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Determining an Optimal Action Portfolio for Water Resource Management by Using Stochastic Programming

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Abstract A regional water management system always contains long-term and short-term actions in practice. The uncertainty of short-term actions increases great complexity for evaluating the performance of action portfolio comprised with long-term and short-term actions. Developing an efficient methodology to define a cost-effective action portfolio is an important task. Hence, this study develops a novel decision model, the Stochastic Programming with Recourse Decision Model (SPRDM), to compute a cost-effective action portfolio. The effectiveness of SPRDM is verified by address a problem of water shortage and financial cost in Taoyuan City, Northern Taiwan. The results shown adding Kaotai Reservoir alone can fulfill the Taoyuan demand most of the time, and the remaining extreme water shortage events can be addressed by short-term and irrigation management actions additionally. When drought duration of water shortage event is longer than 200 days, using irrigation management action to address water deficit has lower expected costs than other short-term actions do. Although the study focuses on Northern Taiwan, the proposed model is applicable to other areas with an integrated water resources management framework.

Keywords Uncertainty · Action portfolio · Decision model

1 Introduction

Water deficit are an emerging problem worldwide because of climate change and population growth. Action portfolio comprise long-term and short-term actions have been implemented for coping with water deficit. Owing to actions differ in costs, capacity, benefits, and

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implementation time, an actions portfolio may meet service objectives more effectively than a single large action can. The challenge of selecting an action portfolio involves the complex relationship between actions and the uncertain environments defined according to spatially and temporally correlated hydrologic inflows. The cost of long-term actions is incurred on implementation. Alternatively, short-term actions, such as water rationing or groundwater pumping, can be implemented only when water shortages occur. Therefore, the cost of short-term actions is event based and occurs with uncertainty. The uncertainty of short-term actions make cost-effective action portfolio optimization becomes a complex stochastic problem.

Uncertainty in water resource management has been addressed using stochastic optimization methods. Labadie (2004) divided stochastic optimization methods into two categories: implicit and explicit. Implicit stochastic optimization (ISO) involves performing deterministic optimization on historical or stochastically generated inflow sequences. Many decision support systems have been built on the basis of the ISO concept. One such system, the California Value Integrated Network (CALVIN), has been applied to various water policy and management problems (Draper 2001; Harou and Lund 2008; Medellin-Azuara et al. (2008); Null and Lund 2006; Pulido-Velazquez et al. 2004; Tanaka et al. 2006). In contrast to ISO, explicit stochastic optimization is designed to operate directly on probabilistic descriptions of random streamflow processes rather than deterministic hydrologic sequences (Labadie 2004; Kim et al. 2007). Gillig et al. (2001) used mixed integer stochastic programming with recourse to identify an optimal portfolio of surface and groundwater resource expansions and operations under variable hydrological conditions. Rosenberg et al. (2008) addressed a water management problem in Jordan by applying stochastic programming with recourse while considering long-term and short-term actions.

The study proposes a Stochastic Programming with Recourse Decision Model (SPRDM) for determining the cost-effective action portfolio for mitigating water shortages. The SPRDM extends Gillig's and Rosenberg's approach by accounting for long-term, short-term, and irrigation management actions simultaneously. When irrigation management action is implemented, it cannot be terminated freely, and the cost must account for the losses of the whole crop season. On the other hand, short-term action is implemented only when a water shortage event occurs and terminated hen the water shortage has ended. The study defined a water shortage event according to not only water shortage volume but also the drought duration of the event. The proposed SPRDM was applied to the regional water management planning problem of the Taoyuan City in Northern Taiwan according to projected water demands in 2021.

2 Methodology

The SPRDM identifies the action portfolio that optimally minimizes expected costs and fulfills the water demands for all water shortage events once the actions are implemented. Stochastic refers to something that is not yet known (i.e., annual rainfall for next year), but has a pattern (i.e., average 2500 mm per year). Recourse permits corrective actions after more information is learned (i.e., rainfall was 1800 mm last year; therefore, we must…) (Rosenberg et al. 2008). The SPRDM uses stochastic programming to identify the most effective action portfolio. The objective is to optimize the total expected costs consisting of long-term and short-term actions. Expected costs of short-term and irrigation management actions are event-specific costs and are weighted according to the probability of each event. The probability of a water shortage event under long-term action portfolio scenario is obtained by water allocation simulation model, GWSM. There are various combinations of long-term, short-term and irrigation management actions, and each combination constitutes a portfolio of actions. The optimal portfolio has the optimal expected cost, fulfills all the water demands and is subjected to the system constraints. The mathematical formulation of the SPRDM is expressed as follows:

$$\begin{aligned} Z = \min\Big(&\textstyle\sum_{i=1}^{I} C1_i(d) + \sum_{e=1}^{E(d)} P_e(d) \sum_{j=1}^{J} C2_j \bullet Day_e(d) \bullet S_{j,e}(d) \\ &+ \textstyle\sum_{e=1}^{E(d)} P_e(d) \sum_{k=1}^{K} C3_j \bullet AS_k \bullet \mathrm{ADay} \bullet A_{k,e}(d) \quad \forall d \subset D \end{aligned} \tag{1}$$

Equation (1) expresses the objective function of the SPRDM. The decision variables are d, $S_{j,e}(d)$ and $A_{k,e}(d)$ which denotes the d-th long-term action portfolio, the amount of supply increment or demand decrement for the j-th short-term action of e-th water shortage event under d-th long-term action portfolio, the binary decision variable for the *k*-th irrigation management actions of the *e*-th water shortage event under d-th long-term action portfolio respectively. $C1_i(d)$ is the annual cost for the *i*-th long-term action under d-th long-term action portfolio; $C2_j$ is the unit operating cost of the supply increment or demand decrement for the *j*-th short-term action; $C3_k$ is the unit operating cost of withholding water for the *k*th irrigation management action; D is a set of long-term action portfolio; $Day_e(d)$ is the duration of e-th water shortage event under d-th long-term action portfolio; *ADay* is the annual rice crop duration; AS_k is the amount of withholding water for the *k*-th irrigation management action; and $P_e(d)$ is the probability for the *e*-th water shortage event under d-th long-term action portfolio with $0 \le P_e(d) \le 1$, $\forall\, e$.

The impact of a water shortage depends on the total water shortage volume and the persistence of the water shortage event. Therefore, this study defined a water shortage event according to two factors: drought duration and the water shortage ratio. The water shortage ratio was further classified into 5 levels: 0%–20%, 20%–40%, 40%–60%, 60%–80%, and 80%–100%. Drought duration can vary from 1 to 365 days. P_e(d) was calculated by event occurrence frequency and defined using eq. (2):

$$P_e(\mathrm{d}) = \frac{N(DDR \cap SR)}{\sum\limits_{DDR=1}^{365} \sum\limits_{SR=1}^{5} N(DDR \cap SR) + \sum\limits_{NDR=1}^{365} N(NDR)} \tag{2}$$

In eq. (2), $DDR \cap SR$ represents a water shortage event *e* in which *DDR* is the drought duration and *SR* is the level of the water shortage ratio. $N(DDR \cap SR)$ is the occurrence frequency of the water shortage event *e*. *NDR* is the duration of the event without water shortage. Therefore, *N*(*NDR*) is the occurrence frequency of the event with an *NDR* duration without a water shortage. Again, the occurrence frequency of shortage events is computed according to the simulation results of a water allocation model under the existing water resource system before applying any new actions.

The objective function (Draper 2001) is subjected to constraints listed as follows:

$$\sum_{i=1}^{I} \mathrm{sf_i(d)} + \sum_{j=1}^{J} \mathrm{Day_e}(d) \bullet \mathrm{S_{j,e}}(d) + \sum_{K=1}^{K} \min(\mathrm{Day_e}(d), \mathrm{ADAY}) \bullet \mathrm{AS_k} \bullet \mathrm{A}_{k,e}(d) \ge \mathrm{Demand_e}. \tag{3}$$

Equation (3) requires that the industrial and domestic water demand must be fulfilled by the implemention of long-term and short-term actions. In eq. (3), $sf_i(d)$ denotes the supply increment or demand decrement of a long-term strategy, and Demand_e is the industrial and domestic water shortage level.

$$S_{j,e}(d) \le S\max_j \forall j = 1, J \tag{4}$$

Equation (4) indicates the capacity contraints of each short-term action, where $S\max_j$ is the associated capacity.

$$S_{j,e}(d) \ge 0 \;\; ; \;\; A_{k,e}(d) \ge 0 \tag{5}$$

Equation (5) expresses the nonnegative constraints of the decision variables. The optimization problem defined using eqs. (1) to (5) was solved using mixed integer linear programming.

3 Case Study

3.1 Study Area

This study applied the SPRDM to Taoyuan City to demonstrate the feasibility of the proposed methodology. Figure 1 shows the main water resource facilities in the study area. Taoyuan City is the major water demand area, located approximately 40 km southwest of Taipei City and covering an area of 1220 km^2. The city has low-lying plains, interconnected hills, and plateaus. It has a long and narrow shape oriented southeast-to-northwest, with mountains in the southeast and Taiwan Strait along the northwest coast. The population of Taoyuan City was 2,056,273 in 2014, and is projected to reach 2,222,000 by 2031. Because of population growth and industrial development, the domestic and industrial water demand is projected to increase from 0.12 million m^3/day in 2014 to 0.179million m^3/day in 2031. The total irrigation area is 36,500 ha and is managed by Shihmen and Taoyuan irrigation associations. The annual irrigation water demand is 39 million m^3 and is concentrated from February to November. The irrigation water demand is not projected to increase and can be fulfilled by the existing water resource system under normal conditions. However, the domestic and industrial water resources will undergo severe shortages within 20 years if new water resource facilities are not developed.

The Taoyuan City water demand is mainly supplied by Shihmen Reservoir and supplemented by Yunshan and Sanxia Weir, as indicated in Fig. 1. Shihmen Reservoir is upstream of Dahan River. Constructed in 1964, it is a multiobjective reservoir designed for irrigation, flood control, hydropower, recreation and water supply for domestic and industry use; water supply has gradually become its primary function. Shihmen Reservoir is undergoing a large amount of sediment deposition. The effective water storage capacity of Shihmen Reservoir has decreased from 309 million to 209 million m^3 according to survey data from 2012, which may severely affect the future reservoir water supply capacity. Yunshan Weir is 19 km downstream of the reservoir and Sanxia Weir is in the tributary of Dahan River.

3.2 Water Supply Simulation

Before applying the SPRDM, the probability of water shortage events as defined in eq. (2) must be computed. The study used a generalized water allocation simulation model (GWSM)

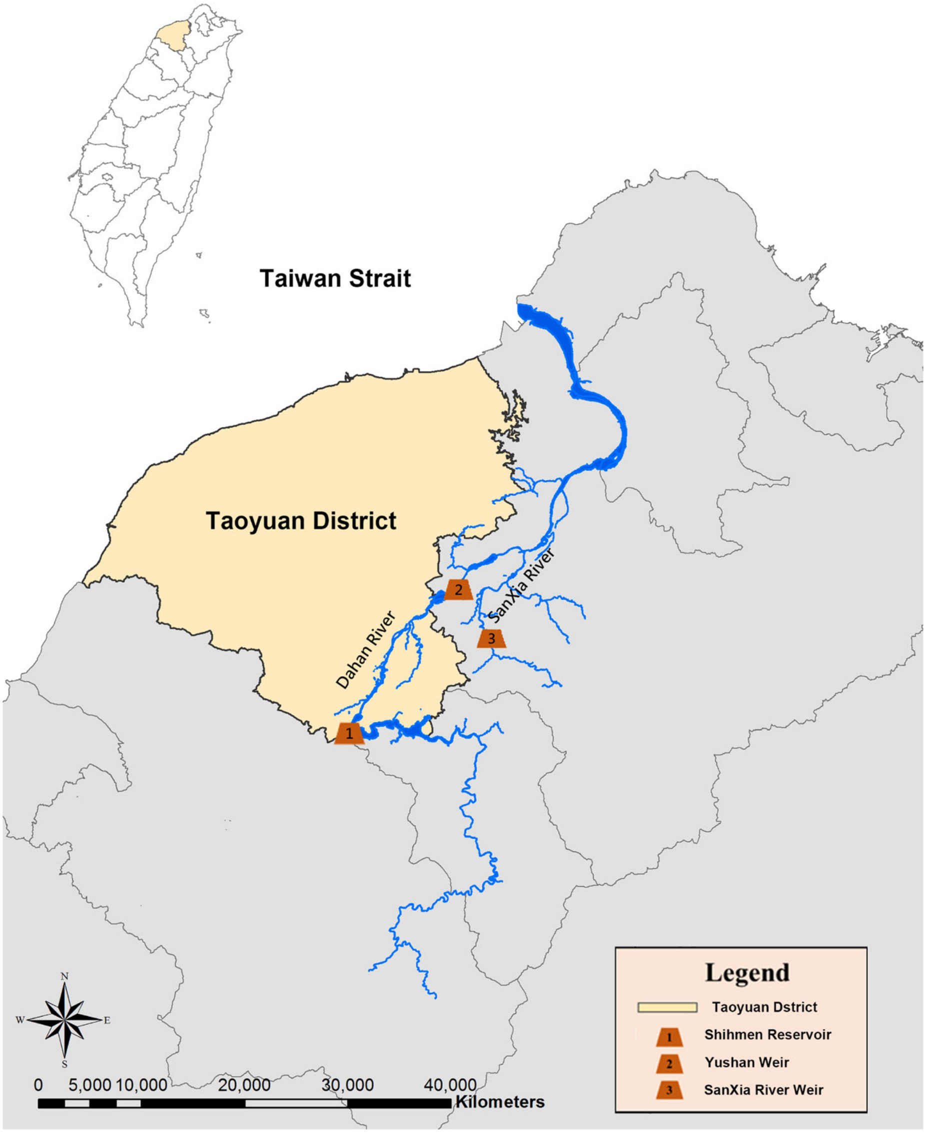

Fig. 1 Study area and major water resources infrastructure

to simulate the water supply of the study area according to the existing water supply facilities. The probability of water shortage events was then calculated according to the simulation results by using eq. (2). A GWSM is a linear programming-based water allocation model which incorporated reservoir operating rules, river base flow conservation and facility capacity constraints. A water resource system is represented as a nodes-links network system in the model. The nodes represent the water infrastructure and water demands, such as reservoirs, weirs, water treatment plant, domestic demands, industrial demands and irrigation demands. The links represent river reaches, pipes and conduits. Figure 2 shows the network system considered in the study area where Shihmen Reservoir is the only water supply reservoir.

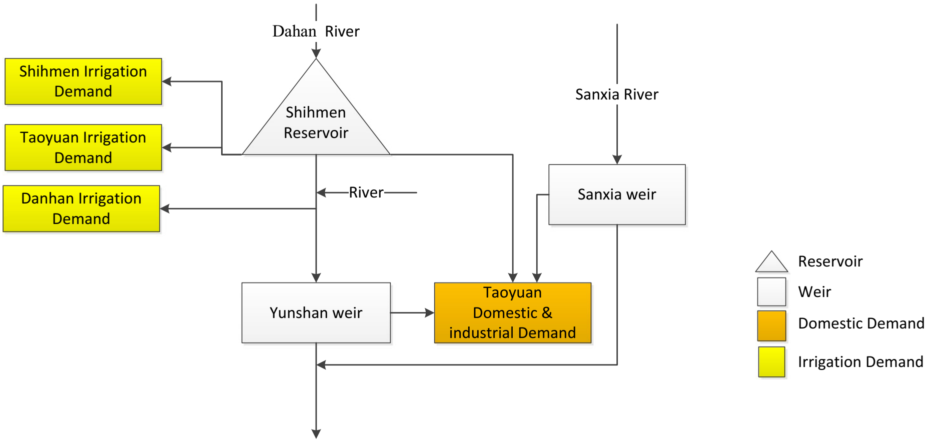

Fig. 2 Water sysetem diagram of Dahan River

GWSMs have been applied in many research projects funded by Taiwan Water Resources Agency (Water Resources Agency, Ministry of Economic Affair 2013). Because this paper focuses on the application of stochastic programming (the SPRDM), the description of the GWSM used in this study is brief, and more detailed information can be found in the references. The water supply simulation was carried out with historical daily inflows to Shihmen Reservoir and Sanxia Weir from 1981 to 2011. The releasing of Shihmen Reservoir is based on the M-5 operating rule.

3.3 Potential Adaptive Actions

As a response to the future domestic and industrial water supply shortage in the area, the Taiwan Water Resources Agency has proposed several potential long-term and short-term adaptive actions (Tables 1 and 2) for mitigate water shortages. The proposed SPRDM is used to identify the optimal action portfolio consisting of selected potential actions. As indicated in Table 1, long-term actions can be classified as supply-side or demand-side. The cost and capacity of each supply increment or demand reduction actions were collected from related reports. There are five long-term water supply increment actions in the area. Kaotai Reservoir,

Table 1 List of potential long-term actions for Taoyuan area

Action		Annual cost (million, NTD)	Capacity of Supply Increment or demand reduction to public water demand ($10^3 m^3$/day)
Supply-Side	Kaotai reservoir	1411	348
	Conservation and management projects in Shihmen Reservoir Watershed	496	24.9
	Sediment sluicing engineering of Shihmen Reservoir	357.8	14.9
	Desalination plant of Taoyuan	255	30
	Water Reclamation of Jongli Water Treatment Plant	5195	156.8
Demand-Side	Domestic water saving	829	48.6
	Industrial water saving	540	74.2

Table 2 List of potential short-term and irrigation management actions for Taoyuan area

Action		Operating cost (NTD/m^3)	Capacity of supply increment or demand reduction to public water demand (10^3m^3/day)
Short-term	Water transport from other water districts	150	8.8
	Preliminary water rationing	1.07	73.8
	Advanced water rationing	39.38	147.5
Irrigation management	Irrigation water transference	31.96	533.6
	Irrigation management enhancement	15.96	302.9

located 80 km upstream from Shihmen Reservoir, will increase by 348 thousand m^3/day. Watershed conservation enhancement for Shihmen Reservoir and Sediment desilting action for Shihmen Reservoir will increase by 24.9 and 14.9 thousand m^3/day of water respectively by reducing the sediment deposition in the reservoir. The desalination plant located in Taoyuan City will have thousand m^3/day capacity. Water Reclamation of the Jongli Water Treatment Plant will increase 156.8 thousand m^3/day. There are two long-term demand reduction actions: domestic water conversation and industrial water conversation. These actions can save 48.6 and 74.2 thousand m^3/day of water, respectively.

The short-term and irrigation management actions are listed in Table 2. There are two types of management actions: irrigation water transference and irrigation management enhancement. Irrigation water transference is a demand transfer action that transfers irrigation water to fulfill the public water demand. The action has a water transference limitation of 533.6 thousand m3/ day, which is higher than that of other short-term actions. The cost of irrigation water transference is the financial compensation to the farmer. Instead of transferring the irrigation water, irrigation management enhancement can increase the water supply to the public by reducing irrigation water use with an upper limit of 302.9 thousand m3/day. The action saves water by enhancing the monitoring and controlling of the channel gates in the irrigation system to increase irrigation water distribution efficiency, which increases operation cost. There are 3

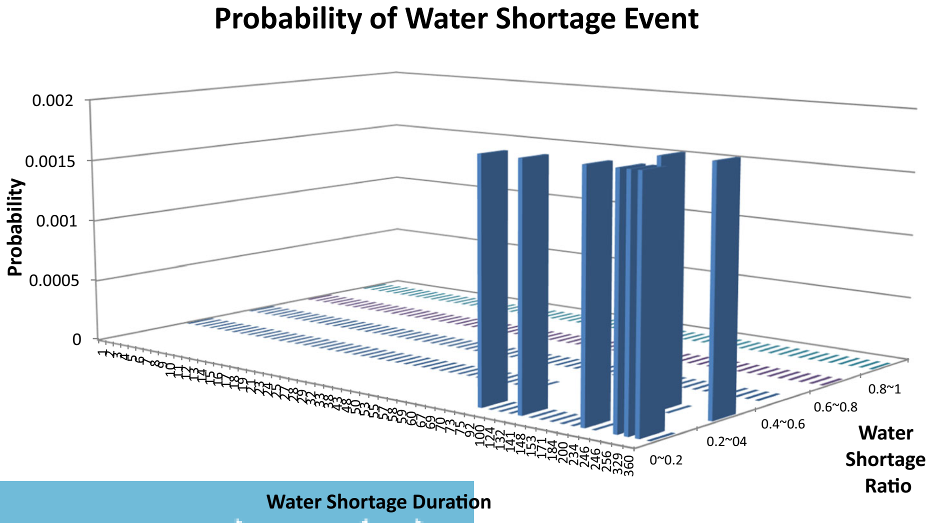

Fig. 3 Ocurring probability of water shortage events in Taoyuan area under considering Kaotai Reservoir action

Table 3 Selected actions of optimal portfolio obtained by SPRDM

Long-term action		ADOPT (Yes or No)	Supply increment or demand decrement ($10^6 m^3$/year)	Expected annual cost (million, NTD)
Long - term	Kaotai reservoir	Y	127.02	1411
	conservation and management projects in Shihmen reservoir watershed	N	-	-
	Sediment sluicing engineering of Shihmen reservoir	N	-	-
	Desalination plant of taoyuan	N	-	-
	Water reclamation of Jongli water treatment plant	N	-	-
	Domestic water saving	N	-	-
	Industrial water saving	N	-	-
	Total	-	127.02	1411
Short-term action		Activated frequency under drought events *	Expected supply increment or demand decrement for short-term actiONS (million m^3/year)	Expected annual cost (million, NTD)
Short-term	Water transport from other water districts	1	0.002	0.37
	Irrigation water transference	2	0.393	12.55
	Irrigation management enhancement	4	0.446	7. 12
	Preliminary water rationing	6	0.103	0.11
	Advanced water rationing	3	0.142	5.61
	Total	-	1.087	25.76
Annual expected cost of optimal portfolio (million, NTD)		1436.76		

*The total number of drought events is 59. After building the Kaotai Reservoir, the water demand of 53 drought events were fulfilled, and only 6 drought events required additional short-term actions

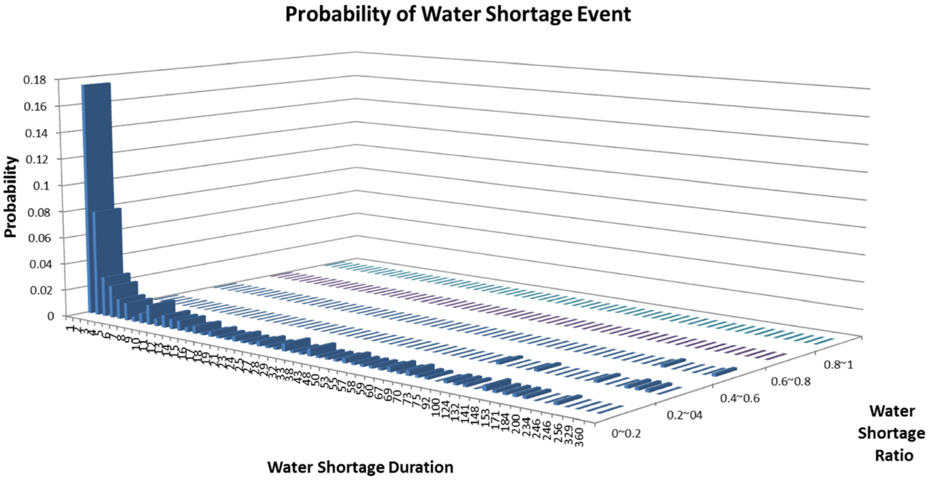

Fig. 4 Ocurring probability of water shortage events in Taoyuan area for existing suppply system

short-term actions: Water transport from other water districts, preliminary and advanced water rationing. Which have upper limits of 8.8, 73.8 and 147.5 thousand m3/day, respectively.

3.4 Result and Discussion

The study deal with decision problems where the decision of long-term action portfolio must be made before the realization of short-term action portfolio is known. The first-stage determine the long-term action portfolio and the portfolio accompany recourse information (the probability for water shortage event). The second-stage optimize the cost-effective short-term action portfolio in response to the recourse information. The probability of water shortage events in different long-term action portfolio was be calculated according to the statistics of water supply simulation results obtained by applying the GWSM to the study area. Figure 3 shows the probability of water shortage events under considering "Kaotai Reservoir" action. The results shown adding a long-term action, Kaotai Reservoir, can fulfill the Taoyuan demand

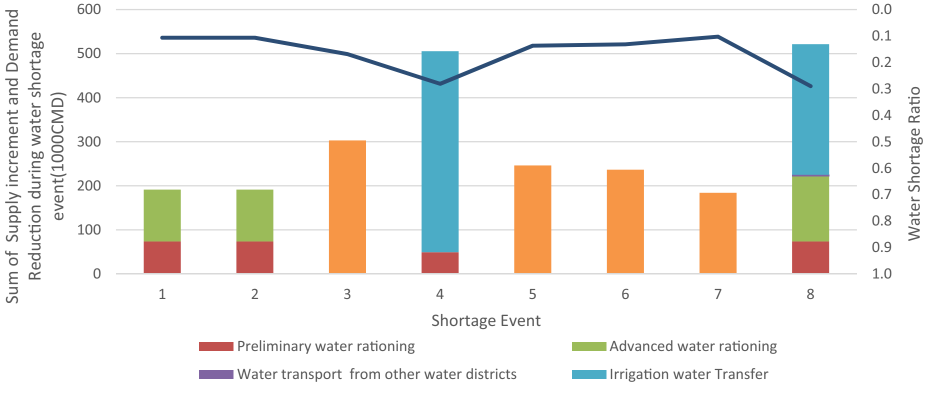

Fig. 5 A Comparison between sum of actions water supply increment (or demand reduction) and water shortage ratio for water shortage events under considering Kaotai Reservoir action

Table 4 List of water shortage events under considering Kaotai Reservoir action

Drought event number	Drought duration	Water Shortage Ratio	Probability (%)	Supply increment or demand decrement for short-term actions (million m^3)					Expected cost of short-term action for drought event (million NT))
				Water transport from other water districts	Irrigation water transference	Irrigation management enhancement	Preliminary water rationing	Advanced water rationing	
1	75	10.6%	0.18%	0	0	0	5.53	8.83	35.347
2	132	10.6%	0.18%	0	0	0	9.74	15.53	1.145
3	200	16.8%	0.18%	0	0	60.58	0.00	0	1.779
4	234	28.1%	0.18%	0	106.72	0	11.56	0	6.299
5	246	13.7%	0.18%	0	0	60.58	0	0	1.779
6	256	13.2%	0.18%	0	0	60.58	0	0	1.779
7	329	10.2%	0.18%	0	0	60.58	0	0	1.779
8	360	29.0%	0.18%	1.33	106.72	0	26.55	53.10	10.544

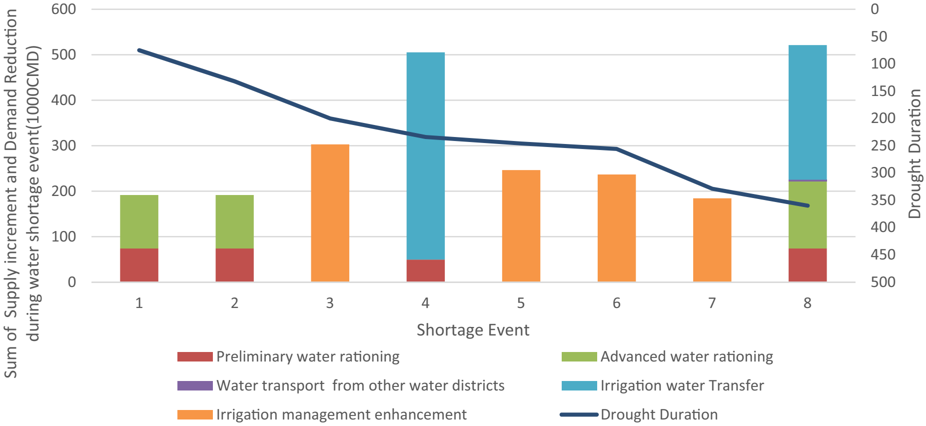

Fig. 6 A Comparison between sum of actions water supply increment (or demand reduction) and drought duration for water shortage events under considering Kaotai Reservoir action

most of the time, and drought duration and water shortage ratio of the remaining extreme water shortage events are all over 75 days and between 10.6 ~ 29% respectively. At the second stage, the remaining extreme water shortage events can be addressed by short-term and irrigation management action portfolio additionally. An optimal action portfolio with the minimum total expected cost was computed by solving the optimal combinatory problem defined using eqs. (1) to (5) with mixed integer linear programming.

Table 3 presents a summary of the results of the optimal actions portfolio consisting of selected long-term and short-term actions. The optimal action portfolio included one long-term action—“Kaotai Reservoir”—and several short-term actions: “preliminary water rationing,” “advanced water rationing,” “water transport from other water districts,” “irrigation water transference” and “irrigation management enhancement.” According to Table 3, the expected annual cost of the optimal action portfolio is NT$1436.76 million. The long-term action Kaotai Reservoir is NT$1.411 billion, and the total expected cost for other short-term actions is only NT$25.76 million. This implies that the demand of high water shortage events can be fulfilled at much lower costs than those of short-term actions.

The results in Table 3 can be explained further by examining Table 1 and Fig. 4. Table 1 indicates the Jongli Water Reclamation Plant action has the highest cost. Therefore, it seems reasonable not to select the action. The cost of other long-term actions is lower than that of the selected Kaotai Reservoir action, but the water supply capacities of those low-cost actions are all markedly limited compared with those of the Kaotai Reservoir action. Table 1 shows that Kaotai Reservoir can supply 348 thousand m^3/day of water, which is 19.4% of the daily water demand. Figure 4 shows the probability of water shortage events for existing supply system. Figure 5 indicates that most of the drought events for existing supply system have water shortages below 20%. These joint conditions indicate that Kaotai Reservoir alone can address most of the water shortage events and the remaining water shortage events can be addressed at much lower expected costs by using only short-term actions. This explains why none of the other long-term actions was selected for the optimal portfolio other than the Kaotai Reservoir action.

Table 4, Figs. 5 and 6 presents a summary of the details of the water shortage events under considering Kaotai Reservoir action. The results shown when drought duration and water shortage ratio of water shortage event is longer than 200 days and lower than 16.8%

respectively, the decision prefer to using irrigation management enhancement to address water deficit. When drought duration and water shortage ratio of water shortage event is longer than 200 days and higher than 28.1% respectively, the decision prefer to using irrigation water transference with short-term actions to address water deficit. The results implied when drought duration close to the days of crop season, using irrigation management action to address water deficit has lower expected costs than other short-term actions do.

4 Conclusion

The SPRDM determined the optimal portfolio according to the optimal total expected cost of the long-term and short-term actions. The optimal action portfolio in Taoyuan involved “Kaotai Reservoir”, “preliminary water rationing,” “advanced water rationing,” “water transport from other water districts,” “irrigation water transference” and “irrigation management enhancement”, and the expected annual cost of the optimal action portfolio is NT$1436.76 million. The simulation results of a case study indicated that to fulfill water demands of a regional water resource system over a long-term period, the most cost-effective strategy is to select long-term actions for fulfilling the water demand for drought events with a higher occurrence probability and short-term actions for extreme drought events with a low occurrence probability. Although a short-term action may have high unit cost, it is still cost effective over a long-term period. An irrigation water supply is commonly treated as a buffer for other water demands and can be allocated to other water demands when extreme water shortage events occur. The results shown when drought duration of water shortage event is longer than 200 days, using irrigation management action to address water deficit has lower expected costs than other short-term actions do. In contrast to other short-term actions, the cost of irrigation water transference is fixed when it is implemented, but it does not depend on the duration of the shortage event. The proposed model considers irrigation water transference and is thus a valuable tool for proposing a regional water resource strategy when the irrigation water demand becomes critical.

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