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A Sensitivity Analysis Approach of Multi-Attribute Decision Making Technique to Rank Flood Mitigation Projects

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Abstract

The goal of this study is to evaluate and rank the effectiveness of the Korean governments' Four Major River Restoration Projects. A hydraulic simulation model and geographic information system tools are used to analyze the flood mitigation effects provided by these projects. In addition, the rankings of four major rivers are derived using two sensitivity analyses to weight values and performance measures for Multi-Attribute Decision Making (MADM) technique. As a result, the flood risk presented by the Nakdong River can be most effectively decreased when considering these weights, and levee freeboards are the most critical criterion in the effectiveness ranking. The Youngsan River's flow capacity criterion is also critical for this problem. This study will be helpful in the robust prioritization of various water resources plans.

Keywords: *four major rivers restoration projects, flood mitigation, Multi-Attribute Decision Making (MADM), sensitivity analysis for MADM*

1. Introduction

Integrated water resources management considers various purposes such as flood mitigation, water supply, navigation, water quality management and others. The decision making process is generally related to many information and data, feasible scenarios, effective models, implementable alternatives, objective decision makers, and conflicting stakeholders. Also, decision making often involves noncommensurable objectives, especially when environmental and social factors are considered. All these features call for Multi-Attribute Decision Making (MADM) method, which provides a framework to deal with noncommensurable aspects and to facilitate stakeholders' participation for collaborative decision making (Hyde *et al.*., 2005; Chung and Lee, 2009a; Chung and Lee, 2009b; Xu and Tung, 2009; Chung *et al.*, 2011a; Jun *et al.*, 2011; Jun *et al.,* 2012).

The Four Major Rivers Restoration Project ('Four Rivers Project' hereafter) of South Korea is the multi-purpose project on the Han River (HR), Nakdong River (NR), Geum River (GR), and Yeongsan River (YR) as shown in Fig. 1. This restoration project is expected to provide water security, flood control, and ecosystem vitality. This project was first announced as part of the 'Green New Deal' policy launched in January 2009. It was later included in the South Korean five-year national plan released by the government in July 2009 and its funding, a total of 14.70 billion USD (1 USD = 1,150 won), is reflected in the five-year plan total investment. This project has five key objectives: 1) securing abundant water resources against water scarcity; 2) implementing comprehensive flood control measures; 3) improving water quality and restoring ecosystems; 4) creation of multipurpose spaces for local residents; and 5) regional development centered on rivers.

Among these five factors, the effects of flood damage mitigation have become the most critical to non-governmental organizations because severe, heavy rainfall occurred in the central region of Korea in August 2011, leading to major economic damage and casualties. Because the Korean government allocated approximately 14.70 billion USD to restoring four major rivers, there has been a need to identify the safety of these rivers and decide which river requires the most extensive upgrades. This problem is closely similar to MADM problems.

In most MADM applications, the weights assigned to decision

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Table 1. Dredging Amounts and Expected Flood Level Drawdown

River	Section	Length (km)	Mean dredging depth (m)	Dredging volume (Mm^3)	Expected flood level drawdown (m)	Cost (US billion dollar)
HR	Paldang dam ~ Chungju dam	114.3	0.2	0.5	1.0~2.6	1.74
NR	Estuary barrage ~Andong dam	334.2	1.3	4.4	0.9~3.9	8.52
GR	Estuary barrage ~Daecheong dam	130.4	0.2	0.5	0.7~0.9	2.17
YR	Estuary barrage ~Damyang dam	111.6	0.6	0.3	0.4~1.5	2.26
Sum		690.5		5.7		14.70

criteria attempt to represent the genuine importance of the criteria in decision making. It is difficult to accurately represent the importance of criteria when they cannot be expressed in quantitative terms. In a situation such as that described above, the decision making process could be considerably improved by identifying the critical criteria and then reevaluating the weights of these criteria more accurately. The intuitive belief is that the criterion with the highest weight is the most critical (Winston, 2003), but this may not always be true, and in some instances the criterion with the lowest value may be the most critical.

The decision maker can make better decisions after determining how critical each criterion is. In other words, the decision maker must describe how sensitive the actual ranking of the alternatives is to changes in the current weights of the decision criteria. With this fact in mind, this study examines two closely related sensitivity analysis problems. In the first problem, the researchers determine how critical each criterion is by performing a sensitivity analysis on the criterion weights, which determines the smallest change in the current criterion weights and can alter the existing alternative ranking. The second problem relates to how critical the alternatives' various performance measures are in the ranking of the alternatives (Masuda, 1990; Traintaphyllou and Sanchez, 1997; Hyde *et al.*, 2005; Hyde and Maier, 2006; Ana *et al.*, 2009; Xu and Tung, 2009; Chung *et al.*, 2011b; Chung, 2012; Li *et al.*, 2012, Yang *et al.*, 2012). This study conducts these two sensitivity analyses for MADM.

This paper describes the two analyses. First, the appraisal of various flood mitigation effects by Four River Project for each river Four Rivers Projects are analyzed using a hydraulic simulation model and Geographic Information System (GIS). Second, based on the results of the simulation and analysis, an evaluation that ranks flood mitigation effects is derived using MADM methods. Two sensitivity analyses are conducted to reduce the uncertainty of the MADM.

2. Methodology

2.1 Hydraulic Analysis

The flood mitigation effects can be evaluated in terms of potential risk or actual damage reduction. The former can be realized through levee-raising work that leaves the flood water level as is or hydraulic conveyance capacity enlargement that brings down the flood water level. The Four Rivers Project falls under the latter description, and the flood water level is expected to be reduced by dredging the riverbeds. The actual damage can have a variety of causes ranging from sewer surcharge flood to structural defects. Therefore, the evaluation of the Four Rivers Project outcome must be accompanied by the estimation of flood water level reduction for various cases (Table 1).

This study conducts a comparison of the design flood variation with and without the implementation of each project. The flood water levels along the main river channels are computed using USACE's HEC-RAS (River Analysis System) package with the assumption of a 1-dimensional steady flow condition. The boundary conditions for the upstream-downstream ends and lateral inflows from tributaries are set to 200-yr river water levels. The only conditions that change according to the project are the cross sections at the computation chains. The simulation is implemented using 238 computational chains over the 95.2 km river channel in the HR, 683 chains over 320.9 km in the NR, 262 chains over 130.5 km in the GR, and 213 chains over the YR. The distance between adjacent chains is 400 m on average.

The major subjects of assessment in the field of flood mitigation include cross-sectional expansion by dredging, channel improvement, the effect of water level drawdown expected by these improvements, the basin's flood defense capability, and the reduction of inundation risk. The major subjects in the field of water use, on the other hand, include increases in water supply capability, improved flow regime, power generation, and the improvement of ground water refilling capability.

Temporal comparisons for the design flood water levels with the existing cross sections, construction cross sections, and final cross sections after project completion are also required. However, because the cross sections during project construction can change at any time according to the project plan, budget, and site conditions, it is difficult to obtain fixed cross sections until the project is completed. Therefore, this factor is excluded from the assessment. The design flood level just before the current project's commencement is adopted as a criterion for the existing cross section before the project starts. Each major river mainstream in the Four Rivers Project master plan is noted in terms of its design flood level on the 'Comprehensive Plan for River Maintenance' in the year 1992 for the HR, 1993 for the NR, 2003 for the GR, and 1998 for the YR. However, the cross sections were continuously changed even after the incorporation of a design flood water level. Therefore, the design flood level before this project is quoted from the calculation results from the flood mitigation facilities plan in use when the Four Rivers

Project's master plan and integrated flood mitigation plan had not yet been executed. The design flood level after the project must be estimated based on the final cross section after project completion, but because the project is currently under progress, the value calculated from the design flood level after the maintenance proposed in the Four Rivers Project's master plan considers the effect of facilities installation that decreases the water levels.

2.1.1 200-yr River Flood Water Level Variation

According to the 'Korean River Design Standards', national-class rivers must be designed for a 100- to 200-yr return periods. In principle, most main river courses in the four major rivers were designed for a 200-yr return, period except for a partial upstream section of the YR. 200-yr flood water levels with and without the project are simulated and compared in this study, and the cross sections provided in the master plan are used as the projected cross sections in the HEC-RAS model setup.

For the hydraulic computation of real-time flood operations, an unsteady flow condition using a time-varying hydrograph at the boundary chains are applied for realistic computation. However, although the computation under the steady flow condition is an overestimation, it tends to be applied to computations at the planning stage for the purpose of assuring conservative engineering safety.

2.1.2 Levee Freeboard

The riverine levees must provide a minimum freeboard above the projected water level of the design flood. The Korean River Design Standards specify minimum freeboard standards according to flood discharges (Table 2). Most sections in national-class river channels must secure a freeboard greater than 2 m. Before the Four Rivers Project was undertaken, a number of segments in the national-class major rivers did not meet the design requirement.

2.1.3 Flow Capacity

The hydraulic conveyance (= $\frac{A}{n}R^{2/3}$) under the design flood level is used to measure flow capacity before and after the project. Under a constant flow rate and bed slope, the hydraulic conveyance tends to be lowered by a decrease in water level and an increase in flow velocity due to the expansion of the cross section from dredging. In this study, the hydraulic conveyances are compared for the different cross sections (before and after the project) at the same design flood level so that the additional flood capacity provided by the project can be evaluated.

Table 2. Korean Design Standard of Freeboard Minimum Requirement by Design Flood Discharge

Design flood discharge (m^3/sec)	Freeboard minimum requirement (m)
less than 200	0.6
200 ~ 500	0.8
500 ~ 2,000	1.0
2,000 ~ 5,000	1.2
5,000 ~ 10,000	1.5
greater than 10,000	2.0

2.1.4 Bank Overflow

The risk of bank overflow is evaluated by computing the probability of flood water levels greater than riverbanks on the computational segments representing the right and left sides of the river. The flood water levels are computed for 80-, 100-, 150-, 200-, and 500-year return periods and the bank overflow probability is estimated from a log-fitted regression curve derived from the points of the five return periods, respectively. The coefficients (R^2) of determination show a relatively high degree of correlation that is greater than 0.95 at most segments.

2.1.5 Inundation Risk

The safety of protected lowland against flooding is measured with the inundation risk, which can be estimated through the extrapolation of the bank overflow probability. The extrapolation is performed using the Kriging scheme within the area of potential flooding, which is assumed to be inundated from a 500-year flood event.

In general, the national-class river sections are designed conservatively and are regarded safe enough against inundation. However, even a single occurrence of inundation can lead to enormous loss of life and property. The Yeoju region, located along the midstream of the HR, is an appropriate example. The region is a typical flood-prone area because it is the confluence point of the downstream Seom River and the Cheongmi Stream. The flood alert river water level is 9.5 m, but a level of 9.9 m was reached in July 2006, an event that could lead to the inundation of the city of Yeoju.

2.2 Sensitivity Analysis for MADM

2.2.1 Weighted Sum Method (WSM)

WSM is the most commonly used approach, especially in single dimensional problems. Each score (a_{ij}) in the matrix is replaced with the value (s_{ij}) according to the following formula:

$$a_{ij} = \frac{s_{ij} - s_{i-}}{s_{i+} - s_{i-}} \tag{1}$$

where s_{ij} is the impact of an scenario (j) with respect to a criterion (i); s_{i-} is the worst score of the criterion (i) with respect to all scenarios, i.e., the worst score in the row (i) of the payoff matrix; and s_{i+} is the 'best' score of the criterion (i) with respect to all scenarios, i.e., the best score in the row (i) of the payoff matrix. This way, all scores in the payoff matrix are scaled between the values of 0.0 and 1.0. An overall value index (P_j) for each scenario is estimated as follows:

$$P_j = \sum_{i=1}^{n} w_i a_{ij} \tag{2}$$

where w_i is the relative weight assigned to criterion (i) and n is the total number of criteria.

2.2.2 Determining the Most Critical Criterion

There must be three assumptions for the first sensitivity analysis to criteria of MADM methods as follows (Triantaphyllou and Sanchez, 1997). First, let $\delta_{k,i,j}$ (for $1 \le i < j \le m$ and $1 \le k \le n$) denote the minimum change in the current weight w_k of criterion c_k such that the ranking of alternatives A_i and A_j will be reversed. Next, $\delta^{l}_{k,i,j}$ is defined as follows:

$$\delta^{l}_{k,i,j} = \delta_{k,i,j} \times \frac{100}{w_k} \text{ for any } 1 \le i < j \le m \text{ and } 1 \le k \le n \tag{3}$$

The parameter $\delta^{l}_{k,i,j}$ expresses changes in relative terms.

Second, two criteria are defined as follows: 1) thee Percent-Top (PT) critical criterion is the criterion which corresponds to the smallest $|\delta^{l}_{k,1,j}|$ (for $1 \le j \le m$ and $1 \le k \le n$) value; and The Percent-Any (PA) critical criterion is the criterion which corresponds to the smallest $|\delta^{l}_{k,i,j}|$ (for $1 \le i < j \le m$ and $1 \le k \le n$) value.

Third, the criticality degree of criterion c_k denoted as D'_k in the smallest percent amount by which the current value of w_k must change, such that the existing ranking of the alternatives will change. This is illustrated in the following relation:

$$D'_k = \min_{1 \le i < j \le m} \{|\delta'^{l}_{k,i,j}|\}, \text{ for all } n \ge k \ge 1 \tag{4}$$

The sensitivity coefficient of criterion c_k denoted as sens(c_k), is the reciprocal of its criticality degree. This is illustrated in the following relation:

$$\text{sens}(c_k) = \frac{1}{D'_k}, \text{ for all } n \ge k \ge 1 \tag{5}$$

If the criticality degree is infeasible (i.e., impossible to change any alternative rank with any weight change), then the coefficient is set to be equal to zero.

For this case, it is assumed that a decision maker used the additive value function and wishes to alter the existing ranking of the two alternatives A_i and A_j by modifying only the current weight w_k of criterion c_k. At this point, the following relation is true: $P_i \ge P_j$. Triantaphyllou and Sanchez (1997) showed the minimum quantity $\delta_{k,i,j}$, needed to reverse the current ranking of the two alternatives A_i and A_j, should satisfy in the following relation:

$$\delta_{k,i,j} < \frac{(P_j - P_i)}{(a_{kj} - a_{ki})}, \text{ if } a_{ki} < a_{kj}, \text{ or } \delta_{k,i,j} > \frac{(P_j - P_i)}{(a_{kj} - a_{ki})}, \text{ if } a_{ki} < a_{kj} \tag{6}$$

Furthermore, the following condition Eq. (8) should also be satisfied for the new weight w^*_k Eq. (7) to be feasible:

$$w^*_k = w_k - \delta_{k,i,j} \tag{7}$$

$$\begin{aligned} &w^*_k \ge 0 && \text{or} \\ &w_k - \delta_{k,i,j} \ge 0 && \text{or} \\ &w_k \ge \delta_{k,i,j} \end{aligned} \tag{8}$$

In these developments it is not required to have $w^*_i \le 1$.

The quantity $\delta_{k,i,j}$ by which the current weight w_k of criterion c_k needs to be modified so that the ranking of the alternatives A_i and A_j will be reversed is given as follows:

$$\delta^{l}_{k,i,j} < \frac{(P_j - P_i)}{(a_{kj} - a_{ki})} \times \frac{100}{w_k}, \text{ if } a_{ki} > a_{kj}, \text{ or}$$

$$\delta^{l}_{k,i,j} > \frac{(P_j - P_i)}{(a_{kj} - a_{ki})} \times \frac{100}{w_k}, \text{ if } a_{ki} < a_{kj} \tag{9}$$

Furthermore, the following condition should also be satisfied for the value of $\delta^{l}_{k,i,j}$ to be feasible:

$$\frac{(P_j - P_i)}{(a_{kj} - a_{ki})} \le w_k \tag{10}$$

2.2.3 Determining the Most Critical Measure of Performance

There must be two assumptions for the second sensitivity analysis to the measure of performance (Triantaphyllou and Sanchez, 1997) as follows.

First, Let $\tau_{i,j,k}$ denote the threshold value of a_{ij}which is the minimum change which has to occur in the current value of a_{ij} such that the current ranking between alternatives A_i and A_j will change. Since there are m alternatives, each a_{ij}performance measure is associated with a total of (m-1) such threshold values. In a similar way as earlier regarding the definition of the $\delta^{l}_{k,i,j}$ values, one can also consider threshold values expressed in relative terms. We denote these relative term threshold values as $\tau^{l}_{k,i,j}$. That is:

$$\tau^{l}_{k,i,j} = \tau_{k,i,j} \times \frac{100}{a_{ij}} \text{ for any } 1 \le i, j \le m \text{ and } 1 \le k \le n \tag{11}$$

Second, the criticality degree of alternative A_i in terms of criterion C_k, denoted as $\Delta^{l}_{i,j}$ is the smallest amount (%) by which the current value of a_{ij} must change, such that the existing ranking of alternative A_i will change. That is, the following relation is true:

$$\Delta^{l}_{k} = \min_{i \ne j} |\tau^{l}_{k,i,j}| \tag{12}$$

Alternative A_L is the most critical alternative if it is associated with the smallest criticality degree. That is, if and only if the following relation is true:

$$\Delta^{l}_{L,j} = \min_{m \ge i \ge 1} \left\{ \min_{n \ge j \ge 1} |\tau^{l}_{k,i,j}| \right\} \tag{13}$$

The sensitivity coefficient of alternative A_i in terms of criterion C_k, denoted as sens(a_{ij}), is the reciprocal of its criticality degree. That is, the following condition is true:

$$\text{sens}(a_{ij}) = \frac{1}{\Delta^{l}_{i,j}} \tag{14}$$

If the criticality degree is infeasible, then the sensitivity coefficient is set to be equal to zero.

When the WSM is used, the threshold value $\tau^{l}_{i,j,k}$ (%) by which the performance measure of alternative A_i in terms of criterion C_k, denoted as a_{ij}, needs to be modified so that the ranking of the alternative A_i and A_j will be reversed, is given as follows:

$$\tau^{l}_{k,i,j} < \frac{(P_i - P_j)}{w_j} \times \frac{100}{a_{ij}}, \text{ if } i < k\text{, or,}$$

$$\tau^{l}_{k,i,j} > \frac{(P_i - P_j)}{w_j} \times \frac{100}{a_{ij}} \text{ if } i > k \qquad (15)$$

Furthermore, the following condition should also be satisfied for the threshold value to be feasible:

$$\tau^{l}_{i,j,k} \le 100 \qquad (16)$$

3. Description of the Study Basins

This study has four study basins: HR, NR, GR, and YR basins as shown in Fig. 1. HR consists of two major tributaries, the Namhan River and Bukhan River, with numerous subsidiary branches. HR is 5,417 km long and drains an area of 26,018 km^2, or 27% of South Korea. Namhan River and Bukhan River join at the Paldang dam to form the main channel of HR. NR located in the southeastern region of the Korean peninsula. NR serves as an important water resource for the south eastern area. The river drains an area of 23,817 km^2 and length of the main stream is over 525 km. The river flow is impounded in the downstream area because of the construction of a river barrage at the estuary to protect fresh water from saltwater intrusion. GR basin is the third largest basin in South Korea, where the watershed area and the total length of the river are 9,843.2 km^2 and 395.9 km, respectively. The GR basin is located in the middle-east region of South Korea. Two multi-purpose reservoirs, the Daecheong and the Yongdam dams, were built on the main stream of the GR. The majority of the water demand in this basin is from the agricultural area. YR is located at the southwest part of Korea, stretching for 136 km, with a basin area of 3,468 km^2. The estuarine dam built at the mouth of YR has not only prevented normal tidal flows, but also stopped the accumulated contaminated water from discharging into the Yellow Sea. Those watersheds of the four rivers are affected by large amounts of precipitation in the monsoon season between June and September with several typhoon events. The mean annual precipitation is about 1,300 mm and more than 60% of the total rainfall occurs during the monsoon season. The rivers, which are four major river systems in South Korea, play an important role as a water resource for agriculture, industry and municipalities in Korea.

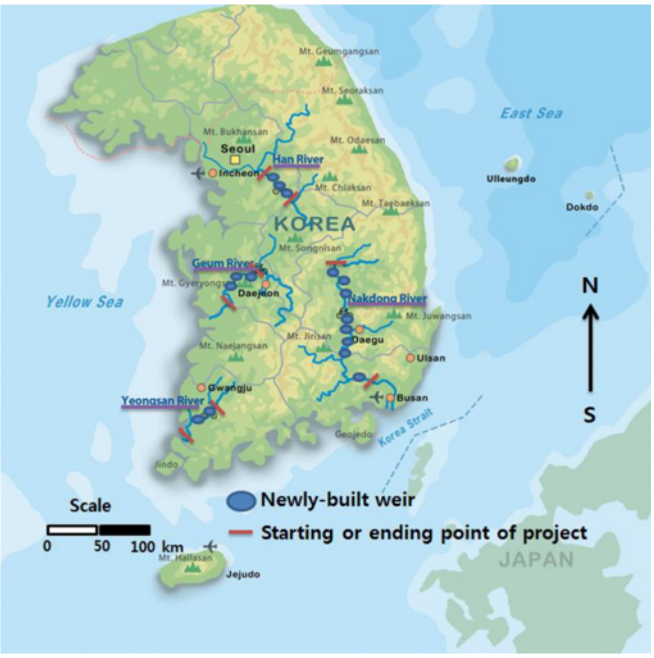


Fig. 1 Map of Four Major Rivers and New Multipurpose Weirs in Korea

4. Results

4.1 Hydraulic Analyses

4.1.1 200-yr Flood River Stage Variation

Due to the expanded cross section caused by dredging, the flood water level is expected to decrease. The computed decrease in the 200-yr flood water level, assuming steady flow analysis, is 0.71 m, 1.65 m, 0.52 m, and 0.38 m on average for the HR, NR, GR, and YR, respectively. Most reduction occurs between the Yeoju and Gangchon Weirs (Fig. 1).

The NR shows the greatest reduction in flood water levels due to it receiving the greatest amount of dredging. 51.4% of the river sections show 1~2 m of reduction. The sections around the

Table 3. Flood Water Level Drawdown due to Four River Restoration Projects

HR			NR		
Flood water level drawdown	# of section	Ratio (%)	Flood water level drawdown	# of section	Ratio (%)
0 ~ 0.4 m	93	35.2	0 ~ 1 m	126	18.1
0.4 ~ 0.8 m	62	23.5	1 ~ 2 m	358	51.4
0.8 ~ 1.2 m	67	25.4	2 ~ 3 m	199	28.5
1.2 ~ 1.6 m	25	9.5	3 ~ 4 m	13	1.9
1.6 ~ 2.0 m	17	6.4	4 ~ 5 m	1	0.1
sum	264	100.0	sum	697	100.0
GR			YR		
Flood water level drawdown	# of section	Ratio (%)	Flood water level drawdown	# of section	Ratio (%)
0 ~ 0.2 m	54	20.5	0 ~ 0.2 m	90	31.5
0.2 ~ 0.4 m	36	13.7	0.2 ~ 0.4 m	114	39.9
0.4 ~ 0.6 m	38	14.5	0.4 ~ 0.6 m	19	6.6
0.6 ~ 0.8 m	98	37.3	0.6 ~ 0.8 m	10	3.5
0.8 ~ 1.0 m	37	14.0	0.8 ~ 1.0 m	53	18.5
sum	263	100	sum	286	100

Nakdan Weir show the greatest reduction, one of which decreases by more than 4 m.

The estimated flood water level reductions in the GR and YR are relatively smaller than in the HR and NR. The amount of dredging (45.6 million m^3) in the GR is similar to that (50.3 million m^3) in the HR, but the flood water level reduction is greater in the HR because 70% of the dredging in the HR was implemented in the midstream sections between the Ipo and Gangchon Weirs, whereas the 55% of dredging in the GR occurred between the estuary barrage and Buyeo Weir in the downstream sections. Individual flood water level drawdowns due to restoration projects are summarized in Table 3.

4.1.2 Levee Freeboard

Before the Four Rivers Project was undertaken, many sections of four national-class rivers did not reach the freeboard height required by the National River Design Standards. While 89.6% of the HR already satisfied the freeboard requirements, indicating relatively high flood control capacity, only 66.9% of the NR was deemed acceptable at the start of the project. However, this percentage has now risen to 91.8%, representing a dramatic reduction in potential flood damage. Thus, more than 90% of the four major rivers are now included in the safety area as shown in Table 4.

4.1.3 Flowing Capacity

Before the Four Rivers Project, many sections of the national class rivers did not reach the freeboard height required by the National River Design Standards. Hydraulic conveyances of NR, and YR due to restoration projects increased largely while HR showed no critical variation. The reason is why 89.6% of the HR did satisfy the freeboard requirements before the project, indicating a relatively high flood control capability.

4.1.4 Bank Overflowing

Before the Four Rivers Project, the return periods for many sections of four national-class rivers did not exceed 200 years. While 75.4% of the HR already satisfied the 200-yr return period before the project, 94.7% of the cross sections eventually satisfied the 200-yr return period after the project. NR, GR and YR showed similar effect. The specific analyses results are shown in Table 6. The risk of bank overflow, which is evaluated by computing the probability of flood water levels greater than the river banks in the computational segments on the right and left sides of the river, shows that the Four Rivers Project could reduce flood vulnerability.

Table 4. Success/Failure for Freeboard Requirement with and without the Project

Success/ Failure	HR		NR		GR		YR	
	Without project	With project	Without project	With project	Without project	With project	Without project	With project
Success	252 (95.5%)	264 (100.0%)	466 (66.9%)	640 (91.8%)	178 (67.7%)	240 (91.3%)	273 (95.5%)	286 (100.0%)
Failure	12 (4.5%)	0 (0.0%)	231 (33.1%)	57 (8.2%)	85 (32.3%)	23 (8.7%)	13 (4.5%)	0 (0.0%)
Sum	264	264	697	697	263	263	286	286

unit : # of sections (ratio, %)

Table 5. Hydraulic Conveyance before and after the Project

Hydraulic conveyance (Mm^3/sec)	HR		NR		GR		YR	
	Without project	With project	Without project	With project	Without project	With project	Without project	With project
~ 1.0	126 (47.7%)	128 (48.5%)	259 (37.2%)	216 (31.6%)	23 (8.7%)	25 (9.5%)	123 (43.0%)	109 (38.1%)
1.0 ~ 1.5	93 (35.2%)	96 (36.4%))	78 (11.2%)	113 (16.2%)	60 (22.8%))	49 (18.6%)	17 (5.9%)	29 (10.1%)
1.5 ~ 2.0	29 (11.0%)	25 (9.5%)	178 (25.5%)	181 (26.0%)	107 (40.7%)	115 (43.7%)	48 (16.8%)	41 (14.3%)
2.0 ~ 2.5	11 (4.2%)	11 (4.2%)	101 (14.5%)	112 (16.1%)	63 (24.0%)	65 (24.7%)	54 (18.9%)	63 (22.0%)
2.5 ~ 3.0	3 (1.1%)	2 (0.8%)	49 (7.0%)	54 (7.7%)	6 (2.3%)	5 (1.9%)	12 (4.2%)	12 (4.2%)
3.0 ~ 3.5	1 (0.4%)	1 (0.4%)	16 (2.3%)	13 (1.9%)	4 (1.5%)	4 (1.5%)	32 (11.2%)	32 (11.2%)
3.5 ~ 4.0	1 (0.4%)	1 (0.4%)	7 (1.0%)	3 (0.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
4.0 ~	0 (0.0%)	0 (0.0%)	9 (1.3%)	5 (0.7%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Sum	264	264	697	697	263	263	286	286

unit : # of sections (ratio, %)

Table 6. Frequency of the Bank Inundation with and without the Project

Frequency (return period)	HR		NR		GR		YR	
	Without project	With project	Without project	With project	Without project	With project	Without project	With project
~ 50yr	12 (4.5%)	1 (0.4%)	6 (0.9%)	0 (0.0%)	21 (8.0%)	12 (4.6%)	48 (16.8%)	2 (0.7%)
50 ~ 80	19 (7.2%)	2 (0.8%)	13 (1.9%)	0 (0.0%)	28 (10.6%)	8 (3.0%)	23 (8.0%)	4 (1.4%)
80 ~ 100	5 (1.9%)	0 (0.0%)	12 (1.7%)	0 (0.0%)	11 (4.2%)	3 (1.1%)	11 (3.8%)	1 (0.3%)
100 ~ 200	29 (11.0%)	11 (4.1%)	91 (13.0%)	0 (0.0%)	67 (25.5%)	55 (20.9%)	23 (8.0%)	57 (19.9%)
200 ~	199 (75.4%)	250 (94.7%)	575 (82.5%)	697 (100.0%)	136 (51.7%)	185 (70.4%)	181 (63.3%)	222 (77.6%)
Sum	264	264	697	697	263	263	286	286

unit : # of sections (ratio, %)

4.1.5 Inundation Risk

The probability of bank overflowing is extrapolated into the potential flood area as shown in Fig. 2. Because of the region's mountainous topographic features, the HR basin has a relatively smaller potential flood area. The improvement of inundation risk in the HR is less dramatic, which indicates that the HR was relatively less vulnerable to inundation before the project. The NR shows the most significant improvement to its inundation risk indicators, which is most remarkable in the sections downstream of the fifth weir from the upstream. A large wetland is located downstream of the NR, around the confluence of a first order tributary, and has been registered in the Ramsar Convention for protection. The area designated for ecosystem and view preservation is approximately 8.54 km^2 (854 ha), which is the area covered by water in the wetland because summer monsoon flooding covers approximately 2,314 km^2. However, the flood mitigation effects are most significant in the NR even when flooding in the wetland is disregarded.

4.2 Decision Matrix and Ranking of Four Major Rivers

We consider an MADM problem defined for the four alternatives A_1 (HR), A_2 (NR), A_3 (GR), and A_4 (YR) and the five criteria C_1 (200-yr flood river stage variation), C_2 (levee freeboard), C_3 (flow capacity), C_4 (bank overflow), and C_5 (inundation risk). Each representative performance value for the five criteria is derived by averaging the increase in these criteria from the hydraulic simulation and GIS analyses.

The decision matrix is derived using a normalization equation Eq. (1), as shown in Table 7. For the WSM application, the weighting values are assumed to be $C_1 = C_2 = C_3 = C_4 = C_5 = 0.2$ because their exact quantification is unclear. As a result, the preferences and ranking are calculated as shown in Table 7, revealing a preference ranking of $P_2 > P_3 > P_4 > P_1$ and a preferred alternative A_2.

4.3 Sensitivity Analysis to Criteria Weights

It can now be observed that all criteria appear to be equally important according to the five criterion weights. A minimum change $\delta_{2,3,4}$ is needed to alter the current weight, w_2, so that the current ranking of the two alternatives A_3 and A_4 will be reversed. Using Eq. (6), $\delta_{k,i,j}$ can be calculated as shown in Table 8. Using Eq. (7), the modified weights needed to reverse the ranking of two alternatives are shown in Table 9. The quantity 0.056 satisfies Eq. (6) because it is less then $\dot{w}_2$. Thus, the modified weight w_2^* of the second criterion is equal to 0.144. If the condition in Eq. (8) is not satisfied from this process, the value is 'NF', which means non-feasible. The values in Table 9 at the same location also become designated as "NF".

Using the results from Table 8 and Eq. (3), the changes in the relative terms can be derived as shown in Table 10. Note that the negative changes in Table 10 indicate an increase, while the positive changes indicate a decrease. The boldfaced numbers in both tables indicate minimum critical changes.

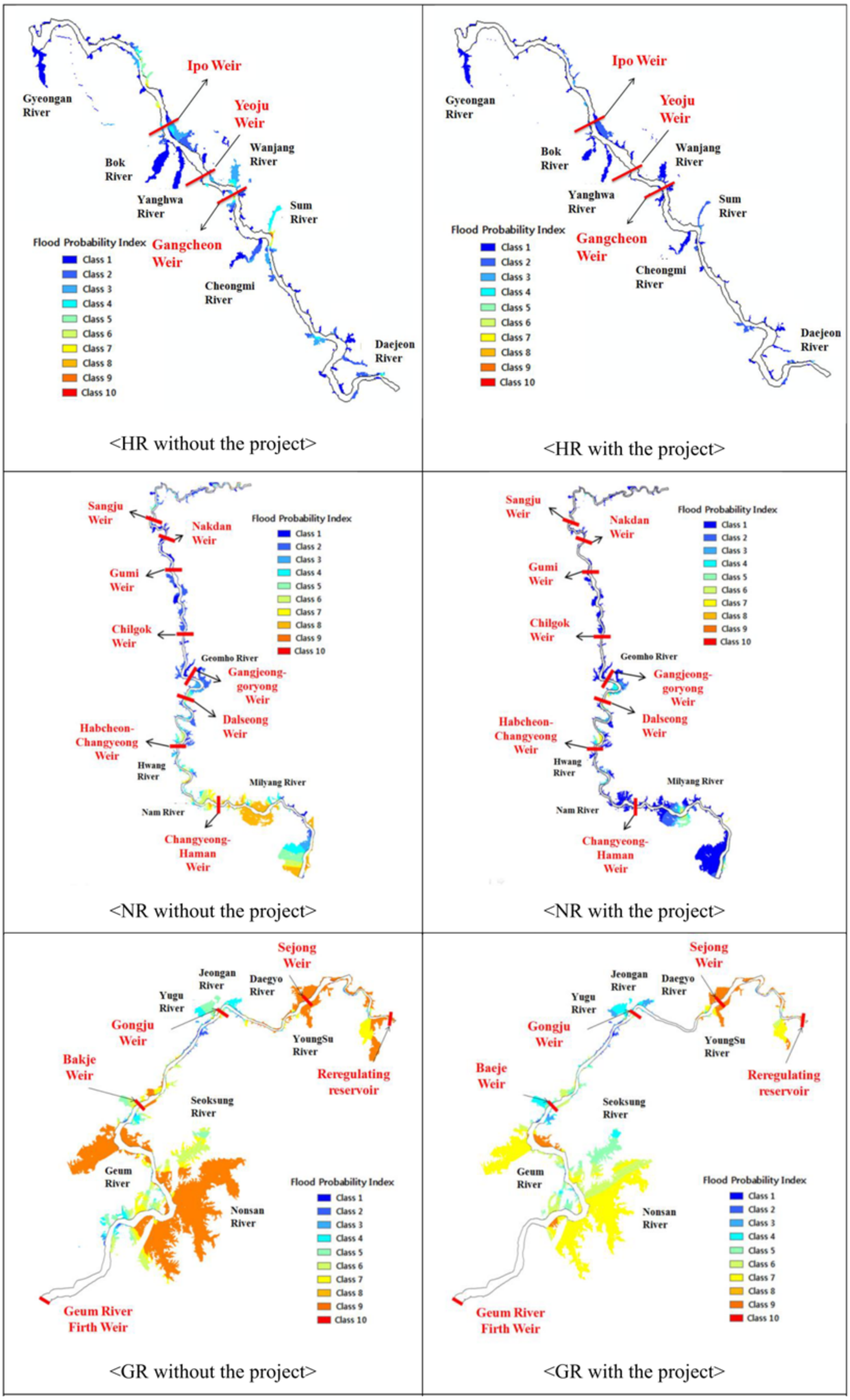
The Percent-Top (PT) critical criterion can be found by looking for the smallest relative value of all the rows related to alternative A_i (i.e., the best alternative) in Table 4. The smallest such percentage (-48.9%) corresponds to criterion C_5 when the pair of alternatives A_1 and A_4 are considered. For criterion C_5, an increase in its current weighting by 48.9% makes A_4 the third preferred alternative, while A_4 is no longer the third alternative.

The Percent-Any (PA) critical criterion can be found by looking for the smallest relative value in Table 10. This smallest value is $\delta_{2,3,4} = 28.1\%$ and corresponds to criterion C_2. Therefore, the PA critical criterion is C_2.

When assumption 3 is used, it follows from Table 10 that the criticality degrees of the five criteria should be calculated using Eq. (5), as shown in Table 11. Therefore, the sensitivity coefficients of the five decision criteria are calculated using Eq. (6), as shown in Table 11. As a result, the sensitivity ranking is $C_2 > C_4 > C_5 > C_3 > C_1$ and C_2, C_4 and C_5 are very critical criteria.

4.4 Sensitivity Analysis to Performance Measure

Using Eq. (15) and Table 7, the corresponding $\tau_{i,j,k}$ threshold values are listed in Table 12. The boldfaced entries in Table 12

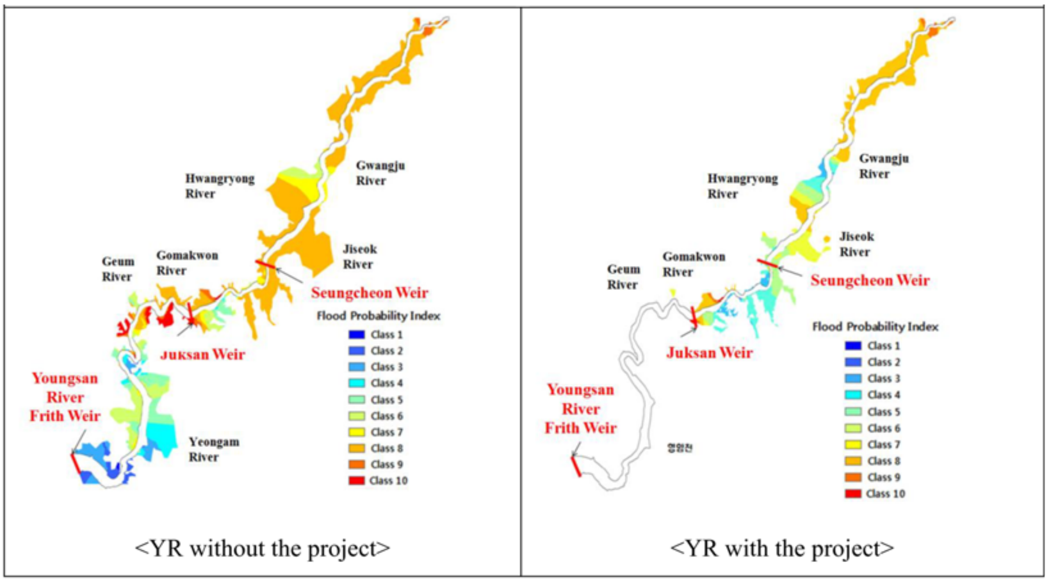


<HR without the project> <HR with the project>

<NR without the project> <NR with the project>

<GR without the project> <GR with the project>

Fig. 2. Maps of Inundation Risk within Potential Flood Area of Four River Restoration Projects



<YR without the project> <YR with the project>

Fig. 2. (Continued)

Table 7. Decision Matrix and Current Final Preferences and Rankings

Alternative	C_1	C_2	C_3	C_4	C_5	Preference	Ranking
Weights	0.2	0.2	0.2	0.2	0.2		
A1	0.382	0.180	0.681	0.183	0.787	0.4425	4
A2	1.000	0.683	0.562	1.000	1.000	0.8490	1
A3	0.315	0.835	0.780	0.412	0.205	0.5092	2
A4	0.218	0.233	0.917	0.557	0.452	0.4754	3

Table 8. All Possible $\delta_{k,i,j}$ Values (Absolute Change in Criteria Weights)

Alt A_i	Alt A_j	C_1	C_2	C_3	C_4	C_5
A1	A2	0.658	0.808	-3.438	0.498	1.912
A1	A3	-1.001	0.102	0.675	0.292	-0.114
A1	A4	-0.201	0.615	0.139	0.088	-0.098
A2	A3	0.496	-2.232	-1.565	0.577	0.427
A2	A4	0.478	0.831	-1.053	0.844	0.681
A3	A4	0.349	0.056	-0.246	-0.233	-0.137

Table 9. All Possible $w^{*}_{k,i,j}$ Values

Alt A_i	Alt Aj	C_1	C_2	C_3	C_4	C_5
A1	A2	NF	NF	NF	NF	NF
A1	A3	NF	0.098	NF	NF	0.314
A1	A4	0.401	NF	0.061	**0.1122**	0.298
A2	A3	NF	NF	NF	NF	NF
A2	A4	NF	NF	NF	NF	NF
A3	A4	NF	0.144	0.446	0.433	0.337

Table 10. All Possible Values $\delta'_{k,i,j}$ (Percent Change in Criteria Weights)

Alt A_i	Alt A_j	C1	C2	C3	C4	C5
A1	A2	NF	NF	NF	NF	NF
A1	A3	NF	50.9%	NF	NF	-57.2%
A1	A4	-100.4%	NF	69.5%	43.9%	-48.9%
A2	A3	NF	NF	NF	NF	NF
A2	A4	NF	NF	NF	NF	NF
A3	A4	NF	28.1%	-123.1%	-116.4%	-68.6%

Table 11. Criticality Degrees and Sensitivity Coefficients of Five Criteria

Category	C1	C2	C3	C4	C5
Criticality	100.4%	28.1%	69.5%	43.9%	48.9%
Sensitivity	0.996	3.556	1.440	2.277	2.045

Table 12. Threshold Values $\tau^{l}_{k,i,j}$ in Relative Terms

Alt A_i	Alt A_j	C1	C2	C3	C4	C5
A1	A2	-532.3%	-1131.8%	-298.6%	-1110.2%	-258.1%
	A3	-87.4%	-185.7%	-49.0%	-182.2%	-42.4%
	A4	**-43.0%**	**-91.4%**	**-24.1%**	**-89.7%**	**-20.9%**
A2	A1	NF	NF	NF	NF	NF
	A3	NF	NF	95.6%	NF	NF
	A4	NF	NF	NF	NF	NF
A3	A1	NF	39.9%	42.8%	81.0%	NF
	A2	-539.1%	-203.5%	-218.0%	-412.8%	-829.4%
	A4	**53.7%**	**20.3%**	**21.7%**	**41.1%**	**82.7%**
A4	A1	**75.3%**	**70.5%**	**17.9%**	**29.5%**	**36.4%**
	A2	-856.3%	-802.0%	-203.7%	-335.4%	-413.8%
	A3	-77.6%	-72.7%	-18.5%	-30.4%	-37.5%

correspond to the criticality degree $\Delta^{l}_{i,j}$, which is the smallest entry per column in each row section, as given in Eq. (12). $\tau_{1,1,4}$ = -43.0% means that the measure of performance $a_{1,1}$ must be increased by 43.0%, from its current value of 0.382 to (1+0.430) × 0.382, for alternative A_1 to become more preferred than alternative A_4. A similar interpretation holds for the rest of the entries. Note that some of the entries in Table 6 are marked as NF because they correspond to non-feasible values that do not satisfy Eq. (16).

Table 13. Criticality Degrees $\Delta^{l}_{i,j}$ for Each a_{ij} Performance Measure

Alt	C1	C2	C3	C4	C5
A1	43.0%	91.4%	24.1%	89.7%	20.9%
A2	NF	NF	42.8%	NF	NF
A3	539.1%	20.3%	21.7%	412.8%	829.4%
A4	75.3%	70.5%	**17.9%**	29.5%	36.4%

Table 14. Sensitivity Coefficients sens($a_{i,j}$) for Each a_{ij} Performance Measure

Alt	C1	C2	C3	C4	C5
A1	2.325	1.094	4.145	1.115	4.795
A2	NF	NF	2.337	NF	NF
A3	0.185	4.932	4.604	0.242	0.121
A4	1.329	1.419	**5.585**	3.392	2.750

Note that the entries in Table 12 are greater than 100 only when the entry's sign is negative, and negative changes correspond to increases in reality. It is acceptable for a rating to become greater than 100, and the numbers in the criterion weights are renormalized to add up to one. The numbers for the performance measures can also be renormalized.

Using Eq. (12) and (14), the criticality degrees and sensitivity coefficients of the five criteria are derived as shown in Tables 13 and 14. It follows from Table 13 that the most critical alternative is A_4 because this alternative corresponds to the minimum criticality degree among all the values. Table 14 presents the various sensitivity coefficients. Note that if any entry of the criticality degree is infeasible, then the corresponding sensitivity coefficient is defined as equal to zero. Based on the results, alternative A_2 is the most preferred alternative, except in the case where a 95.6% decrease occurs for performance measure $a_{2,3}$. However, this case is uncommon, so it can be concluded that A_2 is the most preferred alternative. In other cases, the relative priorities among A_3, A_4 and A_1 are very sensitive. A_3 can be downgraded to third place when the performance measures $a_{3,2}$ and $a_{3,3}$ are reduced to 20.3% and 21.7%, respectively, or $a_{4,3}$ is increased to 18.5%. A_4 can be downgraded to last place when the performance measures $a_{4,3}$ and $a_{4,4}$ are reduced to 17.9% and 29.5%, respectively, or $a_{1,3}$ and $a_{1,5}$ are increased to 24.1% and 20.9%, respectively. Therefore, the sensitivity ranking is $a_4 > a_3 > a_1 \gg a_2$.

5. Conclusions

This study covers three topics: 1) the hydraulic analysis of flood mitigation effects using a hydraulic simulation model and GIS, 2) the prioritization of four major rivers based on the effectiveness results from this analysis, and 3) two sensitivity analyses using MADM. We can make the following conclusions from this study.

- A hydraulic simulation model and GIS can be used together to analyze various aspects of flood mitigation effects.
- The NR shows the highest potential for the greatest flood mitigation when using two sensitivity analyses with MADM techniques that consider all feasible weights.
- The ranking of the criteria's sensitivity is levee freeboard (C_2) > bank overflow (C_4) > inundation risk (C_5) > flow capacity (C_3) > 200-yr flood river stage variation (C_1). C_2, C_4 and C_5 are particularly critical criteria.
- The performance measures a_4 to C_3 are the most critical factors to alternative A_3.
- The sensitivity ranking of the alternative performance measures is YR (A_4) > GR (A_3) > HR (A_1) >> NR (A_2).

This integrated use of hydraulic modeling and GIS can be a guideline for comparing the effectiveness of flood measures before and after flood mitigation projects. The use of MADM with two sensitivity analyses could be very helpful in ranking water resource projects and developing spatial rankings based on various vulnerabilities. The results of this study will also be helpful in determining weighting values and analyzing performance measures in this field.

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