Multiobjective Analysis of the Sedimentation behind Sangju Weir, South Korea

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Abstract: This paper presents a new multiobjective approach to solve sedimentation problems behind weirs and low-head dams. The multicriteria decision analysis (MCDA) framework is used to improve reservoir operation rules for Sangju Weir in South Korea. A series of stage and discharge constraints can be developed to include consideration for reservoir sedimentation, hydropower generation, flood control, water supply, irrigation and drainage, and environment. Seasonally changing operation rules can help mitigate reservoir sedimentation while improving hydropower production, water supply, water quality, and environmental issues. Based on a 22-year daily reservoir operation simulation, improved operation rules to mitigate reservoir sedimentation include: (1) a nonflood season stage kept high (EL 47.0 m); (2) a flood season stage between EL 47.0 m and EL 44.5 m depending on the magnitude of the upstream flow discharge; and (3) gates should be opened during floods ($Q > 600$ m^3/s). **DOI: 10.1061/(ASCE)WR.1943-5452.0000851.**

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Introduction

In Korea, the Four River Restoration Project (FRRP) was initiated in 2009 to improve flood control, restore the river ecosystems, and provide drought relief (Cha 2011). The project was completed in 2013 with a total budget of approximately 18 billion U.S. dollars. The project included the construction of the 16 movable weirs (length: 184–953 m and height: 3.5–11.8 m) with associated hydropower plants. Large-scale dredging operations were conducted to reduce the flood stages and restore floodplains for agriculture in four major rivers of Korea—Han River, Nakdong River, Geum River, and Yeongsan River. The deteriorated levees were reinforced, and approximately 450 million m^3 of material was dredged in order to increase the flood control capacity to handle a 200-year flood. As a result, the lowered riverbeds have increased the flow-carrying capacity of the river cross section, resulting in reduced flood damage to adjacent farming land and residential areas near the rivers. The project successfully lowered the river stages during the 2012 flood season (K-water 2012a).

The construction of consecutive weirs and excavation along major rivers changed many characteristics of alluvial rivers like the Nakdong River. Significant changes in channel morphology such as longitudinal slope, cross-sectional area, and water stage led to changes in erosion and sedimentation patterns along the river. The sedimentation problems in the Nakdong River can be summarized as follows: (1) after consecutive weir construction, sedimentation problems have been more significant upstream of the weirs and near the confluence with tributaries; (2) ambiguous reservoir operation rules may have aggravated the reservoir sedimentation problem; and (3) reservoir sedimentation could result in significant and undesirable excavation costs. The amount of sediment accumulation depends on the sediment load Q_s and trap efficiency T_E which varies according to water stage, particle fall velocity, and inflow rate. When the discharge is low and the water stage is high, the trap efficiency approaches 100%, and all incoming sediment is trapped in the reservoir. For example, reservoir levels are kept high to provide more storage to mitigate drought conditions and to increase hydropower generation. However, this increases flooding risks and reservoir sedimentation rates during wet periods. Attempting to change reservoir operation rules to mitigate sedimentation problems may impact other aspects such as flood control, water supply, and stream ecology, as shown in Fig. 1.

Since the completion of Sangju Weir in 2012, the operation rules (K-water 2012b) have been ambiguous with regard to flow discharge and may have exacerbated the sedimentation problems. For instance, the current operation rules of Sangju Weir (Table 1) completely ignored the sediment issue, which can lead to significant dredging costs. It is important to define operational rules that consider minimizing the reservoir management costs to ensure long-term economic viability of this hydraulic structure.

Multicriteria decision analysis (MCDA) refers to a systematic decision methodology to rank alternatives in situations with multiple conflicting criteria. The main challenge for decision makers is to evaluate the trade-offs between conflicting criteria. The MCDA method: (1) provides a systematic process for analyzing discrete decisions; (2) is based on the familiar concept of an overall score

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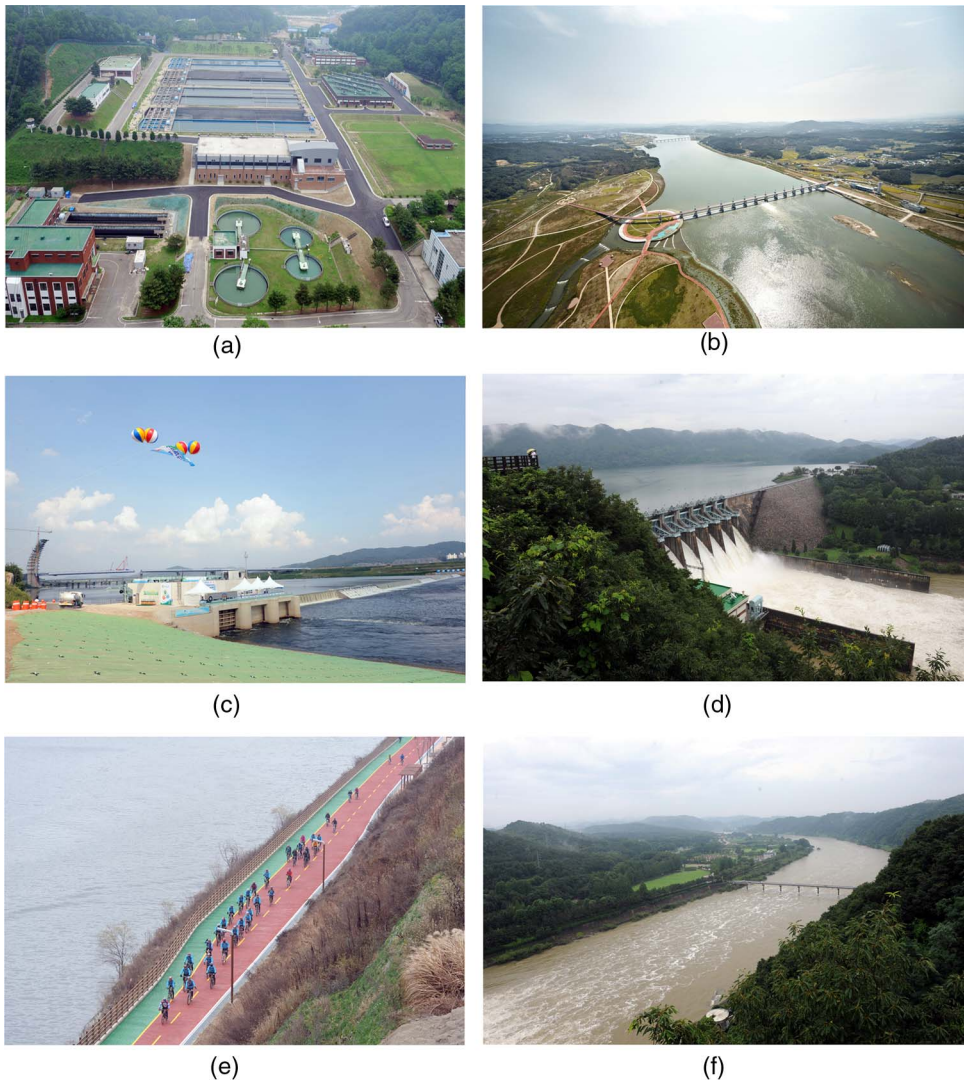


Fig. 1. Issues of reservoir operation (images courtesy of Korea Water Resources Corporation): (a) water supply; (b) stream ecology; (c) hydropower generation; (d) flood control; (e) riverside environment, (f) turbidity

Table 1. Sangju Weir Operation Rule (Data from K-water 2012b)

Div.	Stage (EL. m)	Discharge (m^3/s)	Operation
Drought	Lower 47.0	Below 25	Releasing through fish passage and hydropower plant Changing generating power according to inflow to the weir
Normal	47.0–47.5	25–4,491	Keeping management water stage (EL. 47 m) Open the gate if it is needed to keep management stage.
Flood ascending	47.0–47.5	25–4,491	Fully open the gate if it is needed
	47.5–49.6	4,491–8,808	Fully open the gate if it is needed
	Above 49.6	Above 8,808	Fully open the gate
Flood descending	47.5–47.0	Below 4,491	Gradually close the gates Lower limit (Pungyang intake EL. 44.20 m)

for an alternative; (3) provides a way to document and audit decisions; and (4) can be easily adapted to new information with an iterative procedure. According to Ackoff (1978), MCDA problems are complex, interconnected, and disharmonious, that is, having incompatible criteria. One objective of MCDA is to identify and clarify the status of issues for decision makers. The other core objective of MCDA is to provide the decision makers with mathematical tool for their decision.

The well-established MCDA method has been applied to many field situations involving water quantity and quality, groundwater, and environmental issues. Cohon and Marks (1975) and Cohon et al. (1979) introduced multiobjective programming techniques. Goicoechea et al. (1976) investigated the introduction of a mechanical and chemical treatment method to increase the watershed runoff for the San Pedro River in Arizona. This research analyzed five objectives: runoff increase, sediment reduction, wildlife

balance, recreation, and commercial profit. Tauxe et al. (1979) applied multipurpose dynamic programming to the Shasta reservoir operations in California, in which three objectives were to: (1) maximize the cumulative energy generated above the level of firm energy; (2) minimize the cumulative evaporation; and (3) maximize the firm energy. A typical example of environmental elements shared in a river basin planning was provided by Gershon et al. (1982). Balancing many interests in the Santa Cruz River Basin, Gershon et al. (1982) illustrated the need to span qualitative and quantitative objectives in seeking a desirable solution. Large-scale reservoir systems typically serve many important purposes, including water supply, hydropower production, flood control, and low-flow augmentation for water quality enhancement. Numerous mathematical simulation and optimization models have been developed for reservoir systems analysis. The challenge is to apply these models such that the trade-offs among multiple objectives are clearly identified (Ko et al. 1992). The U.S. Army Corps of Engineers published "Trade-off analysis for environmental projects: An annotated bibliography" (Feather et al. 1995). Flug et al. (2000) applied this research to the evaluation of reservoir operational alternatives to the Glen Canyon dam.

There are few MCDA research studies on water quantity and water quality (Ko et al. 1992), and the impact on erosion and sedimentation problems is largely ignored. Furthermore, research studies performed on dams may not be applicable to weirs because the trap efficiency varies with both stage and discharge. The present research is focused on solving the sedimentation problem associated with weirs and low-head dams, with application at Sangju Weir.

The objectives of this study are to (1) develop a new systematic analysis procedure to mitigate reservoir sedimentation problems in the context of multiple conflicting constraints; (2) test the proposed new procedure to solve the complex Sangju Weir operation problems; and (3) develop better operation rules for the mitigation of the sedimentation problems behind Sangju Weir

Site Description

The Sangju Weir shown in Fig. 2 has been selected for this study because it is representative of these types of sedimentation problems and because there are sufficient data available. Sangju Weir is the uppermost weir constructed on the Nakdong River under the FRRP. It includes two tributaries: Naesung Stream and the Yeong Stream as well as the main Nakdong River.

The Nakdong River is located in the southeastern region of the Korean peninsula with a total drainage area of about 23,384 square kilometers, 25.9% of South Korea, and a total river length of 510.4 km. Besides Sangju Weir (constructed through FRRP in 2012), there are four multipurpose dams in the study area: Andong (completed in 1977), Imha (completed in 1993), Sungdeok (completed in 2014), and Yeongju (completed in 2016). The watershed area and gauging stations are listed in Table 2. The annual rainfall is 1,255 mm, which is about 20 mm less than the average of South Korea, 1,274 mm. Naesung Stream is located within the upper region of the Nakdong River Basin and drains an area of approximately 1,815 km^2 with altitude ranging from 54 to 1,420 m above mean sea level. The Yeongju multipurpose dam was constructed in 2015 on the Naesung Stream 55.6 km upstream from the confluence with the Nakdong River. The Naesung Stream was ranked among the highest sediment load producers of the Nakdong River Basin (K-water 2013; Ji et al. 2014). Consequently, a sediment detention reservoir called the Yeongju multipurpose dam was built in 2015 (Samsung Inc. 2009). Yeong Stream is adjacent to Naesung Stream and covers 914 km^2. This watershed was investigated and monitored since 1991 with a considerable water stage and sediment record at the Jeomchon gauging station.

Reservoir Sedimentation at Sangju Weir

The integrated reservoir sedimentation estimation procedure (IRSEP) was used for estimating the reservoir sedimentation at Sangju Weir. Kim (2016) developed the IRSEP based on the flow-duration and sediment rating curve (FD/SRC) method, the series expansion of the modified Einstein point procedure (SEMEPP), and the trap efficiency T_E. The FD/SRC method combines a sediment rating curve (total sediment discharge as a function of water discharge) and a flow-duration (FD) curve to determine the long-term sediment yield into a reservoir. The FD curves were produced at the mouth of three subbasins: (1) Naesung Stream; (2) Yeong Stream; and (3) Nakdong River. A representative FD curve was obtained from a 20 years' daily discharge record. The sediment rating curve (SRC) gives the relationship between the discharge and the total sediment discharge obtained from field measurements. These two curves were combined to predict long-term sediment yield at the mouth of every watershed. The SEMEPP correction factor (Shah-Fairbank and Julien 2015) was applied to get the total sediment load from suspended load measurements. To determine the sedimentation rate at Sangju Weir, the total sediment yield is multiplied by the trap efficiency T_E, which depends on discharge and stage. Kim (2016) developed a detailed procedure for the calculation of the trap efficiency by size fractions as a function of the flow discharge and reservoir stage.

Table 3 presents a summary of the reservoir sedimentation rates from each of the main tributaries at different stages. Since the reservoir sedimentation rate varies with stage, two extreme cases were examined. The trap efficiency was 78.1% when the water stage was maximum at EL 47.0 m. However, when the gates are fully opened and the stage is kept at the lowest position (EL 37.2 m), the corresponding trap efficiency drops to 50.1%. The corresponding annual rate of reservoir sedimentation, therefore, corresponds to 0.76 and 0.49%, respectively, of the total storage capacity (Table 3). The life expectancy of the reservoir upstream of Sangju Weir is thus expected to exceed 100 years.

Benefit–Cost Analysis

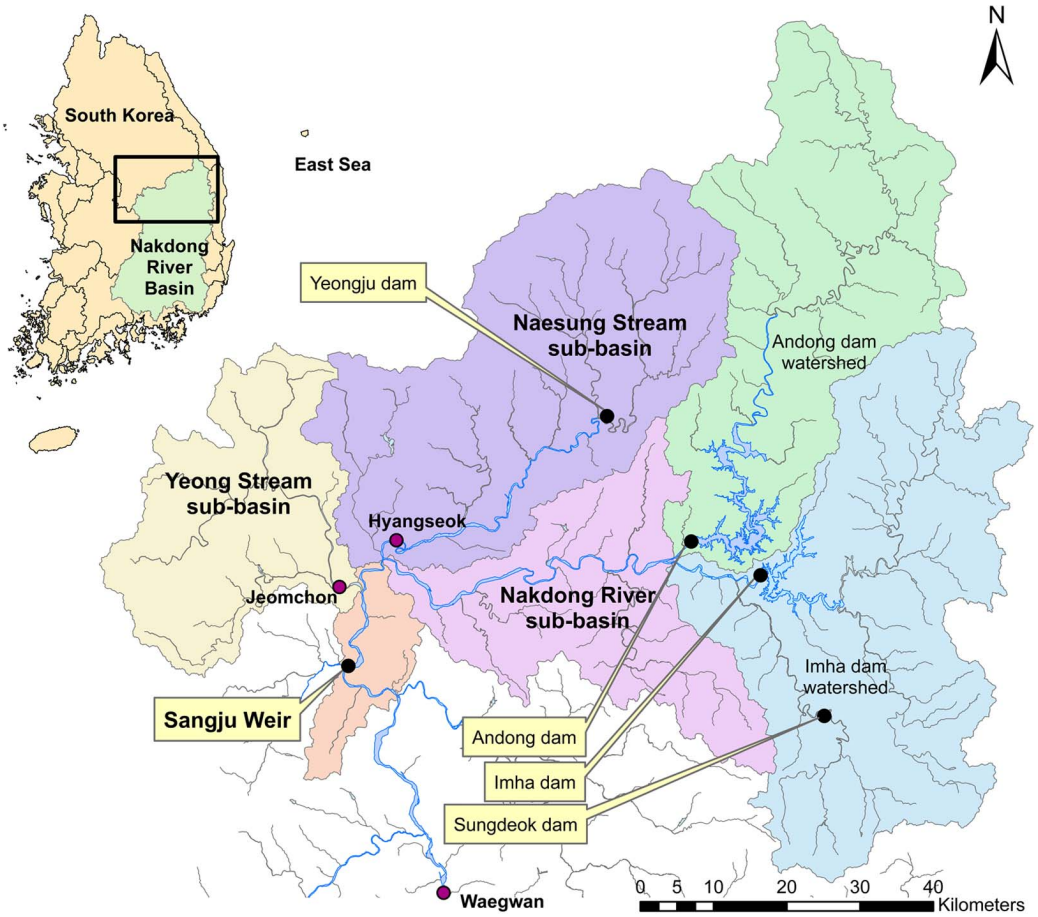
Hydropower Benefits and Dredging Costs

On the revenue side, the amount of hydropower production depends on water discharge, effective head, and operating efficiency

$$P_i = 9.81\eta Q_a H_a \tag{1}$$

where P_i = capacity (kW), η = overall efficiency of the power plant, Q_a = discharge for generation (m^3/s), and H_a = effective head (m).

The hydropower generation capacity at Sangju Weir is 3,000 kW and the annual mean hydro-energy production was estimated to reach 15,900 MWh (Korea Engineering Consultants Corporation 2009). To reach this annual hydro-energy production, the generator must run 221 days in a year and requires a high-water stage at Sangju Weir. If the effective head is lower than 4.07 m, the generator cannot operate. According to the historical power generation and sales record, a unit cost for hydropower generation was estimated as 0.13 USD/kWh. K-water has excavated the bottom of the Nakdong River Estuary Barrage reservoir during the period of



(a)

(b)

Fig. 2. Upper Nakdong River Basin and Sangju Weir (image courtesy of Korea Water Resources Corporation)

Table 2. Basic Information for the Study Area

Basin	Drainage area (km^2)	Ratio (%)	Gauging station
Andong multipurpose dam	1,584	21.4	—
Imha multipurpose dam	1,361	18.4	—
Sungdeok multipurpose dam	41	0.6	—
Yeongju multipurpose dam	500	6.8	—
Naesung Stream	1,315	17.7	Hyangseok
Yeong Stream	914	12.3	Jeomchon
Nakdong River	1,692	22.8	Waegwan
Sangju Weir	7,407	100.0	—

1990–2010. According to the records, the sediment excavation cost per unit volume is estimated at 6.31 USD/m^3.

Long-Term Benefit and Cost Analysis

The balance between hydropower revenues and sediment excavation costs is examined from a benefit and cost analysis (BCA) viewpoint. Two main variables are considered in the analysis: excavation costs and hydropower revenues. A two-year gate operation record is available at Sangju Weir from January 2013 to December 2014. Fig. 3 shows the 10-min operational record at Sangju Weir and the two-year database includes water stage, total discharge release, gate opening, and hydropower discharge. It is noted that the water stage has been kept high regardless of discharge, which contributed to sediment deposition in the reservoir. As shown in Fig. 4, a 22-year simulation period (2013–2034) was investigated by repeating the historical gate operation record (Fig. 3). The cumulative benefits from the hydropower production and cumulative excavation costs are also shown in Fig. 4. As detailed in Table 4, the B/C ratio is 2.28, indicating that the hydropower revenue exceeds the sediment dredging cost under the current Sangju Weir operation rule. The B/C analysis in this paper is not a societal B/C analysis but a financial analysis with respect to hydropower revenues and sediment dredging costs based on reservoir operations.

Hydraulic thresholds for stage and discharge can be determined from the benefit–cost analysis by balancing the hydropower production revenue and the excavation cost. Thresholds of discharge and water stage correspond to a B/C ratio equal to 1 or benefits = costs. The discharge threshold that balances revenues and costs was graphically found to be 600 m^3/s (Kim 2016). This is important because at flows less than 600 m^3/s, the revenues exceed the costs, and the operations are profitable. After daily modeling with fixed water stages (EL 37.2 m–EL 47.0 m), B/C ratios were calculated for every stage, and the threshold stage of EL 43.6 m was obtained.

MCDA Application to Sangju Weir

The systematic process is one of the characteristics of MCDA. To reach the conclusion, MCDA follows seven steps: (1) criteria definition; (2) relative importance factor set-up; (3) constraints analysis; (4) alternatives development; (5) daily modeling for MCDA input; (6) MCDA scaling and rating; and (7) MCDA results.

Criteria Definition

Criteria are the objectives or measures used to evaluate the performance of the potential alternatives. Five main criteria were selected to evaluate the operation of Sangju Weir: (1) reservoir sedimentation; (2) hydropower production; (3) water supply; (4) flood control; and (5) the environment. To better quantify the ratings or scoring of the alternatives with respect to each main criterion, subcriteria were used for each of the main criteria. In this study, 14 subcriteria were selected.

Relative Importance Factors Set-Up

The relative importance factor (RIF) is the relative importance of each subcriterion given by the ratio of the importance of each subcriterion compared to the least important subcriterion. The least important subcriterion has a relative importance factor equal to 1. For a case where all subcriteria are equal, the same relative importance factor of 1 is used for all criteria (i.e., G1 on Fig. 5). Similarly, the RIF values can be assigned to subcriteria as shown in Fig. 6. Normalized weights are obtained by dividing the RIF for a subcriterion by the summation of all the RIF values in the set of subcriteria as shown in Table 5. For this study, a single set of RIF values was used to combine the subcriteria ratings, as shown in Fig. 5 and Table 5.

A similar approach of applying relative importance factors was used to develop the normalized weights for the main criteria so that an overall score for an alternative can be calculated. There can be multiple groups that can influence a decision on reservoir operation, and these groups may have very different viewpoints as to what the relative importance factors related to the various criteria should be. The approach used in this study was to consider a variety of potential decision makers and then look at the suggested ranking of the alternatives for all the groups to see if certain alternatives were consistently ranked as the best. As shown in Fig. 5, a total of seven RIF sets were developed based on potential decision-maker groups: (1) a reservoir operator group; (2) a reservoir operator group with a sedimentation emphasis; (3) a reservoir sedimentation management group; (4) a hydropower production group; (5) a water supply responsibility group; (6) a flood control agency group; and

Table 3. Summary of Sediment Yield

				High stage (EL. 47.0 m)				Low stage (EL. 37.2 m)			
Sub-basin	Measured load, Q_P (tons/year)	Q_P/Q_T ratio (%)	Total load, Q_T (tons/year)	T_E (%)	Reservoir sedimentation in ton (tons/year)	Reservoir sedimentation in volume[a] (m^3/year)	Reservoir filling rate[b] (%)	T_E (%)	Reservoir sedimentation in ton (tons/year)	Reservoir sedimentation in volume[a] (m^3/year)	Reservoir filling rate[b] (%)
Naesung	214,673	90	237,912	78.0	185,532	115,958	0.76	56.4	134,091	83,807	0.49
Yeong	44,402	87	51,143	86.2	44,109	27,568	0.76	49.9	25,520	15,950	0.49
Nakdong	128,155	94	136,155	75.3	102,532	64,083	0.76	39.1	53,258	33,286	0.49
Total	387,230	91	425,210	78.1	332,173	206,608	0.76	50.1	212,869	133,043	0.49

[a]Reservoir sedimentation in volume is the reservoir sedimentation in volume m^3/year calculated by dividing reservoir sedimentation in ton (tons/year) into unit weight of sand (1.6 ton/m^3).

[b]Reservoir filling rate is the annual rate of reservoir sedimentation calculated by dividing summation of reservoir sedimentation in volume into total reservoir volume (27.4 mm^3).

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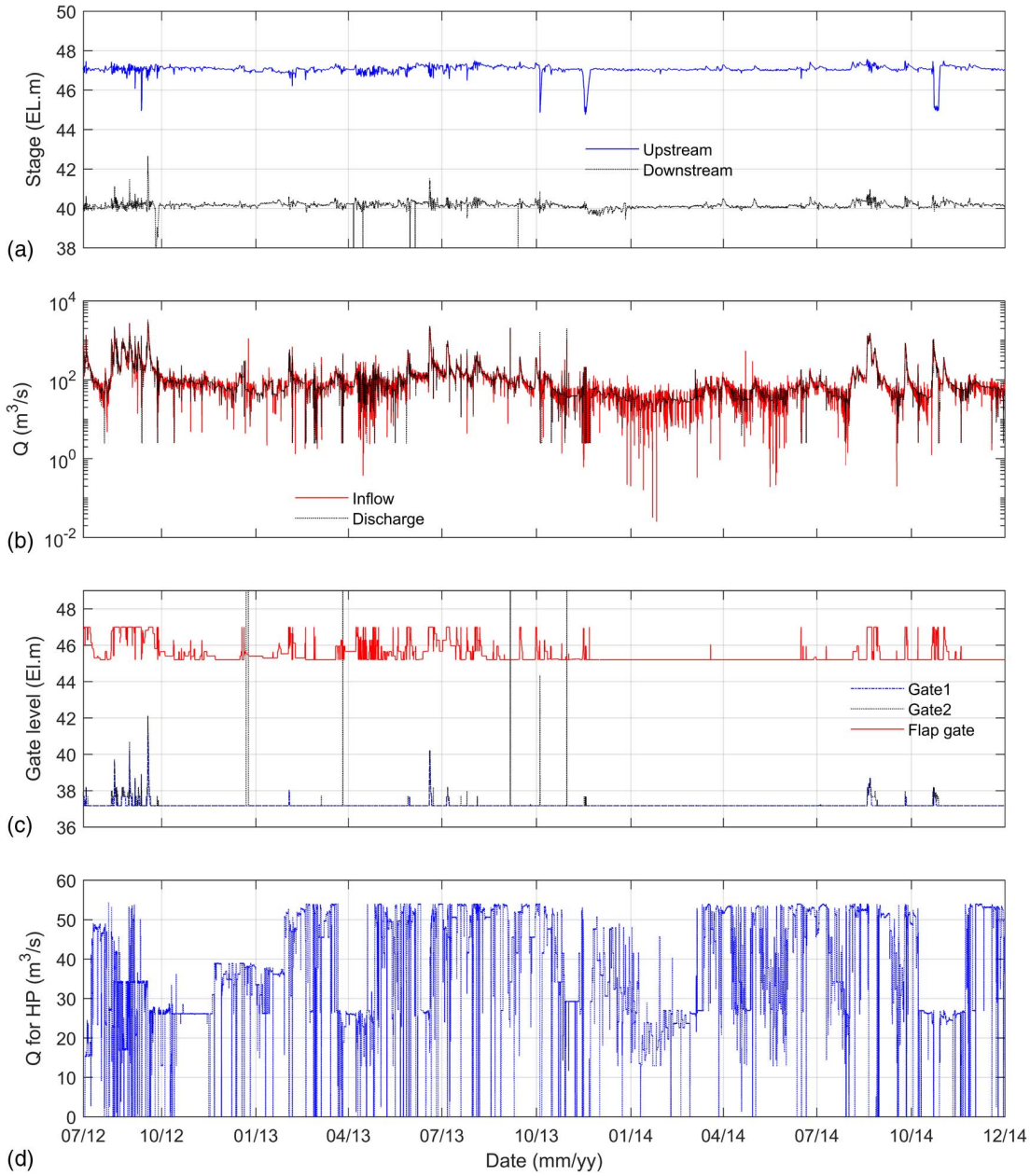

Fig. 3. Historical operational record (2012–2014) at Sangju hydropower discharge weir: (a) stage; (b) inflow and discharge; (c) gate height; (d) discharge for hydropower generation

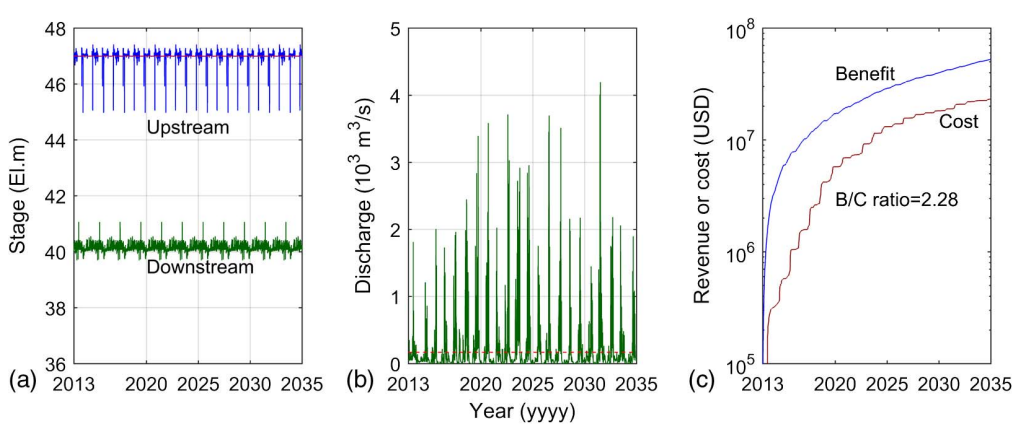

Fig. 4. Modeling conditions: (a) water stage; (b) discharge; (c) B/C ratio for the current operation rule in Sangju Weir

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Table 4. Daily Modeling Results for Historical Data

Items	Modeling results
P_i (kW)	2,106
HP (GWh)	407
Benefit (mil. USD)	52.8
Q_T (mil. tons)	7.4
Avg. T_E (%)	80
Dep. (mil. tons)	5.9
Dep. (mil. m^3)	3.7
Cost (mil. USD)	23.2
B/C ratio	2.28

Note: Avg. = average; Dep. = deposition; Mil. = million.

Decision makers / Main Criteria	G1	G2	G3	G4	G5	G6	G7
Sedimentation	1	4	4	1	1	1	1
Hydropower	1	3	1	4	1	1	1
Water Supply	1	3	1	1	4	1	1
Flood Control	1	2	1	1	1	4	1
Environment	1	1	1	1	1	1	4

G1: Reservoir operator group
G2: Reservoir operator group with sedimentation emphasis
G3: Reservoir sedimentation management group
G4: Hydropower production group
G5: Water supply responsibility group
G6: Flood control agency
G7: Riverside environment & stream ecology group

Fig. 5. Relative importance factor set for main criteria

(7) a riverside environment and stream ecology group. Additional RIF sets can be developed to reflect the views of other decision makers.

Constraints Analysis

Reservoir operators must consider numerous constraints that exist upstream and downstream of Sangju Weir. The constraints can be sorted into categories related to various purposes such as drinking water supply, irrigation, flood drainage, riverside amenities, and environmental issues. Since the construction period, the operators of Sangju Weir have examined the constraints that impact the reservoir operations. According to the annual Sangju Weir operation constraints review (Sangju Weir Operation Office and K-water 2014), 27 upstream constraints were identified. These constraints relate to water supply and flood damage mitigation issues. The constraints analysis defined possible or desirable operational zones for water stage and discharge. Two main components of the constraints analysis are the water stage and the flow discharge.

In terms of water stage, to satisfy the water intake condition for the drinking water facilities, the reservoir stage must be kept above EL 44.2 m (above mean sea level), but for consistent irrigation, the water level must be kept at least above EL 45.0 m during the irrigation period (May–September). In contrast to the water supply issue, some constraints force the reservoir operators to keep the water level low. There are 19 flood drainage facilities that are draining multiple watersheds to the Nakdong River during the flood

Main-Criteria	RIF for G2	Sub-Criteria	Opt. Fun.	Relationship	RIF for sub-criteria
Sedimentation	4	Trap efficiency (T_E, %)	Min.	T_E = f (Q, ω, A)	3
		Water Stage (WS, El.m)	Min.		1
		Water surface area (A, m^2)	Min.	A = f (ws)	2
		Reservoir sedimentation (Dep, m^3)	Min.	Dep = Q_T x T_E	4
Hydropower	3	Stage difference (dH, m)	Max.		1
		Discharge for hydropower (Q_a, m^3/s)	Max.		1
		Hydropower production (P, kWh)	Max.	P= f (Q_a, dH)	4
Water supply	3	Storage above intake facility (V_s, m^3)	Max.		1
		Water supply stability	Max.	Water Supply = f (V_s)	4
Flood control	2	Empty space above water stage (V_f, m^3)	Max.	V_f = f (ws)	2
		Available cross sectional area (A_{xs}, m^2)	Max.	A_{xs} = f (ws)	2
		Flood control and drainage effect	Max.	Fld Cont. = f (V_f, A_{xs})	4
Environment	1	Turbidity downstream (Tur, NTU)	Min.	Tur = f (Q)	4
		Good view station ratio (GVSR, %)	Max.	GVSR = f (ws)	4

Fig. 6. Application of RIF for criteria and optimization functions

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Table 5. Weighted Average Method (WAM)

Resource criteria	G2 main criteria: Relative importance	G2 main criteria: Normalized weights	Attribute normalized weights	Alternatives 1	2	3	4	5
Reservoir sedimentation	4	0.308	—	—	—	—	—	—
Trap efficiency (T_E, %)			0.300	1	1.372	5	1.127	1.266
Water stage (*WS*, El.m)			0.100	1	2.388	5	1.103	1.272
Water surface area (A, m^2)			0.200	1	2.29	5	1.147	1.387
Reservoir sedimentation (Q_s, m^3)			0.400	1	1.372	5	1.127	1.266
			1	1.00	1.66	5.00	1.13	1.29
Hydropower production	3	0.231	—	—	—	—	—	—
Stage difference (dH, m)			0.167	5	3.01	1	4.853	4.61
Discharge for hydropower (Q_a, m^3/s)			0.167	1	5	5	2.539	5
Hydropower production (*HP*, kWh)			0.667	5	2.68	1	4.815	4.488
			1	4.33	3.12	1.67	4.44	4.59
Water supply stability	3	0.231	—	—	—	—	—	—
Storage above intake facility (V_s, m^3)			0.200	5	2.774	1	4.802	4.475
Water supply stability			0.800	5	1	1	5	5
			1	5.00	1.35	1.00	4.96	4.90
Flood control and conveyance	2	0.154	—	—	—	—	—	—
Empty space above water stage (V_f, m^3)			0.250	1	3.226	5	1.789	2.72
Available cross-sectional area (A_{xs}, m^2)			0.250	1	2.363	5	1.401	2.002
Flood control and drainage effect			0.500	1	4	5	2	3
			1	1.00	3.40	5.00	1.80	2.68
Environment and riverside amenity	1	0.077	—	—	—	—	—	—
Turbidity downstream (*T*, NTU)			0.500	5	5	5	5	5
Good-view section ratio (*GVSR*, %)			0.500	5	2.714	1	4.429	4.619
			1	5.00	3.86	3.00	4.71	4.81
	13	1.000	Overall	3.000	2.362	3.154	3.156	3.369
			Rank	4	5	3	2	1

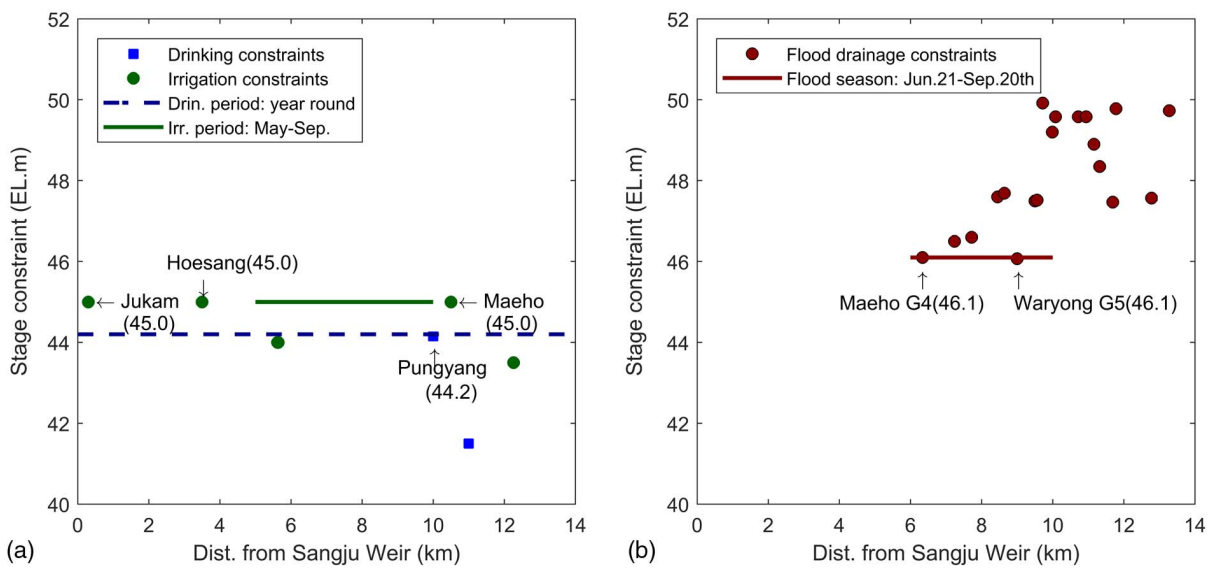


Fig. 7. (a) Water supply constraints; (b) flood drainage constraints of upstream of Sangju Weir

season (June–September). Flooding occurs when Sangju Weir's water stage is higher than EL 46.1 m, which means that paddy fields cannot drain effectively into the river. Hence, these two water stages must be considered for the development of operational alternatives. Fig. 7 presents the water stage constraints for water supply and flood control.

The second important constraint is the flow discharge. Discharge influences many aspects including: (1) hydropower generation; (2) turbidity at the downstream water treatment plant; and (3) reservoir sedimentation. First considering hydropower, the turbines are designed to achieve maximum performance when the discharge is 25 m^3/s. Since there are two generators, a river discharge of at least 50 m^3/s yields optimum hydropower performance. Downstream turbidity is also an important factor correlated with flow discharge. High concentration of sediment flow may damage the water treatment facilities. Kim (2016) examined the relationship between discharge Q and turbidity from the Haepyeong intake facility located downstream of Sangju Weir. A discharge exceeding

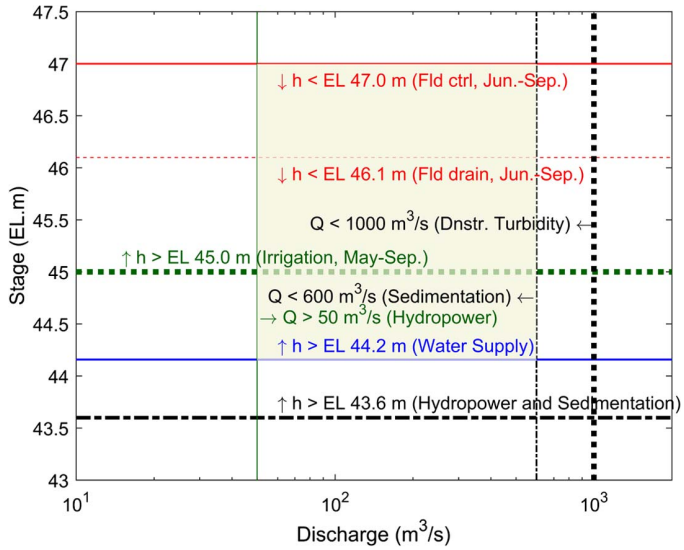


Fig. 8. Constraints with respect to both water stage and discharge

1,000 m^3/s was found to result in excessive turbidity. Finally, the discharge is also related to reservoir sedimentation. To balance the dredging costs and hydropower benefits, the break-even discharge was calculated as 600 m^3/s (Kim 2016). The discharges above the break-even point incur more reservoir sediment excavation costs than hydropower revenues.

Alternatives Development

Based on the constraints analysis shown in Fig. 8, a total of five alternatives were developed as follows:

1. Alternative 1: Full water stage operation (EL 47.0 m) describing current operation rule
2. Alternative 2: Medium water stage operation (EL 43.6 m, stage break-even point)
3. Alternative 3: Lowest water stage operation (EL 37.2 m, fully opened gates status)
4. Alternative 4: Seasonal water stage control
   a. Normal season (EL 47.0 m)
   b. Flood season (EL 46.0 m)
5. Alternative 5: Seasonal stage control considering upstream inflow
   a. Nonflood season (EL 47.0 m)
   b. Flood season (varies with the magnitude of inflow rate):
      (1) $Q \leq 50\ m^3/s \rightarrow$ EL 47.0 m
      (2) $50 < Q \leq 600\ m^3/s \rightarrow$ EL 46.0 m
      (3) $Q > 600\ m^3/s \rightarrow$ EL 44.5 m

Alternative 1 represents the current operational conditions. Alternatives 2 and 3 have fixed water stage (medium, low) regardless of the season. They are based on the analysis (Kim 2016) that lower operational stages would decrease the sedimentation rates. In Alternative 4, the water stage is dropped to EL 46.0 m to meet the requirements for the 19 flood drainage facilities (Sangju Weir Operation Office and K-water 2014) during the flood season. If the reservoir operators use Alternative 4, water can be released more effectively than for the current Alternative 1. Alternative 5 sketched in Fig. 9(b) is the most advanced alternative for mitigation of the sedimentation problem, which includes the effects of water stage and discharge constraints on drainage and flood control. The most attractive feature of this alternative is that the reservoir sediment trap efficiency can be reduced when the stream flow rate is high. Fig. 9 shows the proposed alternatives with seasonal stage difference according to discharges.

Daily Modeling for MCDA Input

Daily modeling was performed for each alternative over a 22-year period so that the performance of the reservoir with respect to each subcriterion could be determined. The performance values were determined based on the daily modeling results. Numerical and word scales were developed so that rating values on a scale of 1 (least) to 5 (best) could be determined. Finally, the ratings were used within the MCDA methodology. Fig. 10 describes the analysis procedure. The daily modeling results were used to estimate the performance of the system with respect to the 14 subcriteria. Since there are 8,035 simulation days, median values were chosen as representative values.

MCDA Scaling and Rating

All subcriteria and criteria performance values were transformed to a common scale between 1 and 5. Further, 12 of the subcriteria can be expressed numerically. Thus, these variables were scaled

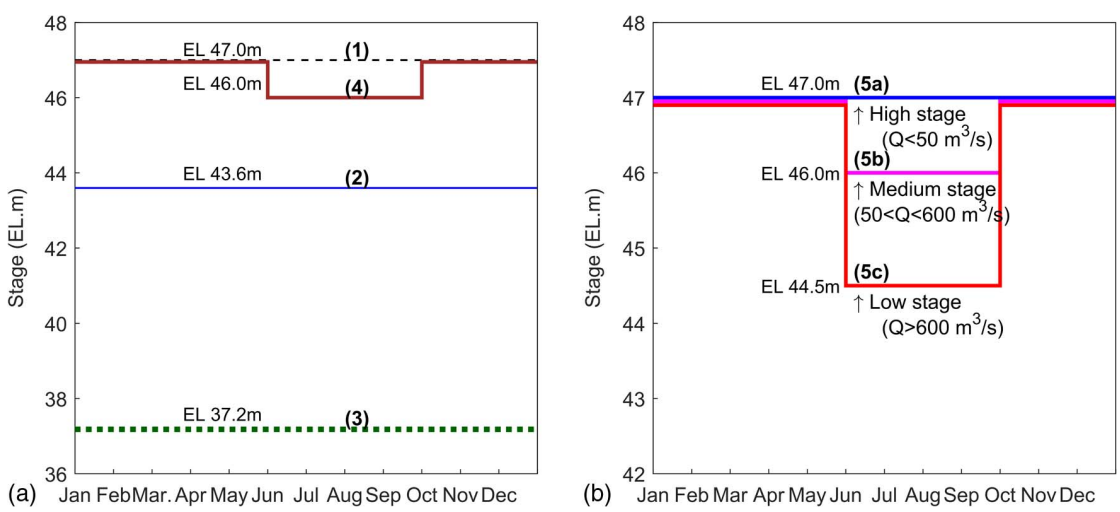


Fig. 9. (a) Alternatives 1–4; (b) Alternative 5 developed for MCDA analysis at Sangju Weir

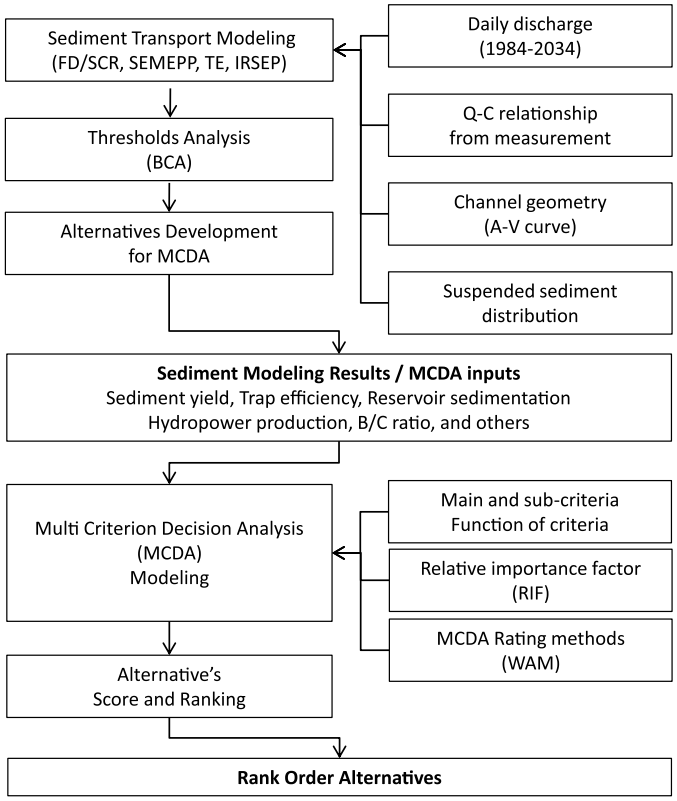


Fig. 10. Specific sediment transport and MCDA modeling procedure

between 1 and 5 based on their magnitude ranging from poor to excellent conditions. However, two of the variables, water supply stability and flood control and drainage effect, were not expressed numerically but using qualitative scores such as "Excellent, Very Good, Good, Poor, and Bad." This word scale enables us to evaluate the effects of water supply and flood prevention according to the volume of reservoir or available flood space. Then, this word scale is converted into corresponding numerical scores, as shown in Fig. 11.

Four different MCDA scaling methods were used to rank the five alternatives. These methods included two value-based methods, the weighted average method (WAM) and a modified form of the compromise programming (CP) method. The other two MCDA methods are outranking methods: (1) the preference ranking organization method for enrichment evaluations (PROMETHEE); and (2) a hybrid method combined WAM with PROMETHEE (PROMETHEE-WAM). A general description of value-based methods and outranking methods, including specific references, is available in Kim (2016). Table 5 shows an example of the WAM results, and Fig. 12(a) shows an example of the interface page display. Fig. 12(b) shows the results for all cases given MCDA input data and modeling results.

MCDA Results

According to the WAM results, Alternative 5 is the preferred alternative (Table 5 and Fig. 12). Also, the overall analysis yields the same result in which all MCDA methods and all the decision-maker groups were considered. This implies that Alternative 5 is the most appropriate alternative after integrating the interests of many stakeholders. In addition, as Table 6 shows, the amount of reservoir sedimentation of Alternative 5 is smaller than the current operation rule (Alternative 1), which supports the conclusion that at least Alternative 5 is better than Alternative 1 with respect to reservoir sedimentation issue. Accordingly, a seasonal stage control with the magnitude of inflow from Sangju Weir upstream is proposed for consideration as the new Sangju Weir operation rule.

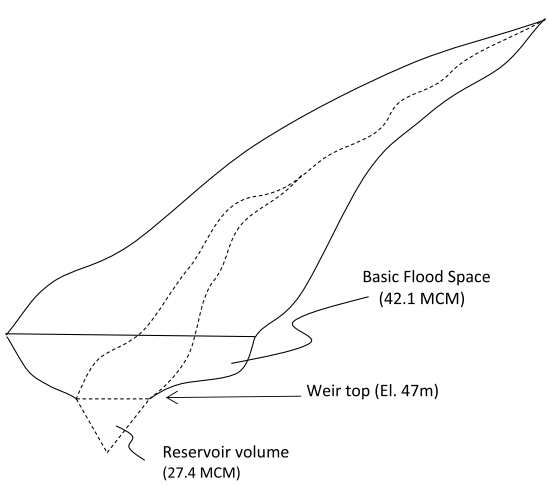
Summary and Conclusions

The conclusions of this research with respect to the sedimentation problems and reservoir operation rule are summarized as follows.

First, a new systematic analysis procedure based on the MCDA has been developed to mitigate reservoir sedimentation problems in the context of multiple conflicting constraints including hydropower, water supply, flood control, and the environment.

Second, the MCDA could be effectively tested to solve the complex Sangju Weir operation problems after considering conflicting demands for hydropower production, reservoir sedimentation, water supply sustainability, flood prevention, and the riverside environment.

Last, based on the daily (MCDA) modeling, the most favorable Sangju Weir operation rules to mitigate reservoir sedimentation were determined in Alternative 5, which considers seasonal



Word scale

Empty space range (m^3)			Word scale	Scaling	Remarks
	~	42,100,000	Poor	1	Basic
42,100,000	~	48,950,000	Fair	2	Basic_25% of Vres
48,950,000	~	55,800,000	Good	3	Basic_50% of Vres
55,800,000	~	62,650,000	Very Good	4	Basic_75% of Vres
62,650,000	~		Excellent	5	Over (Basic_75% of Vres)

Additional percentage (%)	Corresponding storage (m^3)
25%	6,850,000
50%	13,700,000
75%	20,550,000
100%	27,400,000

Note: Vres = volume of reservoir

Fig. 11. Word scale development for flood control and drainage effect criterion

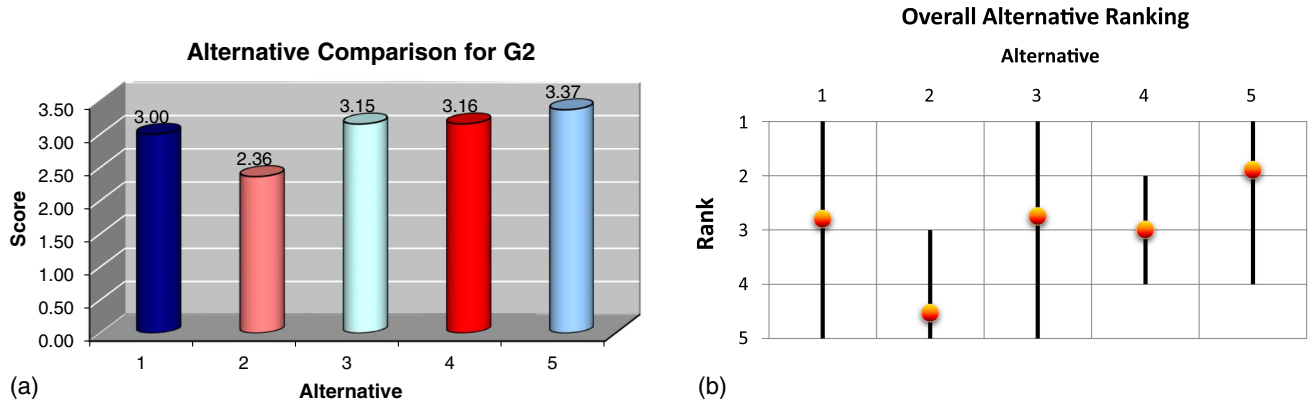


Fig. 12. (a) MCDA simulation result for decision-making group 2 (reservoir operator group with sedimentation emphasis) using WAM method with different RIF for subcriteria; (b) comprehensive MCDA result of overall alternative ranking

Table 6. Comparison of Reservoir Sedimentation and Hydropower Revenues according to Daily Simulations with Five Different Alternatives

Alternatives	Average water stage (EL. m)	Reservoir sedimentation (10^6 tons)	Reservoir sedimentation (10^6 m^3)	Dredging cost (10^6 USD)	Hydropower generation (GWh)	Hydropower benefit (10^6 USD)	B/C
1 (current)	47.0	5.89	3.68	23.22	406.86	52.89	2.28
2	43.6	5.73	3.58	22.58	171.42	22.28	0.99
3	37.2	4.14	2.59	16.32	0.00	0.00	0.00
4	46.7	5.83	3.65	23.00	389.23	50.60	2.20
5	46.3	5.77	3.61	22.76	355.95	46.27	2.03

Table 7. Proposed Sangju Weir Seasonal Stage Management and Operational Rules

Season	Inflow (m^3/s)	Stage (EL. m)
Nonflood season (October–May)	Any	47.0
Flood season (June–September)	Below 50	47.0
	Between 50 and 600	46.0
	Above 600	44.5

management of water stage according to the magnitude of the upstream inflow. Proposed operational rules are listed in Table 7.

Future applications may include more specific engineering constraints such as navigation and environmental considerations, including fish migration. The proposed methodology can also be applied to the other weirs of the Four River Restoration Project, as well as in other countries.

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Notation

The following symbols are used in this paper:

A = water surface area of reservoir (m^2);
A_{xs} = cross-sectional area (m^2);
$Avg.T_E$ = average trap efficiency (%);
Dep = deposition of sediment (tons, m^3);
dH = stage difference between upstream and downstream of weir (m);
$GVSR$ = good view station ratio (%);
H_a = effective head, stage difference between upstream and downstream of weir (m);
HP = amount of hydro-energy generation (GWh);
P_i = hydropower production (kW);
Q = flow discharge (m^3/s);
Q_a = discharge for hydropower generation (m^3/s);
Q_P = measured suspended sediment load (tons/day);
Q_s = sediment discharge (tons/day);
Q_T = total sediment load (tons/day);
T_E = trap efficiency (%);
Tur = turbidity (NTU);
V_f = empty space above the operational reservoir stage (m^3);
V_s = water storage volume above intake facility (m^3);
WS = reservoir operational stage (EL . m);
η = overall efficiency of hydropower plant; and
ω = sediment particle settling velocity (m/s).

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