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Decision of the Water Shortage Mitigation Policy Using Multi-criteria Decision Analysis

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Abstract

Many regions has been facing formidable freshwater management and planning challenges. Concerns about limited water allocations, conservation of environmental and water qualities and policies for sustainable water use have been increased because rising water demand would cause water shortage in the near future. Therefore, it is necessary to look into possible alternative water resources management plans to mitigate the potential water shortage. However, it is not straightforward to predict and analyze the various situations likely to be occurred in the future. Also, finding an optimal solution among many alternatives to mitigate the water shortage is a complex task. In this study, a methodology of predicting and analyzing the water resources situations in the future using the K-WEAP (Korea Water Evaluation and Planning system) is presented and an optimal alternative is determined using the MCDA (Multi-Criteria Decision Analysis) that takes into account the economic, environmental, and social sectors. The proposed methodology is applied to the Nakdong River basin in South Korea to calculate water budget and possible water shortage. An optimal water shortage mitigation policy for the study basin is also suggested to help decision maker develop long-term water resources management strategies.

Keywords: *sustainable water supply, water shortage mitigation, MCDA, K-WEAP, Nakdong River basin*

1. Introduction

There exist worldwide growing concerns worldwide on water shortage, deterioration of water quality and ecosystem that are currently faced and expected in the future. In the case of Korea, water shortage of about 0.8 billion m^3 is predicted in the future, and also the improvement of river water quality and ecosystem has not been keeping up with the public expectation [Korean Ministry of Construction and Transportation (KMOCT), 2006]. Therefore, Korea has been becoming more and more interested in the efficient allocation of limited water resources, water quality improvement, and sustainable water use policy. As integrated water resources planning and management is gaining popularity as way to tackle these problems, there is a shifting from the conventional thought of considering only the quantity side to the integrated approach that takes into account social, economic, and environmental sectors in water resources planning and management. However, when there are many sectors to be considered, the decision to choose the best policy of water resources planning and management becomes difficult.

To solve this problem, many researchers recently have analyzed an optimal alternative using the MCDA (Multi-Criteria Decision Analysis). Roy *et al*. (1992) presented a multi-criteria methodology for decision aid at the stage of programming a water supply system for rural area and Goicoechea *et al*. (1992) evaluated the multiple criteria decision models (MATS-PC, EXPERT CHOICE, ARIADNE, and ELECTRE) to water resources planning. Joubert *et al*. (2000, 2003) analyzed the case study in Sand River and City of Cape Town based on MCDA and suggested the method using various scenarios. Ridgley (1993) suggested the multi-criteria approach method to allocation water during drought and Flug *et al*. (2000) applied the MCDA to Dam operation. In addition to these studies, many researchers have been studying about MCDA in various fields such as sustainability, resolving water policy disputes, wastewater management, groundwater, and desalination (Yasin *et al*., 2002; Thiessen *et al*., 1992; Tecle *et al*., 1988; Duckstein *et al*., 1994; Ahmoud *et al*., 2002).

In Korea, Choi *et al*. (2000) compared the priority of 3 scenarios for policies about water works privatization through MCDA and recommended the analysis method. Park (2002) suggested the evaluation perspective of stream weight using AHP (Analytic Hierarchy Process), Lee *et al*. (2002) suggested the decision making method for priority of water allocation during drought using AHP and presented that AHP is a reasonable method about

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decision making for complex water resources systems.

To make the MCDA for water resources management and planning, several scenarios of water resource system in the future has to be estimated. So, many models were developed for simulating current water balances and evaluating water resources planning and management strategies. Raskin *et al*. (1992) simulated the water supply and demand in the Aral Sea region based on WEAP (Water Evaluation and Planning System). In addition this study, many researchers have been studying the estimation of water resources systems based on several models.

In this study, to estimate the water resources system in the future, K-WEAP (Korea Water Evaluation and Planning System) was used as simulation model to assist the decision process in comparing and ranking different alternatives, where MCDA was used as a methodology. Finally, this paper suggested the tool for the evaluation and setup of policy on water resources, water quality, and environment at watershed and the methodology for the evaluation of alternatives for water resources development and management.

2. Korea Water Evaluation and Planning System (K-WEAP)

K-WEAP is an integrated water resources planning system and was co-developed by KICT (Korea Institute of Construction Technology) and SEI-B (Stockholm Environment Institute-Boston Center) in Tellus Institute in order to improve original WEAP system to better suit the Korean circumstances. The original WEAP, which is the foundation of K-WEAP, was first developed by SEI-US, and has been continuously updated for 10 years. K-WEAP is a customized Korean version with the improvement in WEAP's water balance analysis module and evaluation methodology. Furthermore, river water quality simulation module has been improved in order to couple water quality with water quantity in the water budget analysis.

2.1 Water Allocation Simulation using LP

In the K-WEAP model, Linear Program (LP) is used in order to maximize the coverage against demand sites and guarantee the same coverage against the same priority level, which is repeatedly applied to the same supply priority and demand preference depending on the priority level in consideration with water demand/supply and other constraints (SEI-B, 2001). During such process to repeat the LP, water is allocated to the demand sites under the principle of mass balance. However, it differs in nature from the optimization that aims at minimum cost or maximum profit, but can be defined as the simulation process properly allocating the water resources according to the given allocation order. In K-WEAP, the objective function is same as the Eq. (1) and the constraints are as shown in the Eqs. (2), (3), (4), and (5).

- Objective Function : Maximize (Coverage(final)) (1)
- Constraints

$$\text{Node : }\Sigma\text{Node inflow} - \Sigma\text{Node outflow} \pm \text{Addition to Storage} - \text{Consumption} = 0 \quad (2)$$

$$\text{Link : }\Sigma\text{Link inflow} - \text{Link outflow} - \text{Losses} = 0 \quad (3)$$

$$\text{Coverage : }\Sigma\text{Demand site inflow} - \text{Supply requirement} * \text{Coverage} = 0$$
$$0 \le \text{Coverage(demand site)} \le 1 \quad (4)$$

$$\text{Equity constraint : Coverage(A)} - \text{Coverage(final)} = 0$$
$$\text{Coverage(B)} - \text{Coverage(final)} = 0, \cdots$$
$$0 \le \text{Coverage(final)} \le 1 \quad (5)$$

where coverage is the percent of each demand site's requirement that was met, from 0% to 100%. A and B are demand sites.

2.2 Water Quality Calculations

The K-WEAP tracks water quality, including pollution generation at demand sites, waste removal at wastewater treatment plants, effluent flows to surface and groundwater sources, and water quality modeling in rivers. K-WEAP model simulates the water quality parameters of conservative substances, constituents which decay according to an exponential decay function, oxygen (DO) and Biological Oxygen Demand (BOD) from sources, and water temperature. Also, surface water quality can be modeled using the US EPA model, QUAL2K. QUAL2K provides much more detailed water quality modeling than K-WEAP including diurnal simulations and modeling of nitrogen, phosphorous, sedimentation, algae, pH and pathogens. By linking the K-WEAP constituents to QUAL2K's, providing water quality data for river headflows, surface water and groundwater inflows, climate, distance markers, and wastewater generation and treatment, K-WEAP is to send data to QUAL2K, run QUAL2K, and retrieve results for each time step.

3. Multi-criteria Decision Analysis (MCDA)

Belton *et al*. (2002) used the expression MCDA as an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter. MCDA can provide support for the various alternatives and this support comes in the form of problem structuring, the inclusion of different types of information, providing information to decision-makers about the trade-offs implied by different choices, and by allowing meaningful participation of stakeholders in the analysis of alternatives. MCDA is a process of identification, structuring, modeling and exploring, it is not an algorithm. It is an aid to integrating objective measurement with value judgment and to coherent management of subjectivity such as a human activity system and applied to a variety of different problematiques. The generic and iterative stages of an MCDA approach are shown in Fig. 1.

4. Assessment of Water Shortage

The study area is the Nakdong River basin which is one of 4 largest basins of South Korea. The watershed area and the total length of the river are 31,785.0 km^2 and 68,888.45 km, respec-

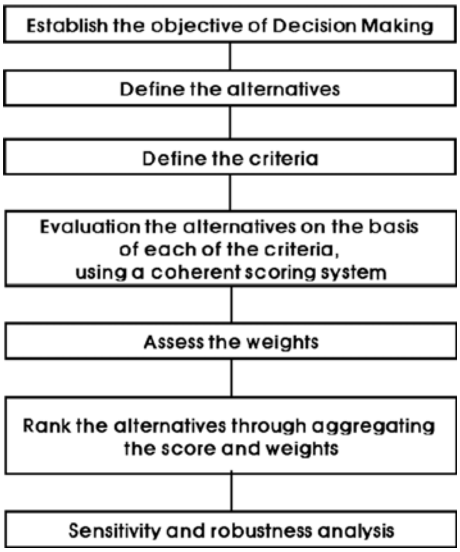

Fig. 1. The Generic and Iterative Stages of an MCDA Approach

tively. The Nakdong River basin is located in the southeast region of South Korea and can be divided into 33 sub-basins based on the National Water Resources Plan (2006-2020) provided by the KMOCT (Fig. 2).

Water budget and water quality analysis were carried out based on K-WEAP model where the fundamental data for analyzing water demand, runoff, reservoir data, diversion data, flow requirement data, and others (return flow rate, loss rate, etc.) are required. Therefore, water demand by regions (municipal water, industrial water, agricultural water) was predicted in the future. Runoff data was estimated based on the data from 1967~2003

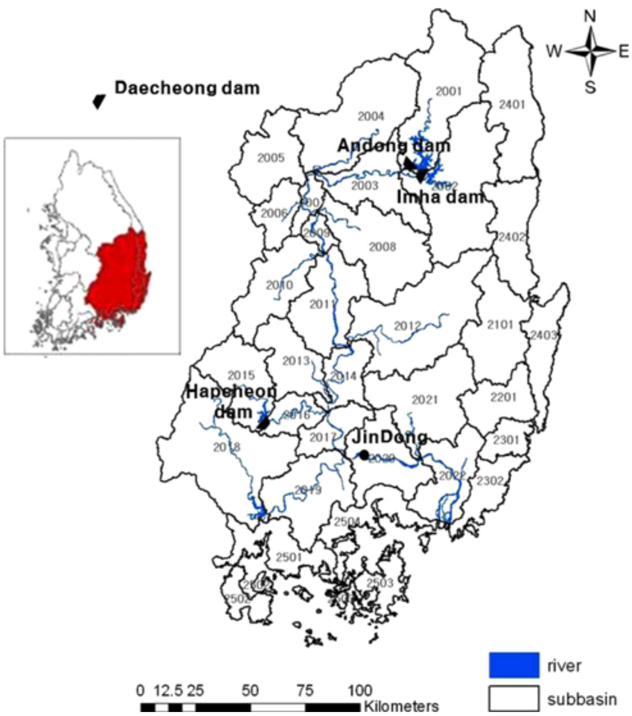

Fig. 2. The Map of Nakdong River Basin, South Korea

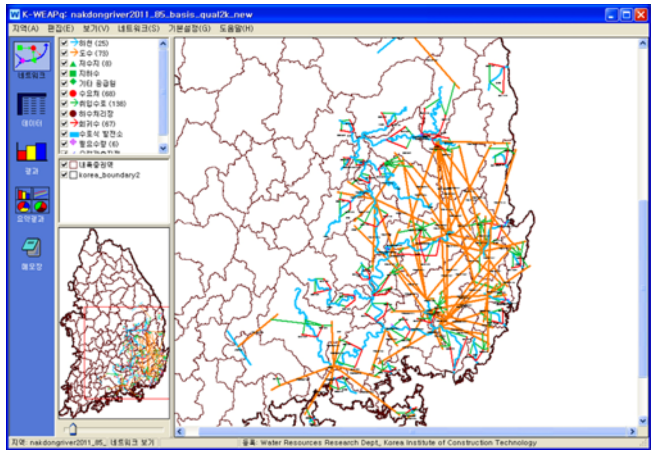

Fig. 3. Composition of Network on Water Budget and Water Quality Analysis based on K-WEAP

using the tank model which is a rainfall-runoff model. Also, for the simulation the water quality, data at demand sites, waste removal at wastewater treatment plants, effluent flows to surface and groundwater sources was needed. Each basic data by regions was estimated using the data provided through a various kinds of research and survey in South Korea (National Water Resources Plan (2006-2020), Basin Survey project, etc.) to execute the water budget and water quality analysis. Fig. 3 shows the network of water budget and water quality analysis of Nakdong River basin.

In the water budget analysis, frequency analysis is implemented to calculate water shortage in each basin using the rainfall data of the driest year among the recent 37 years. By surveying and analyzing the basic data, water budget analysis with current water resources system was executed in the future using K-WEAP, and water shortage was estimated considering basin-wise sources (agricultural reservoir, groundwater, water supply dam, and river mouth). Analysis result is shown in Fig. 4 and water shortage of

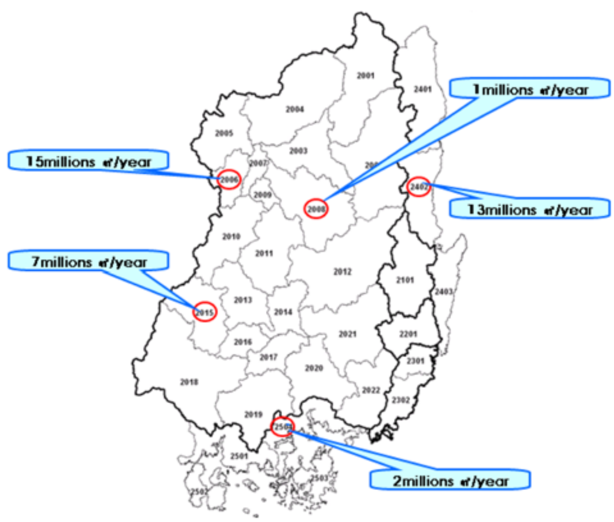

Fig. 4. Analysis Result of Water Shortage for Each Region in the Future

each sub-basin occurred in the agricultural water demand.

5. Alternatives and Criteria

5.1 Identification of Alternatives

Long-term measures are considered in this study and 8 measures which mitigate the water shortage in Nakdong River basin are defined. More specifically, the selected measures are as follows:

1. Water transfer (diversion). This measure comprises of transferring the water from Andong dam and Hapcheon dam, which will have surplus in surcharge storage for target year, to regions which there will be water shortage in.
2. Development of Multi-regional water supply system. This measure tries to connect the pipes from Daecheong dam which located in Guem River basin and Imha dam which have the facilities of Multi-regional water supply system and surplus supplies to water shortage regions.
3. Construction of small agricultural reservoirs. This measure suggests constructing small agricultural reservoirs in water shortage regions. Construction of agricultural reservoirs in each region will be restricted by various circumstances and so this study assumed that reservoirs of each region have 200 million m^3 as effective storage capacity.
4. Development of resources from groundwater. This measure considers developing the groundwater in water shortage regions. It sets limits to withdrawal capacity in each region.
5. Water demand management. This measure considers the execution of the water demand management such as water leakage reduction in leak of water, installation of devices to save water and etc. in entire Nakdong River basin.
6. Decrease in farm land space. This measure suggests decreasing in farm land space in entire Nakdong River basin by rice market opening.
7. Current system. This measure suggests maintaining the current system without development and management of water resources system.
8. Government aids. This measure suggests the financial support for the damaged farm land owners through the government.

The alternatives for water shortage mitigation are a combination of measures. 7 alternatives are suggested in this paper. The alternatives are summarized in Table 1.

Table 1. Alternatives of Water Shortage Mitigation

Measures \ Alternatives	A	B	C	D	E	F	G
Water transfer (1)			○				
Multi-regional water supply system (2)				○			
Agricultural reservoir (3)					○		
Groundwater (4)						○	
Water demand management (5)		○	○	○	○	○	○
Decrease in land space (6)							○
Current system (7)	○						
Government aids (8)	○	○	○	○	○	○	○

5.2 Definition of Criteria

Until now, water resources development and management policy has considered only the economic sector. However, recently, many researcher and decision makers are inclining toward sustainable development, where economic, social, and environmental sectors must be considered in water resources planning and management. The criteria to assess each alternative have been chosen in order to take into account the different economic, environmental, and social consequences of water shortage mitigation measures adopted in each alternative. The three selected criteria are as follow:

5.2.1 Economic Criteria

- *a*: Construction costs is expressed in billions of Won.
- *b*: Estimated damage is computed as cost. The water shortage for target year is predicted as agricultural water demand and Korean Ministry of Science and Technology (2007) estimated the value of agricultural water as 117 won/m^3~660 won/m^3 in South Korea. So, by multiplying water shortage by 500 won/m^3 which was the value of agricultural water, the estimated damage was estimated and expressed in billions of Won.

5.2.2 Environmental Criteria

- *c*: Sustainability is a qualitative criterion taking into account the different sustainability degrees of each alternative.
- *d*: Surface water quality is computed as the concentration of BOD (Biochemical Oxygen Demand). Monthly average concentration of BOD in JinDong point which is representative point of Nakdong River is analyzed.

5.2.3 Social Criteria

- *e*: Water shortage duration is computed as the number of months with water shortage.
- *f*: Employment increase is a qualitative criterion taking into account the increase in employed persons during the phases of construction and operation and maintenance of the infrastructures.

The objective, criteria and alternatives are then organized into a ‘value tree’ (Fig. 5).

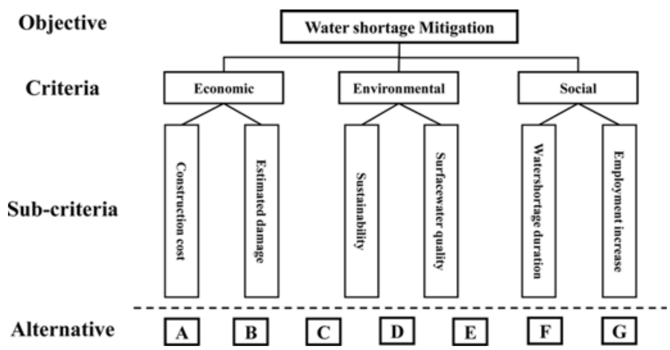

Fig. 5. Value Tree Structure

6. Results

6.1 Evaluation of Impacts of Alternatives on Criteria

The impacts of each alternative were assessed by simulating the system based on K-WEAP. The impact analysis matrix was reported in Table 2. For criteria *a*, the impact was roughly estimated through various kinds of research and survey, and on-site cost data, etc. in South Korea. For criteria *b*, *d*, and *e*, the results were computed based on simulation model (K-WEAP) and for criteria *c* and *f*, they were estimated through questionnaires from water resources researchers. For qualitative criteria, the impact was classed in six 6 groups as EB (extremely bad), VB (very bad), B (bad), M (moderate), G (good), and VG (very good).

6.2 Value Measurement

Scoring is the process of assessing the value derived by the decision maker from the performance of alternatives against the relevant criteria. That is, the assessment of the partial value functions, $v_i(a)$. If criteria are structured as a value tree then the alternatives must be scored against each of the bottom-level criteria of the tree. These are often taken to be the bottom and top of the scale, to which are assigned values such as 0 and 100, but other reference points can be used. In this study, the alternative which did best on a particular criterion was assigned a score of 100 and the one which did least well is assigned a score of 0. All other alternatives received intermediate scores which reflect their performance relative to these two end points. To convert a number linearly to a 0-100 scale, the score for alternatives on criteria *a*, *b*, *d* and *e* which were "less is better" criteria was calculated by Eq. (6) as quantitative measurement (OECD, 2005).

$$\text{Re-scaling method : } v_i(a)=100\times(\max - z_i(a))/(\max - \min) \quad (6)$$

Where $v_i(a)$ is the value score reflecting alternative *a*'s performance on criterion *i*, $z_i(a)$ is the impact reflecting alternative *a*'s performance on criterion *i*, max is the maximum among the impacts on criterion *i*, min is the minimum among the impacts on criterion *i*.

The score for alternatives on criteria *c* and *f* which were qualitative measurement was estimated through constructing qualitative value scale. The score of it are follows: EB(0), VB(20), B(40), M(60), G(80) and VG(100). In Table 3, the result of scoring was reported.

Table 2. Impact Analysis Matrix

Criteria / Alternative	a (billion won)	b (billion won)	c (quality)	d (mg/L)	e (months)	f (quality)
A	0	19.0	EB	25.73	11	EB
B	517.40	17.3	G	25.16	8	B
C	1198.31	0.3	B	25.05	1	G
D	645.01	12.6	M	25.83	6	VG
E	697.40	14.2	VG	25.09	6	VG
F	829.82	0.4	VB	25.06	1	M
G	517.40	14.1	VG	24.82	6	VB

Table 3. Scoring for Alternatives on Criteria

Value score / Alternative	$v_i(a)$	$v_i(b)$	$v_i(c)$	$v_i(d)$	$v_i(e)$	$v_i(f)$
A	100	0	0	10.00	0	0
B	56.82	9.12	80	66.39	30	40
C	0	100	40	77.66	100	80
D	46.17	34.02	60	0	50	100
E	41.80	25.55	100	73.39	50	100
F	30.75	99.08	20	76.08	100	60
G	56.82	26.39	100	100	50	20

6.3 Assessment of Weights

To assess weights, the swing weight method was used. The "swing" which is usually considered is that from the worst value to the best value on each criterion. If the value tree is small, then the decision maker may be asked to consider all bottom-level criteria simultaneously and to assess which swing gives the greatest increase in overall value. This criterion will have the highest weight. The process is repeated on the remaining set of criteria, and so on, until the order of benefit resulting from a swing from worst to best on each criterion has been determined, thereby defining a ranking of the criteria weights. To assign values to the weights the decision maker must assess the relative value of the swings (Belton and Stewart, 2002). Weights were assessed by swing method through questionnaires from 32 water resources researchers. Fig. 6 shows results of assessment of weights and the values in boldface are relative weights and they in italics are cumulative weights. The weights for each criterion made little difference and recently, many researchers consider not only economic but also social and environmental sectors in water resources development and management.

6.4 Ranking of Alternatives

To rank the alternatives, the overall evaluation of an alternative is needed. It is determined by first multiplying its value score on

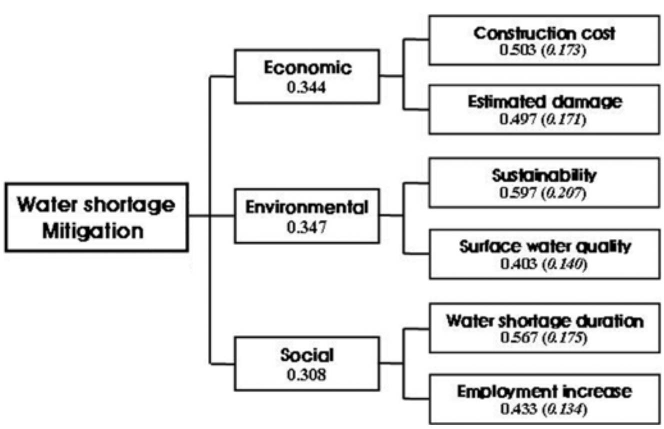

Fig. 6. Assessment of Weights using Swing Method

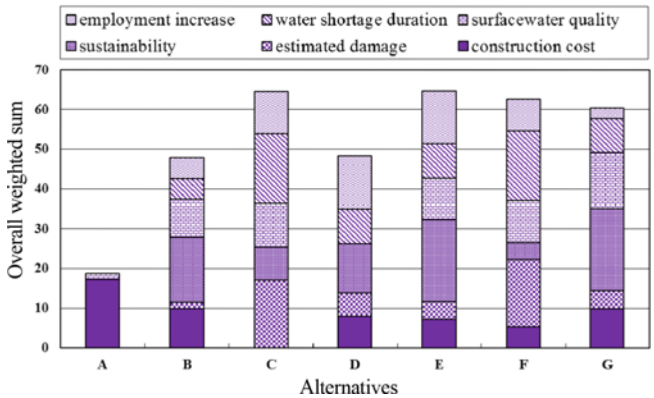

Fig. 7. Overall Evaluation of Alternatives

each bottom-level criterion by the cumulative weight of that criterion and then adding the resultant values. If the values relating to individual criteria have been assessed on a 0 to 100 scale and the weights are normalized to sum 1 then the overall values will lie on a 0 to 100 scale. The simplest and most widely used form of value function is the additive model:

$$V(a) = \sum_{i=1}^{m} w_i v_i(a) \tag{7}$$

where $V(a)$ is the overall value of alternatives a, w_i is the weight assigned to reflect the importance of criterion i.

The result provides the final ranking of the alternatives. It can be inferred that the alternatives with the highest ranking are E (construction of small agricultural reservoirs, water demand management and government aids). The current system and government aids (alternative A) have the lowest ranking. Though alternatives C (water transfer, water demand management and government aids), F (development of resources from groundwater, water demand management and government aids) did not have the highest ranking, in principle they should be preferred. Overall evaluation of alternatives is shown in Fig. 7.

7. Conclusions

In this study, an optimal water shortage mitigation policy is determined using Multi-Criteria Decision Analysis (MCDA) with the scenarios of future water resources availabilities in K-WEAP. For coping with water shortage, mitigation alternatives based on several measures plays a key role, but there is still a lack of standardized methodologies for the assessment of water shortage mitigation measures. The goal of this study is to suggest a proactive approach for water shortage mitigation and to propose a methodology for assessing alternatives using an MCDA that takes into account economic, environmental, and social sectors. The effects of the different measures were assessed using a simulation model (K-WEAP).

Water quantity and quality simulation modules are coupled in K-WEAP system which is capable of evaluation of policy scenarios with transparent planning process by realizing the concept of sustainability. In this study, comprehensive alternatives on water resources development and management with the concerns of multiple and competing water usage are evaluated using K-WEAP. Also, K-WEAP is used to simulate many different situations that might occur in the next decade, or more than 20 years into the distant future. Water shortage can be anticipated and or resolved depending on the future situation, thus, various plans are evaluated using K-WEAP based on decided criteria to derive and obtain reasonable alternatives.

As a result, alternative E (construction of small agricultural reservoirs, water demand management and government aids) is selected as an optimal alternative. Because of nature of water shortage, for example, conflicting opinions among some influential stakeholders, alternative E might not be the best water shortage mitigation policy in actual decision making. Therefore, the methodology using MCDA proposed in this study assigned a high weight in the opinions, considered sectors as criteria as many as possible and assessed the different alternatives to consider variability. Selecting the best policy for water resources development and management, MCDA could be potentially useful tool for decision makers. If the MCDA analysis is implemented, more information could be provided to policy decision makers and the general public, where the future directions of related policies for water resources can be clearer.

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