

2) Technical complexity: Feasibility of the solution is analyzed under these criteria. If it is very complex the uncertainty and risk of failure of intended solution presumed to be increased resulting unfeasible solution.

3) Social impact: This criterion indicates safety of the local people and impact on society thus reducing the risk of flooding under the implementation of intended solution as both for short and long term solution.

4) Time for implementation: This criterion discusses the required time of implementation of the intended solution for its effectiveness.

5) Environmental impact: This criterion deals with the impact of intended solution on environment especially focusing on influence of intended solution to local people, their lives, land and displacements if any. It also covers impacts on the flora and fauna after the implementation of intended solution.

6) Impact on irrigated area: This criterion covers the impact on existing irrigation facilities especially head works, canals under Morang-Sunsari irrigation project which currently serving thousands of hectares of command area both in Nepal and India.

7) Cooperation with India: -being a trans-boundary river both governments of India and Nepal have signed a treaty on Koshi River in 1953. For the implementation of any intended solution needs cooperation in political level between both government authorities.

3.5. Methodology

The methodology of this study is basically formulated in the sequences of criteria weighting, preference ranking of alternatives and recommendation of optimal alternatives with established MCDM techniques. Based on advantages and disadvantages, stakeholder's opinion, each criteria are valued in very positive (+++) to very negative (−−−). Indicators for each alternative and criteria for both hydraulic measures and sediment control measures are summarized in **Table 2**. Weighting indexes are estimated using Entropy, AHP, and the combination Entropy and AHP techniques. Shannon's Entropy is a well-known method in obtaining the weights for MCDM problems especially when obtaining a suitable weight based on the preferences and decision-making experiments are not possible. Analytic hierarchy process method (AHP) proposed by Saaty (1980) is the proven subjective method for determining weight. When applying the AHP, the preferences of the decision criteria are compared in a pairwise manner with regard to the criterion preceding them in the hierarchy. If two criteria are of equal importance, a value of 1 is given in the comparison, whereas a value of 9 indicates the absolute importance of one criterion over the other (**Table 3**). The weighting indexes for third technique *i.e.* combination of entropy and AHP are obtained using Equation (1). The preference ranking of alternatives for both

Table 2. Proposed alternatives with criteria.

	Alternatives		Criteria						
		Short description	Costs	Technical complexity solution	Social impact	Time for implementation	Environmental impact	Impact on irrigated area	Cooperation with India
Hydraulic measures	Q1	Raising embankments	+++	++	−−−	+++	+++	+++	−
	Q2	Sleeper dikes	+	+++	++	++	−−	−	+++
	Q3	Use of old Koshi channel	−−	++	−	−	−	−	−−
	Q4	Flood storage	−	+	+	−	−	+	++
	Q5	Koshi High Dam	−−−	−−	++	−−−	−−	−−−	+/−
Sediment control measures	S1	Reduction of upstream sediment supply	−−−	+++	−	−−−	+	−	+++
	S2	Koshi High Dam	−−−	−−	+++	−−−	−−−	−	−−−
	S3	Narrowing of river by permanent structures	−−	+++	−	−−	+++	+/−	−−
	S4	Narrowing of river by recurrent measures	+/−	++	+/−	++	+++	++	−
	S5	Dredging	−−−	+	−	+	++	−	−−
	S6	Controlled flooding and sedimentation using old course	−−	−	++	−	−−	−	−−
	S7	Controlled flooding, with deposition areas	−−	−−	−−−	−−	−−	−−	++
	S8	Removing embankments and Koshi barrage	−−	+	+	−−	−−−	−−−	−−

Table 3. The Saaty scale definition (Saaty 1980).

Definition	Intensity of Importance
Equal Importance	1
Moderate Importance	3
Strong Importance	5
Very Strong Importance	7
Extreme Importance	9
Can be used to express intermediate values	2, 4, 6, 8

hydraulic measures and sediment control measures for all criteria weighting indexes estimated from entropy, AHP and combination of both are assessed by three MCDM methods—ELECTRE, TOPSIS and SAW. Results for combinations of criteria weighting techniques and preference ranking methods are averaged and final preference ranking is determined.

$$w_j = \frac{v_j u_j}{\sum_{j=1}^{n} v_j * u_j} \tag{1}$$

where, w_j = final weight of the composition of Entropy and AHP, v_j = Entropy weighting index, u_j = AHP weighting index.

ELECTRE is a family of MCDM methods that originated in Europe and was first proposed by Bernard Roy in mid-1960s [21]. The acronym ELECTRE stands for Elimination and Choice Expressing Reality. It is an outranking method based on outranking relation and concordance analysis.

TOPSIS is a MCDM method originally developed by Hwang and Yoon in 1981 with further developments by Yoon in 1987, and Hwang, Lai and Liu in 1993 [22]. The acronym TOPSIS stands for the Technique for Order of Preference by Similarity to Ideal Solution. It is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution [22]. It is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion, normalizing scores for each criterion and calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion.

SAW abbreviated for Simple Additive Weighting, which is also known as, weighted linear combination or scoring methods is a simple and most often used multi attribute decision technique. The method is based on the weighted average. It is one of the simplest methods of the MCDM methods [23]. An evaluation score is calculated for each alternative by multiplying the scaled value given to the alternative of that attribute with the weights of relative importance directly assigned by decision maker followed by summing of the products for all criteria (**Table 4**).

4. Results

4.1. Preference Ranking of Alternatives

Altogether nine combinations of criteria weighting and preference ranking MCDM methods are analyzed to prioritize alternatives for both hydraulic measures and sediment control measures and results are presented in tabular form (**Table 5**, **Table 6**).

From the final ranking of alternatives the preferred solutions for hydraulic measures can be prioritized as follow:

Q3 > Q5 > Q2 > Q4 > Q1

Where, AE-E = weighting by AHP and Entropy and preference ranking by ELECTRE method, AE-T = Weighting by AHP and Entropy and preference ranking by TOPSIS method, AE-S = Weighting by AHP and Entropy and

Table 4. Score and weightage.

Indicator	Score	Criteria	Weightage		
			Entropy	AHP	AHP & Entropy
Positive (+)	50	Cost (C1)	0.360	0.434	0.602
More positive (++)	75	Social impact (C2)	0.383	0.225	0.333
Very positive (+++)	100	Technical complexity solution (C3)	0.054	0.036	0.008
Negative (−)	40	Time for implementation (C4)	0.043	0.147	0.024
More negative (−−)	20	Environmental impact (C5)	0.057	0.047	0.010
Very negative (−−−)	10	Impact on irrigated area (C6)	0.050	0.049	0.010
		Cooperation with India (C7)	0.053	0.061	0.013

Table 5. Final preference ranking (Hydraulic measures).

Alternatives	Combination of weightage and preference ranking methods									Average	Final Preference Rank
	AE-E	AE-T	AE-S	EE	ET	ES	AE	AT	AS		
Q1	2	5	5	2	5	4	3	5	5	4.00	5
Q2	2	4	3	2	2	1	3	4	3	2.67	3
Q3	2	1	2	2	1	3	1	1	2	1.67	1
Q4	1	3	4	1	3	5	1	3	4	2.78	4
Q5	2	2	1	2	4	2	3	2	1	2.11	2

Table 6. Final preference ranking (Sediment control measures).

Alternatives	Combination of weightage and preference ranking methods									Average	Final Preference Rank
	AE-E	AE-T	AE-S	EE	ET	ES	AE	AT	AS		
S1	4	2	1	3	2	1	2	1	1	1.89	1
S2	1	4	7	3	5	7	4	4	4	4.33	5
S3	6	5	2	3	4	2	7	5	2	4.00	4
S4	6	1	3	1	1	3	7	2	3	3.00	2
S5	4	3	4	1	3	4	4	3	5	3.44	3
S6	3	6	6	3	6	6	1	7	7	5.00	6
S7	1	7	8	3	7	8	2	6	8	5.56	7
S8	6	8	5	3	8	5	4	8	6	5.89	8

preference ranking by SAW method, EE = Weighting by Entropy and preference ranking by ELECTRE method, ET = Weighting by Entropy and preference ranking by TOPSIS method, ES = Weighting by Entropy and preference ranking by SAW method, AE = Weighting by AHP and preference ranking by ELECTRE method, AT = Weighting by AHP and preference ranking by TOPSIS method, AS = Weighting by AHP and preference ranking by SAW method.

From the final ranking of alternatives the preferred solutions for sediment control measures can be prioritized as follow:

S1 > S4 > S5 > S3 > S2 > S6 > S7 > S8

5. Discussion

Based on this study, it is evident that different alternative solutions of flood risk and sediment control measures of Koshi alluvial fan have different prioritization levels (Table 5). For flood control hydraulic measures, among nine combinations of criteria weighting and preference ranking methods, an alternate solution Koshi high dam (Q5) is first prioritized with combinations of criteria weighting methods AHP, AHP & Entropy and preference ranking method SAW. However, combination of criteria weighting method Entropy and preference ranking method SAW prioritize sleeper dikes as first rank followed by Koshi high dam (Q5). In contrast, combination of all criteria weighting methods with preference ranking method ELECTRE results highest priority for floods storage (Q4) measure. Similarly, combination of all criteria weighting methods with preference ranking method TOPSIS list the alternate solution of using old Koshi channel (Q3) as the highest priority measure over others. The results show deviations on preference ranking with different methods. This may be due to variations in criteria weighting index. Considering average value of results for all nine set of combinations of criteria weighting techniques and preference ranking methods, an alternate solution of using old Koshi channel (Q3) is recommended as top prioritized solution for flood control followed by Q5, Q2, Q4 and Q1 respectively. The intended solution of raising embankments is least prioritized. The recommended solution lowers the flood peak by extracting discharge using an old course during the flood. Suitable regulating hydraulic structures of around 250 m to 300 m wide to open bifurcation channel need to be constructed in appropriate location along the old course. This measure reduces discharge in downstream resulting smaller loads in embankments. This helps people to be prepared and location of inundation in known. Additional construction of bridges along highway, additional construction of embankments along the old course, acquirement of large agriculture land, protection of bank erosion increases the implementation time with costs.

For sediment control measures, among nine combinations of criteria weighting and preference ranking methods, an alternate measure, reduction of upstream sediment supply (S1) is first prioritized with all combinations of criteria weighting techniques Entropy, AHP, AHP & Entropy and preference ranking method SAW (Table 6). However, combination of two criteria weighting techniques Entropy and Entropy-AHP with preference ranking method TOPSIS results narrowing river by recurrent measures (S4) solution the highest priority over other alternatives. However, combination of criteria weighting methods AHP with preference ranking method TOPSIS orders reduction of upstream sediment supply (S1) solution as paramount. Similarly, combination of each criteria-weighting techniques with preference ranking method ELECTRE provides different preference ranking. A combination of criteria weighting method Entropy and AHP with preference ranking method ELECTRE prioritizes two alternate solutions Koshi high dam (S2) and controlled flooding with deposition areas (S7) simultaneously as the highest ranks. Two alternate solutions narrowing river by recurrent measures (S4) and dredging (S5) are simultaneously prioritized the top ranks by combination of criteria weighting method Entropy with preference ranking method ELECTRE. Besides, combination of criteria-weighting technique AHP with preference ranking method ELECTRE ranks controlled flooding and sedimentation using old course (S6) in the first position over others. The results show deviations on preference ranking with different methods. This may be due to variations in criteria weighting index. Considering average value of results for all nine set of combinations of criteria weighting methods and preference ranking methods, an alternate solution prescribing reduction on upstream sediment supply (S1) is recommended as top prioritized and removing embankments and Koshi barrage (S8) as the least prioritized measures for sediment control. The recommended top prioritized measure comprises bottom or bank protection; check dams and reforestation to decrease the supply of sediment at its origin. The processes which are responsible for the high sediment load of the river *i.e.* landslides, bank and bottom erosion and GLOFs, have to be reduced. However, its tedious job and takes long time to realize the results.

The recommended measures are also assessed against sustainability. Fairness, reversibility, risk and consensus are four conceptual criteria recommended by Simonovic [24] to satisfy the sustainability of all kinds of structural measures applied for flood risk management. Fairness provides a meaningful format for assessing the distribution of benefits. Risk has measurable qualities, provided the proper risk events are identified and the probabilities can be calculated. Reversibility evaluates the degree to which the aggregated set of anticipated or unanticipated impacts of a development project can be mitigated. Consensus describes the level in which stakeholders are satisfied with a solution to a problem under consideration. The recommended hydraulic measures of using old Koshi course for flood risk management and reduction of upstream sediment supply for sediment control are fair in distribution of benefits. Both the solutions have less risk with low probability of failure. Both measures meet the criteria of reversibility. There is less chance of dispute among stakeholders on implementation of the measures leading broader consensus.

The results of this study can be utilized by local authority as base line information for the structural measures for sustainable flood risk management and sediment control. On implementation of the recommended measures, local people of Saptari, Sunsari and Morang districts of Nepal will be highly benefited. The surrounding areas can be protected from inundation thus ensuring safety of local people. More agricultural lands can be reclaimed enhancing local people's economic condition. Moreover, the recommended measures protect the environment and using embanked old Koshi channel creates opportunity to flora and fauna as well.

6. Sensitivity Analysis

6.1. Criteria Weighting Techniques

6.1.1. Spearman's Rank Correlation Coefficient

The weighting indexes are estimated using Entropy, AHP and combination of Entropy and AHP methods. The correlation between these indexes is determined by Spearman's rank correlation coefficient. The Spearman correlation between two variables is equal to the Pearson correlation between the rank values of those two variables. If there are no repeated data values, a perfect Spearman correlation of +1 or −1 occurs when each of the variables is a perfect monotone function of the other. Intuitively, the Spearman correlation between two variables will be high when observations have a similar rank between the two variables, and low when observations have a dissimilar rank between the two variables. Mathematically, Spearman correlation coefficient (γ_s) is computed as:

$$\gamma_s = 1 - \frac{6\sum d_i^2}{n\left(n^2 - 1\right)} \tag{2}$$

where, d_i = difference between the two ranks of each observation, n = number of observation.

The results (Table 7) show that correlation coefficient for combination of criteria weighting techniques AHP with AHP-Entropy is very high (0.964). This suggests that the results of these two techniques are very close together and while the correlation between Entropy and AHP technique is much lower (0.321) indicating the lack of consistency in the results of those two techniques together. The t-test of Spearman's rank correlation coefficient in significance level (a) = 0.05 and degree of freedom (n − 2) = 5, correlates the weighting techniques establishing the correlation status (Table 8).

The correlation status shows that results of the two techniques, Entropy and AHP, are not correlated. In other words, the results of these techniques are very different from each other. On the other hand, the combination of weighting techniques AHP and AHP-Entropy possess high correlation showing the closer results. Moreover, a combination of Entropy and AHP-Entropy possess low correlation.

Table 7. Spearman's rank correlation coefficient.

Weighting technique	Spearman' rank correlation coefficient
AHP and Entropy	0.321
Entropy and AHP-Entropy	0.429
AHP and AHP-Entropy	0.964

Table 8. Correlation status using t-test.

Correlation status	Weighting technique
Lack of correlation	AHP and Entropy
Correlation	Entropy and AHP-Entropy
Correlation	AHP and AHP-Entropy

6.2. Combined Weighting and Prioritization Techniques

6.2.1. Euclidean Distance

Sensitivity analysis of the preference raking results is carried out determining and comparing Euclidean distance for each pairs of criteria weighting and prioritization techniques. Altogether 36 pairs are formed and Euclidean distance for each pair is determined (Table 9, Table 10). In this approach, calculated distance between two techniques shows degree of similarity between these techniques. If the calculated distance is less, there is more similarity between two techniques and vice-versa.

In Table 9 & Table 10, values in the rows 18, 21 and 33 reflect stability of SAW method of preference ranking. Similarly, rows 11, 14 and 29 are related to TOPSIS and rows 3, 6 and 24 to ELECTRE. The results show that all three MCDM techniques of preference ranking ELECTRE, TOPSIS and SAW are not very stable and are sensitive to weighting.

7. Conclusions

Multi-criteria decision making approaches were applied to assess prioritization of technical measures for flood risk management and sediment control in Koshi alluvial fan. Criteria weighting indexes were estimated using weighting techniques Entropy, AHP and AHP-Entropy. Preference ranking of alternatives of technical measures was completed using multi-criteria decision making (MCDM) methods—ELECTRE, TOPSIS and SAW. Five alternate measures for flood risk management and eight alternate measures for sediment control with seven evaluation criteria comprising economic, social, political and environmental aspects were taken into account. The Spearman's rank correlation coefficient and t-test showed strong correlation between the criteria weighting techniques AHP and AHP-Entropy, weak correlation between Entropy and AHP-Entropy and no correlation between AHP and Entropy. Preference ranks were determined using nine combinations of criteria weighting techniques and preference ranking methods. Considering average value of results for all nine combinations, alternate measures were prioritized and recommended. In the case of flood risk management, among intended hydraulic measures, using of old Koshi channel was recommended as the highest prioritized and raising embankments, the least prioritized measure. Similarly, for sediment control, reduction of upstream sediment supply and removing embankments and Koshi barrage were recommended as top and least prioritized measures respectively. The Euclidean distance test for each pair of criteria weighting and prioritization

Table 9. Euclidean distance for combined weighting and prioritization techniques (Hydraulic measures).

S.N	Techniques compared	Euclidean distance	S.N	Techniques compared	Euclidean distance
1	(AE-E)-(AE-T)	4.243	19	(AE-S)-(AE)	4.243
2	(AE-E)-(AE-S)	4.472	20	(AE-S)-(AT)	2.000
3	(AE-E)-(EE)	0.000	21	(AE-S)-(AS)	0.000
4	(AE-E)-(ET)	4.243	22	EE-ET	4.243
5	(AE-T)-(ES)	4.690	23	EE-ES	4.690
6	(AE-E)-(AE)	2.000	24	EE-AE	2.000
7	(AE-E)-(AT)	4.243	25	EE-AT	4.243
8	(AE-E)-(AS)	4.472	26	EE-AS	4.472
9	(AE-T)-(AE-S)	2.000	27	ET-ES	3.742
10	(AE-T)-(EE)	4.243	28	ET-AE	3.162
11	(AE-T)-(ET)	2.828	29	ET-AT	2.828
12	(AE-T)-(ES)	4.243	30	ET-AS	3.464
13	(AE-T)-(AE)	3.162	31	ES-AE	5.099
14	(AE-T)-(AT)	0.000	32	ES-AT	4.243
15	(AE-T)-(AS)	2.000	33	ES-AS	2.828
16	(AE-S)-(EE)	4.472	34	AE-AT	3.162
17	(AE-S)-(ET)	3.464	35	AE-AS	4.243
18	(AE-S)-(ES)	2.828	36	AT-AS	2.000

Table 10. Euclidean distance for combined weighting and prioritization techniques (Sediment control measures).

S.N	Techniques compared	Euclidean distance	S.N	Techniques compared	Euclidean distance
1	(AE-E)-(AE-T)	9.434	19	(AE-S)-(AE)	10.630
2	(AE-E)-(AE-S)	11.358	20	(AE-S)-(AT)	5.831
3	(AE-E)-(EE)	7.810	21	(AE-S)-(AS)	3.464
4	(AE-E)-(ET)	9.950	22	EE-ET	7.746
5	(AE-T)-(ES)	11.358	23	EE-ES	8.845
6	(AE-E)-(AE)	4.899	24	EE-AE	8.307
7	(AE-E)-(AT)	9.000	25	EE-AT	8.000
8	(AE-E)-(AS)	10.440	26	EE-AS	8.718
9	(AE-T)-(AE-S)	5.831	27	ET-ES	4.899
10	(AE-T)-(EE)	7.746	28	ET-AE	10.630
11	(AE-T)-(ET)	1.414	29	ET-AT	2.449
12	(AE-T)-(ES)	5.831	30	ET-AS	4.472
13	(AE-T)-(AE)	10.344	31	ES-AE	10.360
14	(AE-T)-(AT)	2.000	32	ES-AT	5.831
15	(AE-T)-(AS)	4.899	33	ES-AS	3.464
16	(AE-S)-(EE)	8.485	34	AE-AT	9.950
17	(AE-S)-(ET)	4.899	35	AE-AS	10.909
18	(AE-S)-(ES)	0.000	36	AT-AS	4.690

methods showed all three MCDM methods of preference ranking ELECTRE, TOPSIS and SAW were sensitive to weighting.

The results of this study can be utilized by local authority as base line information for the structural measures for sustainable flood risk management and sediment control. The methodology used in this study can be applied to other rivers having similar physical characteristics and dynamic alluvial fan. On implementation of the recommended measures, local people of Saptari, Sunsari and Morang districts of Nepal will be highly benefited. The study didn't incorporate non-structural measures of flood risk management including mapping vulnerable areas, changing cropping pattern and establishment of flood early warning system (FEWS) and recommended for further study.

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Author Contributions

Mukesh Raj Kafle was responsible for this current research article in the framework of his PhD program and initially wrote the manuscript. Narendra Man Shakya directed the study by helping to interpret the results and improving the quality of manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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