A drought early warning system on real-time multireservoir operations

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[1] A color-coded early warning system is developed and proposed for drought management on the real-time reservoir operation. The system consists of three essential elements, namely, (1) drought watch, (2) water consumption measure, and (3) policy making. A new drought alert index is used to characterize the alert level of drought severity. For demonstration the drought warning procedures were effectively applied to a real-world two-parallel-reservoir region in northern Taiwan. The implementation of such a system proves that the decision support-like system can help the water authorities concerned take a timely action while confronting drought threats. *INDEX TERMS:* 1812 Hydrology: Drought; 1857 Hydrology: Reservoirs (surface); 1884 Hydrology: Water supply; *KEYWORDS:* drought alert index, early warning system, reservoir operation

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1. Introduction

[2] In general, drought can be classified into three categories: meteorological drought, hydrological drought, and water supply drought. Several studies have been done regarding the drought definitions [*Palmer*, 1965; *Yevjevich*, 1967; *Takeuchi*, 1974; *Tase*, 1976]. The Palmer drought severity index (PDSI), based on soil moisture excess and deficit, is widely applied on the effects of meteorological drought [*Guttman*, 1991; *Piechota and Dracup*, 1996; *Pesti et al.*, 1996; *Lohani and Loganathan*, 1997; *Pongracz et al.*, 2003]. Furthermore, the surface water supply index (SWSI), an indicator of the surface water available in river basins in terms of precipitation, snowpack, and reservoir storage, is commonly used in the United States (see the Natural Resources Conservation Service Web site, http://www.wcc.nrcs.usda.gov/wsf/ and the Colorado Division of Water Resources Web site, http://water.state.co.us/). These indicators, however, do not describe exactly how to respond to each of the alert categories. Besides, they are limited in their applicability for the operation of individual reservoirs for drought management [*Johnson and Kohne*, 1993]. Although much research has been devoted to drought watch, little work is available on the applicability of a drought early warning system to real-time reservoir operations. This may be due to a possible gap between theory and practice for user-research interactions [*Yeh*, 1985].

[3] Amid real-time reservoir operations, not only some kind of indices for drought watch but also eligible rules for operation are required. Prior to the real-time drought management, system analysis should develop appropriate operating rules in reservoir operation. The reservoir policies are usually determined either by stochastic dynamic programming (SDP) or by simulation. The former searches an optimal option among large set of alternatives, while the latter intends to select the best from a small list of predetermined alternatives. Thus SDP is for a problem of design, as compared with simulation for a problem of choice. *Yeh* [1985] extensively reviewed the state of the art of the above techniques developed for reservoir operations. In practical use a rule curve based on the current storage level to specify the release of the next period would be preferred by reservoir operators because of its mathematic simplicity and versatility. The general descriptions of simulation procedures for dealing with reservoir operations are given by *Loucks et al.* [1981], *Viessman et al.* [1989], and *Mays* [2001]. These rules provide guidance only. Accounting for the variability of incoming inflows, reservoir operators could encounter a difficulty of how to properly operate reservoir releases, particularly at the onset of the dry season. For the real-time reservoir operation a more comprehensive and refined procedure is indispensable.

2. Statement of the Problem

[4] A water shortage affecting human life and economic growth is a chronic problem appreciably different from flood impact. Northern Taiwan is a political and high-tech center. It is an area with more uniform rainfall distribution than other areas of Taiwan. The annual rainfall approximates 2934 mm, with 62% coming during the wet season (May through October) and 38% during the dry season (November through April). The occurrence probability of a small-scale drought in terms of consecutive 50 days without rainfall would be <0.01 per year. However, northern Taiwan is vulnerable to water shortage because of its large amount of water consumption. Thus reservoirs built in a deficit-prone area should be considered for its primary purpose to retain excess water for drought mitigation, such as the Feitsui and Shihmen reservoirs, the largest and most important ones in northern Taiwan (Figure 1).

[5] *Huang et al.* [2001] mentioned that the Hsinchu area, the location of Taiwan's "Silicon Valley" in northern Taiwan, is an area frequently suffering water deficit. Obviously, water shortage will bring considerable concerns on

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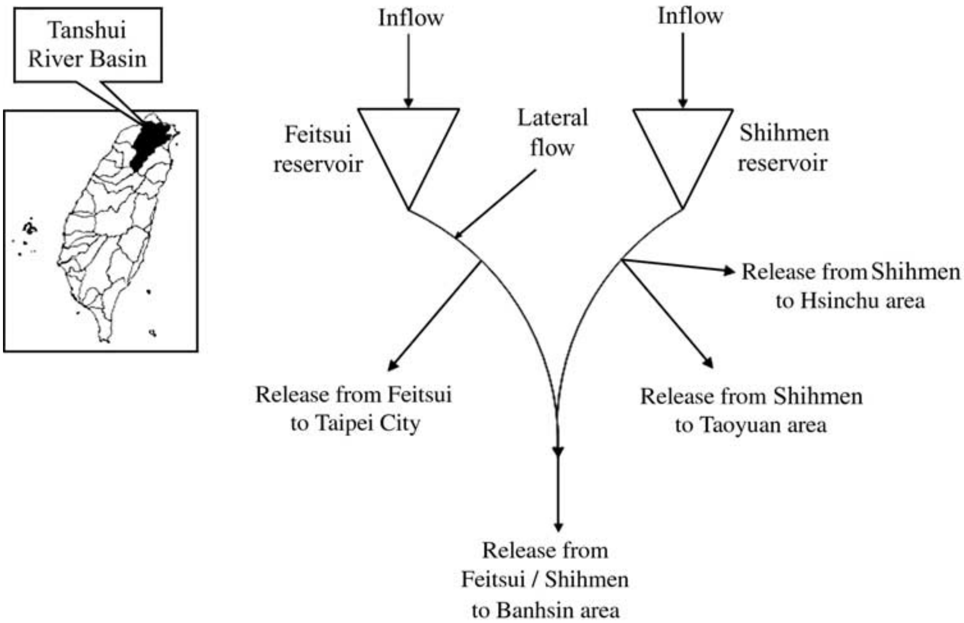

Figure 1. Case study system in northern Taiwan.

the global high-tech industry as well as the stock market. Before completion of the Baoshan II Reservoir in 2006, the most feasible options to offset the water deficiency are suggested as importing water from the northern Shihmen Reservoir and irrigation usage. Furthermore, a joint operation between the Feitsui and Shihmen reservoirs, located in the Tanshui River basin, is also recommended because water deficit usually occur in Shihmen's operation while Feitsui has much surplus water lacking effective utilization. It has been shown that Feitsui's surplus water can fill Shihmen's deficit water without affecting Feitsui's main function as Taipei's water supply [*Huang et al.*, 2002].

[6] A severe drought hit northern Taiwan in the spring of 2002. It brought immense impacts not only to people's daily life but also to the operation of the Hsinchu Science-based Industrial Park (HSIP). Unfortunately, the drought early warning system in Taiwan is not well developed, and the alert categories are in their infancy and quite vague in their definitions. The drought event has revealed the decision maker's slow response to the water shortage crisis threatening the metropolis, the high-tech industry, and agriculture over northern Taiwan. Amid the event, ineffective water allocation in reservoir management cost the government a great deal of effort. Consequently, public criticism to the flaw was inevitable. Obviously, a handy early warning system for drought management plays a very important and critical role in the real-time reservoir operation.

[7] In this article, an early warning system is developed to provide a complete procedure for drought management on the real-time operation of a multireservoir system. The real 2002 drought event occurred in northern Taiwan is selected to demonstrate the applicability of the proposed methodology.

3. Mechanism of the Drought Early Warning System

[8] The mechanism of the developed drought warning system is shown in Figure 2. It contains (1) drought watch, (2) water consumption analysis, and (3) policy making. The system is used to determine suitable reservoir operating policies during an uncertain environment. One of the most substantial characteristics of the drought early warning system is its recursive procedure that processes observations

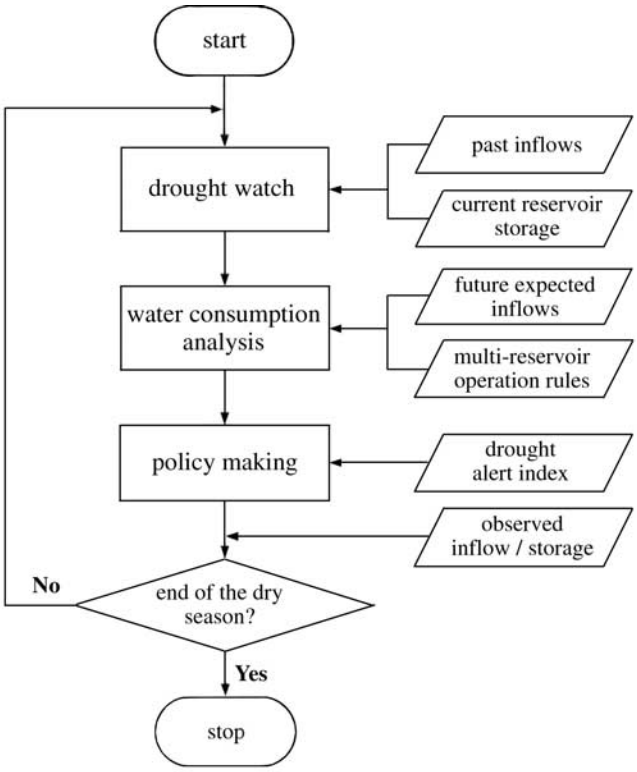

Figure 2. Mechanism of the drought early warning system.

to renew the evaluation. The details of the scheme are given below.

3.1. Drought Watch

[9] The drought watch is to oversee the recent drought situations concerning both hydrologic and water supply droughts. Here we develop a fuzzy-based drought watch keen to specify the present drought status, and the procedure is as follows.

[10] 1. Define an attribute set (U) illustrating the variables of vital importance to reservoir operation. Generally, the variables like rainfall, streamflow, and reservoir rule are the main elements to influence reservoir operation. Here restrictions have been placed on the use of groundwater to prevent land subsidence. Further, since the reservoir inflow would be proportional to the rainfall through rainfall-runoff relationship, only the reservoir's inflow and operating rule are selected as key factors in this study. That is, U = {reservoir inflow (U_1), reservoir water level (U_2)}.

[11] In order to ease the monthly flow fluctuation highly sensitive to drought watch, U_1 represents an exceedence probability of the cumulative flow of a 3-month-long period. Meanwhile, the capacity of a reservoir is divided into four zones throughout the year by three rule curves (upper, lower, and critical curves).

[12] 2. Define an evaluation set (V) representing the categories to drought assessment. They are V = {none (V_1), slightly severe (V_2), fairly severe (V_3), severe (V_4), very severe (V_5)}.

[13] As known, the fuzzy set theory is basically a theory of graded concepts. "Fuzzy" indicates that information is vague rather than crisp, and everything is a matter of degree. Detailed descriptions of fuzzy sets and their operations are given by *Chen and Hwang* [1992] and *Zimmermann* [1991]. Because of their vague boundaries, a fuzzy set is defined in terms of membership function numerically indicating the degree to which an element belongs to a set. Let $\mu_j(U_i)$ represent the membership function of fuzzy set V_j which is associated with criterion U_i; $\mu_j(U_i)$ is called a normalized membership function such that $0 \le \mu_j(U_i) \le 1$. In general, trapezoidal membership functions are frequently used and are specified by a quadruplet. Furthermore, a triangular membership function is a special case of this.

[14] Here the trapezoidal membership functions $V_j(U_i)$ for the attributes U_1 and U_2, respectively, are given by $V_1(U_1)$ = (0.0, 0.0, 0.5, 0.6), $V_2(U_1)$ = (0.5, 0.6, 0.7, 0.8), $V_3(U_1)$ = (0.7, 0.8, 0.8, 0.9), $V_4(U_1)$ = (0.8, 0.9, 0.9, 1.0), and $V_5(U_1)$ = (0.9, 1.0, 1.0, 1.0). $V_1(U_2)$ = (full, full, upper rule × 50% + lower rule × 50%, upper rule × 20% + lower rule × 80%), $V_2(U_2)$ = (upper rule × 50% + lower rule × 50%, upper rule × 20% +lower rule × 80%, lower rule × 80% + critical rule × 20%, lower rule × 50% + critical rule × 50%), $V_3(U_2)$ = (lower rule × 80% + critical rule × 20%, lower rule × 50% + critical rule × 50%, lower rule × 50% + critical rule × 50%, critical rule), $V_4(U_2)$ = (lower rule × 50% + critical rule × 50%, critical rule, critical rule, empty), and $V_5(U_2)$ = (critical rule, empty, empty, empty). These membership functions, represented by a quadruplet for both attributes (inflow and water level), are illustrated in Figures 3 and 4, respectively.

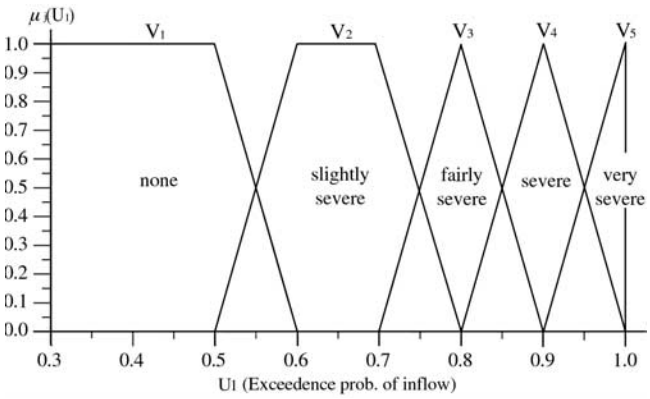

Figure 3. Membership functions for reservoir inflow.

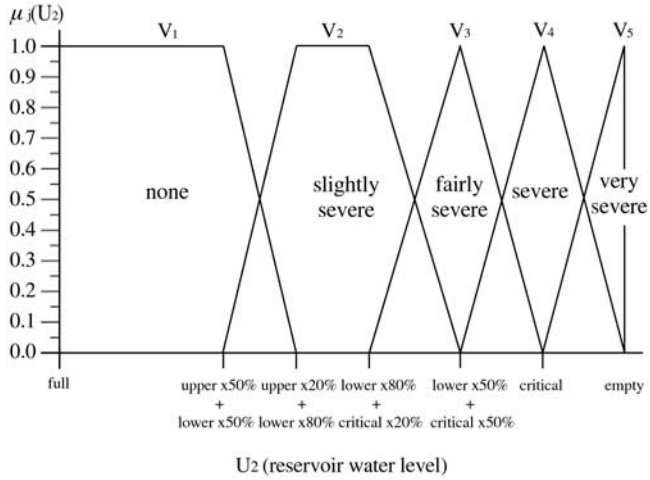

Figure 4. Membership functions for reservoir water level.

[15] 3. Establish a decision matrix (**R**) by

$$\mathbf{R} = \begin{bmatrix} r_{11}, r_{12}, r_{13}, r_{14}, r_{15} \\ \\ r_{21}, r_{22}, r_{23}, r_{24}, r_{25} \end{bmatrix}, \quad (1)$$

where r_{ij} shows the performance of attribute U_i associated with fuzzy set V_j.

[16] 4. Formulate the weighted average judgment vector (**Z**) in terms of the relative importance of each attribute. That is,

$$\mathbf{Z} = W\mathbf{R} = (z_1, z_2, z_3, z_4, z_5), \quad (2)$$

where $W = (w_1, w_2)$ gives a set of assigned weights to the attributes.

[17] In this study the average values of historical data of each criterion are used to estimate their relative importance. Obviously, the accumulated inflow volume over longer period will carry greater weight to the drought impact assessment. The weighted average judgment vectors (**Z**) would be evidently influenced due to heavy weight change, so a reasonable choice of the period considered would be necessary. The water authorities in Taiwan customarily predict water consumption on the basis of 3-month-long future inflows. The past 3-month-long accumulated inflow is chosen to represent the attribute value of reservoir inflow. The value z_i inside vector **Z** reflects the degree of membership of attributes in the fuzzy set V_i, where state n with

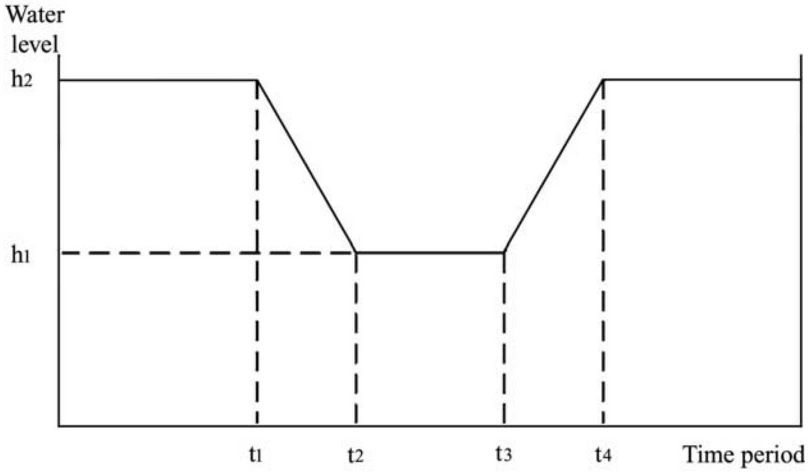

Figure 5. Variable definition of an operating rule.

$\sum_{i=1}^{n} z_i > 0.5 > \sum_{i=1}^{n-1} z_i$ indicates what status the drought watch belongs to.

3.2. Water Consumption Measure

3.2.1. Derivation of Operating Rules

[18] In deriving rule curves for a complex multireservoir system, obviously, simulation methods need enormous computational effort for getting closer to the optimum. The procedure to find the solutions might be tedious. In this study a genetic algorithm- based simulation model, a combination of optimization and simulation, is presented to specify how simple rule curves are efficiently developed in a multireservoir system. Genetic algorithms (GA) are a search method based on the principles of Darwinian natural selection and survival of the fittest, which compares favorably to the traditional optimization methods. Since 1975, GA have been applied to a variety of fields [*Goldberg*, 1989]. Indeed, GA give robust procedures to explore broad and potential regions of solutions and to narrow the possibilities of being trapped at the local optimum. For the two-parallel-reservoir system (the Feitsui and Shihmen reservoir system in northern Taiwan) the procedure of a GA-based simulation model in searching for operating rules is similar to the steps of GA-based SDP proposed by *Huang et al.* [2002]. The curves are shaped to change seasonally in response to the nature of inflows and demands. The chromosome represents the water allocation parameter (the percentage of required water quantity released from any specific reservoir to demand site) and a set of rule parameters indicating the release policy (Figure 5). The variables t_i shown in Figure 5 indicate the periods in which the curves' slopes change, and variables h_j reflect curves' water levels during the dry and wet seasons, respectively.

[19] The rule curves identify the storage zones associated with a certain operational behavior. In Taiwan the rule curves are defined with a 10-day-long time period. Since the designated rules only depend on the current water level, the operating policies of the Feitsui reservoir, for example, would be (1) to meet demand and generate as much electricity as possible if the water level is above the "upper rule," (2) to meet demand and generate 6-hour-long electricity if the water level is between the "upper rule" and "lower rule," (3) to fulfill demand and generate electricity on the basis of the released water if the water level is between the "lower rule" and "critical rule," and (4) to curtail demand by at least 20% if the water level is below the "critical rule" and to generate electricity if available. Two allocation parameters of water supply ratio for the wet and dry seasons, respectively, are considered inside the chromosome associated with releases from the Feitsui reservoir to the Banhsin plant. In addition, the designated chromosome includes six 8-bit substrings for each curve. That is, each reservoir needs 18 variables to represent the aforementioned rule curves inside a chromosome. Consequently, a chromosome herein has a total of 38 variables.

[20] The GA search begins with a randomly generated population of strings. In this study, multiple-point crossover is applied to diversify rule curves. In addition, there are 100 individuals in a generation with a maximum of 200 generations, and crossover and mutation probabilities are assigned to 1.0 and 0.01 individually. The GA fitness function is set to minimize both the water shortage and the spilled water over simulation period as follows:

$$\text{Minimize } \frac{X_i}{\sum_i X_i} + \frac{Y_i}{\sum_i Y_i}, \qquad i = 1, 2, \ldots, 100, \tag{3}$$

where X_i and Y_i are the average annual water shortage and spilled water of the ith chromosome's performance within the specified generation, respectively.

[21] Subsequently, an optimal joint operation of GA-based rule curves for the Feitsui and Shihmen reservoirs can be derived. Figure 6 gives the variation of the minimum and average losses (sum of shortage and spilled water) of each generation individually. Although fluctuation may exist among the generations, the performance approaches steady after 160 generations. In fact, the computation time with a Pentium IV processor is only 5 min throughout 200 generations. The optimal water allocation parameters (0.776, 0.957) show that during the wet and dry seasons 77.6 and 95.7%, respectively, of Banhsin's demand (one million tons per day) come from Feitsui's support. By means of the allocation percentages and the optimal joint operating rule curves (Figure 7) the measures of water consumption emerge.

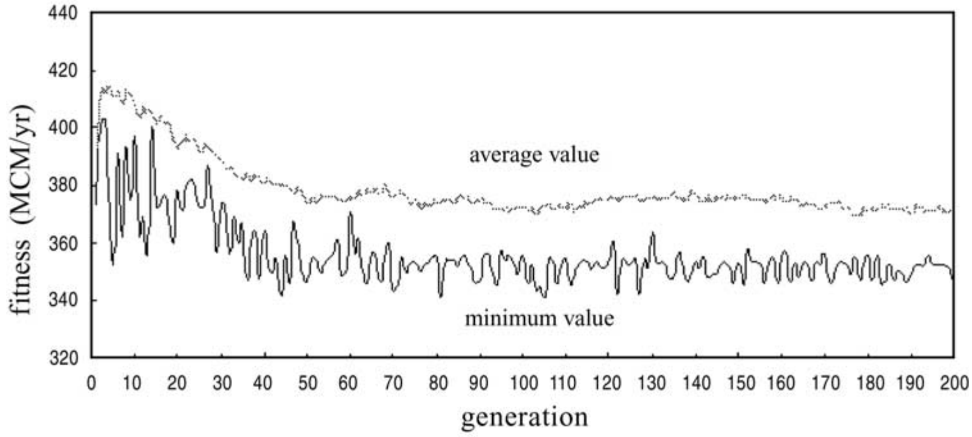

Figure 6. Variation of water deficit and excess loss over generations.

3.2.2. Future Expected Inflow

[22] In the case of given inflows the situation of whether or not the future water demand is satisfied would be clear. Nevertheless, reservoir operators may feel some hesitation in making decision for reservoir releases in a highly uncertain hydrological condition. So, in addition to the rule curves, an approach is provided by the authors on the basis of exceedence probability of inflow to assist reservoir

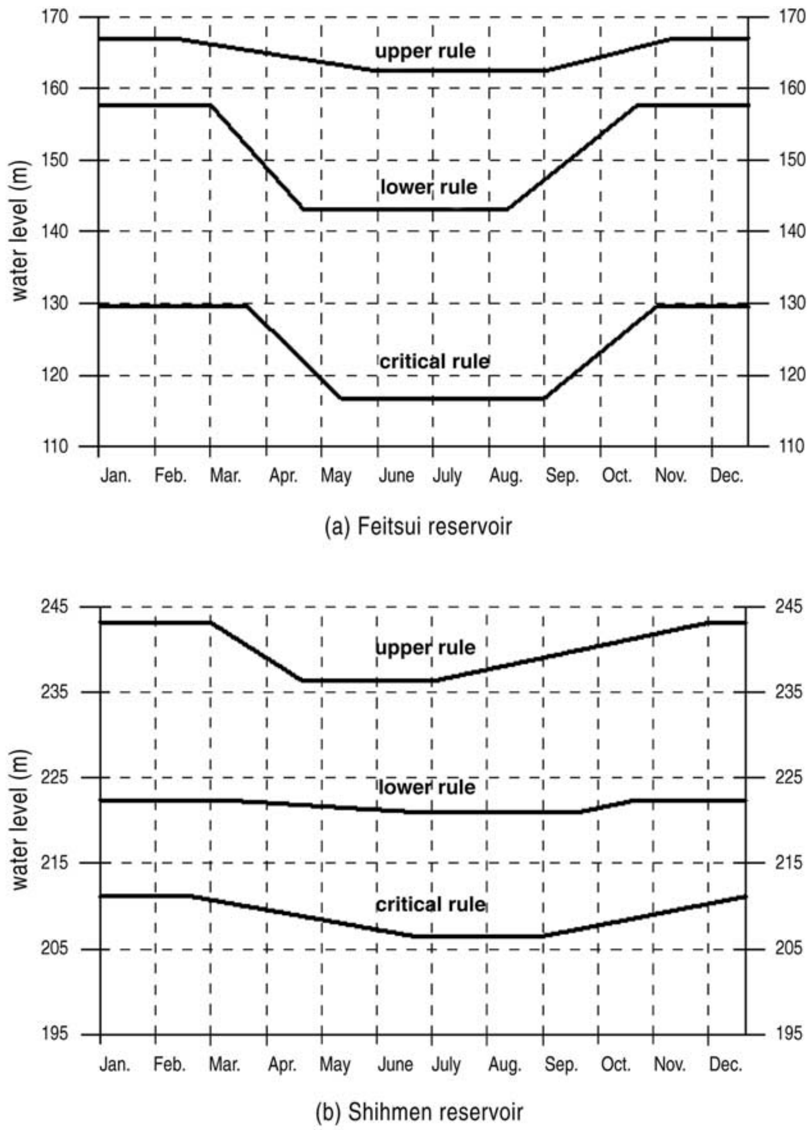

Figure 7. Optimal rule curves for joint operation.

Table 1. Judgments of Drought Severity

Severity Level	Drought Watch D	Water Shortage Rate S,[a] %		
		Irrigation	PWS1	PWS2
1	none	0	0	0
2	slightly severe	0–30	0–10	0–5
3	fairly severe	30–40	10–20	5–15
4	severe	40–50	20–30	15–30
5	very severe	>50	>30	>30

[a]PWS1 is public water supply in cooperation with irrigation, and PWS2 is public water supply alone.

managers to work out applicable rules for real-time reservoir operation [*Huang and Yang*, 1999]. That is,

$$P_r\left[Q \geq q_{(m)}\right] = \frac{m}{(n+1)}, \tag{4}$$

where Q is the streamflow at any specific site, a random variable in period t; $q_{(\mathrm{m})}$ is a possible value of Q, the mth largest observation; and n equals the total number of observations.

[23] Performances on the basis of 3-month-long future inflows are measured across a range of possible conditions, from optimistic (based on a 30% exceedence probability of streamflow) to pessimistic (based on 95% exceedence probability). The water consumption measures give helpful information assisting reservoir operators to examine potential variation of reservoir storage in the near future.

3.3. Policy Making

[24] Truly, during the real-time reservoir operation, the aforementioned rule curves are only guides and may not definitely ensure the most rational utilization of water resources. Under uncertain nature, one of the most challenging tasks inherent in the real-time operation of a reservoir is to decide when to alter release policy and allocate storage space, for example, for the purpose of public water supply instead of using it for hydropower generation. This reservoir management problem is frequently encountered in Taiwan, which is dominated by a long dry season and a subsequent typhoon-borne rainy season.

[25] Amid the decision-making in terms of current drought watch, future inflows, and possible water consumption status the policy would require the subjective judgment of the decision maker [*Hwang and Yoon*, 1981; *Zeleny*, 1982]. For simplicity, with an eye to practical use, numerical judgments are made using a five-point scale to quantify the order for the present drought condition (D) and future water consumption state (S) (Table 1). Note that for a multipurpose reservoir with irrigation and public water supply the state S corresponds to the worse of the two. As a matter of convenience, a mapping of the degree of drought severity in the interval 0 to 1 is assigned, a normalization of the specified indices by linear-scale transformation would be essential for drought impact assessment. Given exceedence probability of inflows (Q_i), a standardized drought alert index (DAI) for drought management is defined as

$$\mathrm{DAI} = f(D, S|Q_i) = \frac{D}{5} \times \frac{S}{5} = \frac{DS}{25}. \tag{5}$$

It is clear that $0 < \mathrm{DAI} \leqq 1$, and the outcome is more favorable as DAI approaches 0. In this study a five-level, color-coded scale, together with the responses corresponding to each of the warning categories, is introduced, as shown in Table 2. The signal identifying an intensity of drought severity may warn authorities to be on the alert for potential water deficit. The responses may vary with case studies. As a rule, public water supply will acquire a priority for water use over irrigation if water restriction is imposed. Under the "blue" alert level, for example, the agricultural requirement during the growing season would be curtailed up to 30%, while the demand for municipality and industry remained the same.

[26] For the sake of convenient reference to the water authorities, it is acceptable to choose an inflow exceedence probability of 95% as a critical level. For example, in the case of D in level 3, $(S|Q_{95})$ in level 4, the DAI value of 0.48 indicates an alert level of "orange," suggesting an action of water reduction by a predetermined 50% at least for irrigation and by 10–30% for public water supply in response to potential severe water shortage during the next 3 months. Note that in response to possible water shortage, because of emergency assistance from irrigation, the reduction rate of public water supply on a multipurpose reservoir (e.g., the Shihmen) would possibly be lower than that on the single-purpose one (e.g., the Feitsui). The pressure from water deficit, of course, would be reduced by a timely water cut and/or better hydrologic conditions, possibly resulting in lower alert levels. As a result of proper water reduction, it is presumed that the warning signal should turn to "green" in those cases with drought conditions better than the V_3 level (fairly severe) and upgrade to "blue" for the others.

4. Applicability of the Drought Early Warning System

[27] There was much debate about the timing of water rationing, both during the drought and in the aftermath of the 2002 event. Occasionally, the decision-making process may be hampered by politics. Thus openly professional discussion for what is proper in determining a policy is needed. Here detailed descriptions of the application of the developed warning system are presented, and the results for the 2002 drought case are as follows.

4.1. Decision Making in January of 2002

4.1.1. Joint Operation

[28] The accumulated quantity of 3-month-long inflow to Shihmen from November through January equaled 130.53×10^6 m^3, ~35% of the exceedence probability, belonging to an abundant inflow (see Table 3). In the meantime, the actual storage of the Shihmen reservoir was

Table 2. Responses to Drought Severity

Alert Signal	Drought Alert Index (DAI)	Water Cut Rate, %		
		Irrigation	PWS1	PWS2
Green	$(\mathrm{DAI} \leq 0.1)$	0	0	0
Blue	$(0.1 < \mathrm{DAI} \leq 0.25)$	~0–30	0	~0–5
Yellow	$(0.25 < \mathrm{DAI} \leq 0.4)$	~30–50	~0–10	~5–10
Orange	$(0.4 < \mathrm{DAI} \leq 0.65)$	>50	~10–20	~10–30
Red	$(0.65 < \mathrm{DAI} \leq 1)$	100	>20	>30

Table 3. Real-Time Drought Watch of Joint Operation in 2002

	Shihmen Reservoir						Feitsui Reservoir					
	Jan.	Feb.	March	April	May	June	Jan.	Feb.	March	April	May	June
Weight of inflow	0.40	0.40	0.48	0.55	0.59	0.63	0.48	0.44	0.43	0.40	0.39	0.43
Weight of storage	0.60	0.60	0.52	0.45	0.41	0.37	0.52	0.56	0.57	0.60	0.61	0.57
Past 3-month-long inflows, $\times 10^6$ m^3	130.53	93.76	81.53	77.67	73.93	91.55	130.21	127.96	78.10	70.31	53.65	68.74
Exceedence probability	0.35	0.63	0.85	0.9	0.93	0.97	0.93	0.93	0.96	0.91	0.94	0.97
Current water level M	231.42	223.37	214.82	204.84	198.98	204.43	156.07	153.17	144.3	133.91	122.38	119.44
Effective storage, %	57.0	38.0	22.2	8.8	3.1	8.3	64.5	58.5	42.0	26.0	10.7	7.6
Membership of level 1	0.820	0	0	0	0	0	0	0	0	0	0	0
Membership of level 2	0.180	1	0	0	0	0	0.520	0.558	0.285	0.120	0	0
Membership of level 3	0	0	0.605	0	0	0	0	0	0.285	0.478	0.307	0.114
Membership of level 4	0	0	0.395	0.819	0.537	0.411	0.336	0.309	0.172	0.362	0.539	0.585
Membership of level 5	0	0	0	0.181	0.463	0.589	0.144	0.133	0.258	0.040	0.155	0.301
Drought severity D	none (1)	slightly severe (2)	fairly severe (3)	severe (4)	severe (4)	very severe (5)	slightly severe (2)	slightly severe (2)	fairly severe (3)	fairly severe (3)	severe (4)	severe (4)

Table 4. Real-Time Water Consumption Measure of Joint Operation in 2002

Exceedence Probability of Potential Inflow	Shihmen Reservoir, %												Feitsui Reservoir, %					
	Jan.		Feb.		March		April		May		June		Jan.	Feb.	March	April	May	June
	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	PWS2	PWS2	PWS2	PWS2	PWS2	PWS2
Q_{30}	3.3	2.3	9.6	6.7	6.9	3.7	5.7	4.3	0.0	4.3	3.3	2.1	0.0	0.0	0.0	0.0	0.0	0.0
Q_{50}	3.3	2.3	18.9	14.1	26.5	17.6	15.0	10.9	0.0	4.3	6.8	4.3	0.0	0.0	0.0	0.0	0.0	0.0
Q_{70}	6.6	4.6	26.1	14.1	30.0	20.0	30.0	20.0	14.9	13.1	21.0	13.0	0.0	0.0	0.0	0.0	10.7	8.8
Q_{80}	10.2	6.9	35.9	16.0	30.0	20.0	30.0	20.0	30.0	20.0	30.0	20.0	0.0	0.0	0.0	0.0	23.2	18.6
Q_{90}	10.2	6.9	48.0	18.0	45.1	20.0	48.0	20.0	30.0	20.0	33.4	20.0	0.0	0.0	13.5	12.3	39.2	37.7
Q_{95}	17.0	6.9	53.7	24.7	49.6	23.2	66.3	23.0	55.8	20.0	52.4	20.0	0.0	11.9	30.8	30.5	51.8	49.5

Table 5. Real-Time Drought Management of Joint Operation in 2002

	Shihmen Reservoir						Feitsui Reservoir					
	Jan.	Feb.	March	April	May	June	Jan.	Feb.	March	April	May	June
Drought severity D	1	2	3	4	4	5	2	2	3	3	4	4
Water Consumption State S												
$S \mid Q_{30}$	2	2	2	2	2	2	1	1	1	1	1	1
$S \mid Q_{50}$	2	3	3	2	2	2	1	1	1	1	1	1
$S \mid Q_{70}$	2	3	3	3	3	3	1	1	1	1	3	3
$S \mid Q_{80}$	2	3	3	3	3	3	1	1	1	1	4	4
$S \mid Q_{90}$	2	4	4	4	3	3	1	1	3	3	5	5
$S \mid Q_{95}$	2	5	4	5	5	5	1	3	5	5	5	5
Drought Alert Index (DAI)												
Q_{30}	0.08	0.16	0.24	0.32	0.32	0.4	0.08	0.08	0.08	0.12	0.16	0.16
Q_{50}	0.08	0.24	0.36	0.32	0.32	0.4	0.08	0.08	0.08	0.12	0.16	0.16
Q_{70}	0.08	0.24	0.36	0.48	0.48	0.6	0.08	0.08	0.08	0.12	0.48	0.48
Q_{80}	0.08	0.24	0.36	0.48	0.48	0.6	0.08	0.08	0.08	0.12	0.64	0.64
Q_{90}	0.08	0.32	0.48	0.64	0.48	0.6	0.08	0.08	0.36	0.36	0.8	0.8
Q_{95}	0.08	0.4	0.48	0.8	0.8	1	0.08	0.24	0.6	0.6	0.8	0.8
Drought Warning Level												
Q_{30}	G	B	B	Y	Y	Y	G	G	G	B	B	B
Q_{50}	G	B	Y	Y	Y	Y	G	G	G	B	B	B
Q_{70}	G	B	Y	O	O	O	G	G	G	B	O	O
Q_{80}	G	B	Y	O	O	O	G	G	G	B	O	O
Q_{90}	G	Y	O	O	O	O	G	G	Y	Y	R	R
Q_{95}	G	Y	O	R	R	R	G	B	O	O	R	R
Suggested alert signal	G	B	Y	O	O	O	G	G	Y	O	R	R

135.21×10^6 m^3, ~57% of the active storage. Following equation (1), their outcomes associated with the fuzzy set would be (1, 0, 0, 0, 0) and (0.7, 0.3, 0, 0, 0), respectively. Moreover, in terms of their estimated weight ratio, (0.4:0.6), the measure of the drought indices, equal to (0.82, 0.18, 0, 0, 0), appeared good at the "none" level (i.e., drought condition $D = 1$), the lowest in a five-level scale. However, the past 3-month inflow into Feitsui appeared poor, close to 93% of the exceedence probability. Fortunately, the current reservoir storage remained fruitful with 231.56×10^6 m^3, 64.5% of the active storage. The present drought condition (D) in drought watch was found at level 2, where the concurrent weight ratio of inflow to storage volume is 0.48:0.52.

[29] By using the GA-based rule curves in Figure 7 and potential hydrologic conditions corresponding to (Q_{30}, Q_{50}, Q_{70}, Q_{80}, Q_{90}, Q_{95}), the associated possible water shortage rates in Shihmen for the next 3 months equaled (3.3%, 3.3%, 6.6%, 10.2%, 10.2%, 17%) and (2.3%, 2.3%, 4.6%, 6.9%, 6.9%, 6.9%)for irrigation and public water supply, respectively (Table 4). Subsequently, on the basis of the shortage zone shown in Table 1 the water consumption measures ($S|Q_i$) yielded to (2, 2, 2, 2, 2, 2) levels. By using equation (5) the DAI values equaled (0.08, 0.08, 0.08, 0.08, 0.08, 0.08). That is, the early warning system appeared all to be at the (G, G, G, G, G, G) signals (Table 5). This indicates a decision where the "green" announcement would be the most appropriate one at this time. Again, following the derived GA-based curves of Feitsui, no shortage occurred for the next 3 months (February through April), regardless of hydrologic conditions within the same periods (Table 4). Therefore, similar to Shihmen's operation, the DAI gave a unique value at 0.08, indicating a "green" signal for Feitsui's operation as well. Thus, in the case of joint operation, both reservoirs can release water as scheduled.

4.1.2. Independent Operation

[30] For the case of independent reservoir operations by Shihmen and Feitsui, during the process of drought watch, the outcome for the attribute of reservoir inflow will be the same as above but may not be the same for the attribute of reservoir storage because of the use of nonoptimal rule curves. Therefore, as seen in Table 6, the present drought condition in Shihmen fell into a worse level of 3. Furthermore, the water shortage in Shihmen for the irrigation and public water supply will obviously deteriorate without assistance of Feitsui, up to (17.8%, 17.8%, 32.2%, 38.4%, 42.9%, 45.2%) and (11.2%, 11.2%, 13.4%, 13.4%, 19.5%, 25.2%) instead (see Table 7). By choosing worse conditions between the two, the water consumption measures ($S|Q_i$) gave (3, 3, 3, 3, 4, 4) levels. Accordingly, in terms of the calculated DAI values an alarm of potential water shortage emerged at the status of (Y, Y, Y, Y, O, O), corresponding to the picked hydrologic conditions of (Q_{30}, Q_{50}, Q_{70}, Q_{80}, Q_{90}, Q_{95}), as presented in Table 8. Alarm signals no better than "yellow" warned authorities to be on the alert for water deficit as a dry spell continues. In response to the designated warning signals categorized in Table 2, at least a 30% water cut in irrigation should be taken along with a slight cut for public water supply from early February. In comparison with Shihmen's operation at high pressure, results in Tables 6–8 indicate that Feitsui was free of any shortage, where D remained at level 2, resulting in the "green" level. Obviously, it is not as efficient that Feitsui's surplus water cannot be utilized to replace Shihmen's deficit water.

[31] The administration of Shihmen reservoir actually estimated the area probably encounters a deficit situation after mid-March. Furthermore, the Central Weather Bureau predicted less-than-normal rainfall in the coming months.

Table 6. Real-Time Drought Watch of Independent Operation in 2002

	Shihmen Reservoir						Feitsui Reservoir					
	Jan.	Feb.	March	April	May	June	Jan.	Feb.	March	April	May	June
Weight of inflow	0.40	0.40	0.48	0.55	0.59	0.63	0.48	0.44	0.43	0.40	0.39	0.43
Weight of storage	0.60	0.60	0.52	0.45	0.41	0.37	0.52	0.56	0.57	0.60	0.61	0.57
Past 3-month-long inflows, $\times 10^6$ m^3	130.53	93.76	81.53	77.67	73.93	91.55	130.21	127.96	78.10	70.31	53.65	68.74
Exceedence probability	0.35	0.63	0.85	0.9	0.93	0.97	0.93	0.93	0.96	0.91	0.94	0.97
Current water level M	231.42	223.37	214.82	204.84	198.98	204.43	156.07	153.17	144.3	133.91	122.38	119.44
Effective storage, %	57.0	38.0	22.2	8.8	3.1	8.3	64.5	58.5	42.0	26.0	10.7	7.6
Membership of level 1	0.401	0	0	0	0	0	0	0	0	0	0	0
Membership of level 2	0	0.399	0	0	0	0	0.520	0.558	0.570	0.120	0	0
Membership of level 3	0.479	0.300	0.238	0	0	0	0	0	0	0.478	0.307	0.057
Membership of level 4	0.120	0.300	0.605	0.774	0.537	0.523	0.336	0.309	0.172	0.362	0.539	0.642
Membership of level 5	0	0	0.157	0.226	0.463	0.477	0.144	0.133	0.258	0.040	0.155	0.301
Drought severity D	fairly severe (3)	fairly severe (3)	severe (4)	severe (4)	severe (4)	severe (4)	slightly severe (2)	slightly severe (2)	slightly severe (2)	fairly severe (3)	severe (4)	severe (4)

Table 7. Real-Time Water Consumption Measure of Independent Operation in 2002

Exceedence Probability of Potential Inflow	Shihmen Reservoir, %												Feitsui Reservoir, %					
	Jan.		Feb.		March		April		May		June		Jan.	Feb.	March	April	May	June
	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	Irrigation	PWS1	PWS2	PWS2	PWS2	PWS2	PWS2	PWS2
Q_{30}	17.8	11.2	30.0	20.0	30.0	20.0	8.5	6.5	0.0	4.3	3.3	2.2	0.0	0.0	0.0	0.0	0.0	0.0
Q_{50}	17.8	11.2	39.3	20.0	30.0	20.0	25.9	17.7	14.9	13.2	14.1	8.7	0.0	0.0	0.0	0.0	0.0	0.0
Q_{70}	32.2	13.4	60.8	22.2	42.7	20.0	43.9	20.0	30.0	20.0	30.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0
Q_{80}	38.4	13.4	65.8	24.3	53.4	20.1	57.1	20.3	32.4	20.0	32.4	20.0	0.0	0.0	0.0	0.0	6.9	6.3
Q_{90}	42.9	19.5	68.2	34.9	69.0	23.9	74.2	23.6	58.0	20.0	59.8	20.0	0.0	0.0	0.0	9.8	18.2	20.0
Q_{95}	45.2	25.2	71.9	40.9	76.2	33.4	84.9	34.8	80.3	22.1	78.9	20.0	0.0	0.0	12.7	28.4	36.9	33.2

Table 8. Real-Time Drought Management of Independent Operation in 2002

	Shihmen Reservoir						Feitsui Reservoir					
	Jan.	Feb.	March	April	May	June	Jan.	Feb.	March	April	May	June
Drought severity (D)	3	3	4	4	4	4	2	2	2	3	4	4
Water Consumption State S												
$S \mid Q_{30}$	3	3	3	2	2	2	1	1	1	1	1	1
$S \mid Q_{50}$	3	3	3	3	3	2	1	1	1	1	1	1
$S \mid Q_{70}$	3	5	4	4	3	3	1	1	1	1	1	1
$S \mid Q_{80}$	3	5	5	5	3	3	1	1	1	1	3	3
$S \mid Q_{90}$	4	5	5	5	5	5	1	1	1	3	4	4
$S \mid Q_{95}$	4	5	5	5	5	5	1	1	3	4	5	5
Drought Alert Index DAI												
Q_{30}	0.36	0.36	0.48	0.32	0.32	0.32	0.08	0.08	0.08	0.12	0.16	0.16
Q_{50}	0.36	0.36	0.48	0.48	0.48	0.32	0.08	0.08	0.08	0.12	0.16	0.16
Q_{70}	0.36	0.6	0.64	0.64	0.48	0.48	0.08	0.08	0.08	0.12	0.16	0.16
Q_{80}	0.36	0.6	0.8	0.8	0.48	0.48	0.08	0.08	0.08	0.12	0.48	0.48
Q_{90}	0.48	0.6	0.8	0.8	0.8	0.8	0.08	0.08	0.08	0.36	0.64	0.64
Q_{95}	0.48	0.6	0.8	0.8	0.8	0.8	0.08	0.08	0.24	0.48	0.8	0.8
Drought Warning Level												
Q_{30}	Y	Y	O	Y	Y	Y	G	G	G	B	B	B
Q_{50}	Y	Y	O	O	O	Y	G	G	G	B	B	B
Q_{70}	Y	O	O	O	O	O	G	G	G	B	B	B
Q_{80}	Y	O	R	R	O	O	G	G	G	B	O	O
Q_{90}	O	O	R	R	R	R	G	G	G	Y	O	O
Q_{95}	O	O	R	R	R	R	G	G	B	O	R	R
Suggested alert signal	Y	O	R	R	R	R	G	G	G	O	O	R

Thus the administration warned that water rationing to curtail water supply might be needed soon. It is regrettable that this warning was overlooked at the time of the cabinet reshuffle in February. As scheduled, the demand for irrigation (1.8×10^6 m^3/d) and public water supply (1.5×10^6 m^3/d) from the Shihmen reservoir remained the same in February; that is, instead of the suggested ‘‘yellow’’ level, no action, comparable to the ‘‘green’’ level, was taken. Furthermore, the Shihmen began to deliver an extra quantity of 55,000 tons of water per day to the HSIP after mid-February. Since the government decided to keep the planting schedule of rice without change, the ‘‘green’’ level decision was criticized and identified as ‘‘inappropriate’’ afterward. The authorities did not catch the timing for water rationing at the end of January.

4.2. Decision Making in February of 2002

4.2.1. Joint Operation

[32] Since an improper decision was made by the authorities at the end of January, the reservoir storage in Shihmen fell dramatically from 135.21×10^6 m^3 to 92.45×10^6 m^3 within 1 month. Additionally, at the end of February the accumulated amount of inflow to Shihmen from December to February retained only 93.76×10^6 m^3, nearly 63% of the exceedence probability. Together with 92.45×10^6 m^3 left in Shihmen storage, the fuzzy drought assessments for both hydrology and water supply simultaneously yielded (0, 1, 0, 0, 0). The drought condition appeared worse, and the overall drought watch descended to the ‘‘slightly severe’’ level (i.e., $D = 2$). Furthermore, the inflow into Feitsui during the same period remained poor at 93% of the exceedence probability. Together with the remaining volume of 209.93×10^6 m^3, the assessment of drought condition in Feitsui was then unchanged at level 2.

[33] Again, following the GA-based rule curves, the water deficit in Shihmen over the next 3 months could rise to (9.6%, 18.9%, 26.1%, 35.9%, 48.0%, 53.7%) in agriculture and (6.7%, 14.1%, 14.1%, 16%, 18%, 24.7%) in municipal use. Therefore the water consumption measures ($S|Q_i$) turned worse to (2, 3, 3, 3, 4, 5) levels, making DAI values equal (0.16, 0.24, 0.24, 0.24, 0.32, 0.4). The early warning system thus yielded signals of (B, B, B, B, Y, Y) depending on potential inflow of the next 3 months. Feitsui, simultaneously, attained the colors of (G, G, G, G, G, B), where water deficit could emerge in May as the hydrologic condition inferior to Q_{90} occurs.

[34] The ranking shows signs of deterioration in February. At this point, the decision maker may consider what signal should be announced; perhaps optimistically with ‘‘green’’ in Feitsui and pessimistically with ‘‘yellow’’ in Shihmen? The signal obviously depends on the incoming rainfall/inflow within the next 3 months. Since decision making under uncertainty might be difficult, the decision maker would be in favor of more information for a prospective operation by a forecast of future expected rainfall/inflows to the reservoir(s). Nevertheless, accurate prediction will not be easy. No single forecasting model would be universal, and they all rely upon the characteristics of the particular water resources system. Here the information from the Central Weather Bureau is the most influential for reservoir operators. In general, every incoming 3-month-long rainfall will be provided in Taiwan. On 28 February, the weather bureau predicted insignificant amounts of rainfall in March over the area and normal amounts in April and May. Thus a ‘‘blue’’ alarm in Shihmen and ‘‘green’’ in Feitsui would be more appropriate. Under the proposed methodology a plan to reduce 30% of water, at a maximum, from irrigation in Shihmen should be imposed (Table 2).

Table 9. Drought Relief After Taking Action

	Shihmen Reservoir						Feitsui Reservoir					
	Jan.	Feb.	March	April	May	June	Jan.	Feb.	March	April	May	June
	After Government's Action											
Q_{30}	Y	B	B	B	B	B	G	G	G	B	B	B
Q_{50}	Y	B	B	B	B	B	G	G	G	B	B	B
Q_{70}	Y	B	Y	B	B	Y	G	G	G	B	B	B
Q_{80}	Y	B	O	B	Y	Y	G	G	G	B	B	B
Q_{90}	O	Y	O	Y	Y	O	G	G	G	B	B	B
Q_{95}	O	O	R	Y	O	R	G	G	Y	B	O	O
	Suggested Action for Independent Operation											
	Y	O	R	R	R	R	G	G	G	O	O	R
	After Suggested Action for Independent Operation											
Q_{30}	B	B	B	B	B	B	G	G	G	B	B	B
Q_{50}	B	B	B	B	B	B	G	G	G	B	B	B
Q_{70}	B	B	B	B	B	B	G	G	G	B	B	B
Q_{80}	B	B	B	B	B	B	G	G	G	B	B	B
Q_{90}	B	B	B	B	B	B	G	G	G	B	B	B
Q_{95}	B	B	B	B	B	B	G	G	B	B	Y	B
	Suggested Action for Joint Operation											
	G	B	Y	O	O	O	G	G	Y	O	R	R
	After Suggested Action for Joint Operation											
Q_{30}	G	G	B	B	B	B	G	G	G	B	B	B
Q_{50}	G	G	B	B	B	B	G	G	G	B	B	B
Q_{70}	G	B	B	B	B	B	G	G	G	B	B	B
Q_{80}	G	B	B	B	B	B	G	G	G	B	B	B
Q_{90}	G	B	B	B	B	B	G	G	B	B	B	B
Q_{95}	G	B	B	Y	B	B	G	B	Y	B	B	B

4.2.2. Independent Operation

[35] For an independent operation, clearly, Feitsui has little problem with water supply. Together with drought survey at $D = 2$, the water demand of the next 3 months can be completely satisfied. There is no problem to proclaim "green" status for Feitsui at this time. Shihmen, however, has to bear the whole burden of feeding the Banhsin area alone. Consequently, potential water shortage rates for the next 3 months will dramatically rise to (30%, 39.3%, 60.8%, 65.8%, 68.2%, 71.9%) for irrigation and (20%, 20%, 22.2%, 24.3%, 34.9%, 40.9%) for water supply. The water consumption measures would then stick to (3, 3, 5, 5, 5, 5) levels. On the other hand, the present drought condition was found at level 3. Subsequently, through the DAI examination the early warning system shows the water deficit signals by (Y, Y, O, O, O, O). Either "yellow" or "orange" reflects signs of water shortage severity in Shihmen, and an irrigation fallow project (from late February through June) should be introduced as early as possible. Here holding action in response to the "orange" warning signal is suggested.

[36] In fact, two farming communities are in charge of 10,000 and 25,000 hectares of farmland, respectively, in the Shihmen area. When fallow is imperative, three options would be available. In response to the warning signals the "yellow" level denotes terminating the impending irrigation projects of the former, while "orange" implies to quit the latter so as to assure the public water supply. On the basis of the published material the government, however, should compensate owners for farmland to be left idle for water rationing, at a rate of NT$46,000 per hectare. Then a total fund of NT$460 million (approximately US$13 million) for 10,000 hectares to be left idle in the Shihmen's irrigation area would be required.

[37] Actually, as from 1 March, the government made a decision akin to the "yellow" option to fallow 10,000 hectares of farmland. The water authorities approved Shihmen to furnish water for agriculture at 0.9×10^6 m^3 per day (i.e., 30% off the demand for the other 25,000 hectares of farmland) and for domestic use at 1.5×10^6 m^3 per day. By taking this option, the prior signals (Y, Y, O, O, O, O) would change to (B, B, B, Y, O, O), as presented in Table 9. Along with future inflows above 70% exceedence probability the loading would be still too heavy in Shihmen to descend to the "blue" level. In fact, the approaching hydrologic condition was getting worse, and the option eventually brought insignificant relief to the deficit. Later, the authorities revised to give 0.77×10^6 m^3/d for irrigation (40% off) and nearly 1.425×10^6 m^3/d for domestic use (5% off) beginning from 15 March. If an "orange" action were taken instead, more water could be reserved for domestic use, and the warnings of (Y, Y, O, O, O, O) could come down to (B, B, B, B, B, B). It shows to catch a right timing for water rationing is considerably crucial and influential. Because of an inappropriate decision, as such, a water deficit crisis gripped the Shihmen area starting in March. Subsequently, a fight to cope with the suffering began, including numerous criticisms on "mismanagement."

4.3. Decision Making After February of 2002

[38] With no significant relief in sight the persistent drought continued to hit northern Taiwan over the next 4 months. The drought indices used for joint/independent operations were getting worse and worse (see Tables 3

and 6). The prolonged drought deepened the water shortage crisis (see Tables 4 and 7). Since Taiwan usually abounds with rain in May and June, it was expected to bring plentiful rainfall as needed during the period. In reality, a total rainfall of 328.1 and 267.3 mm fell into Feitsui and Shihmen basins, respectively, for this period, bringing little relief to the parched areas.

[39] On 1 July, the water level in Feitsui had dropped to an all-time low with effective storage of 26.21×10^6 m^3, ∼ 7.7% of the active capacity. Also, the effective storage in Shihmen approximated 18.78×10^6 m^3, ∼8% of the active capacity. Timely rainfall brought by typhoons would be the only solution to the prolonged dry spell. The typhoon season most often begins in July. Fortunately, beginning on 3 July, Typhoon Rammasun brought torrential rainfall over northern Taiwan. The accumulated rainfall reached 247 mm in Feitsui's catchment within 48 hours and 443 mm in Shihmen's catchment as well. The abundant rains gave a rapid increase of reservoir storages to 85.66×10^6 m^3 in Feitsui and 183.51×10^6 m^3 in Shihmen. On 5 July, the end of water rationing was announced by the government and the prolonged drought was finally over.

4.3.1. Joint Operation

[40] Both the drought watch and water consumption measures are related to the remaining reservoir storage, no matter how operators have run the reservoir before. That is, the joint real-time operation may start with the initial storage out of a prior proper/improper decision. Because of a string of inappropriate decisions made by authorities, Shihmen's storage plummeted quickly. There were only 22.2 and 8.8% of the effective storages left in the end of March and April, respectively (Table 3). The situation will definitely deteriorate the outcomes of the joint operation after February. Thus a "yellow" alert at the end of March and an elevated "orange" warning after April (Table 5) is suggested. On the other hand, unlike in Shihmen, the option of obtaining water from the agricultural sector is not available in Feitsui. It appeared that Taipei could encounter serious water deficit after April if the approaching hydrologic conditions remained poor, above 90% exceedence probability. In response, Feitsui's alert level should be raised from "green" in February promptly to "yellow" in March and elevated to "orange" in April. The worst signal, "red," would be advisable in May and June.

4.3.2. Independent Operation

[41] In the case of independent operation the highest "red" alert against drought was inevitable in Shihmen after March (Table 8). That is, from 1 April, a policy to immediately stop all irrigation water and to curtail public water supply by at least 20% was the only choice in Shihmen. However, no further stricter action was given by the authorities until 1 May. Table 8 indicates that the water supply in Feitsui can remain normal until the end of April. The suggestion of an "orange" alert in Feitsui would be preferred then. The drought plaguing northern Taiwan persisted and prompted the central government to form a Drought Disaster Relief Center on 1 May to deal with the worsening water shortage problem. A series of water-saving actions, akin to a "red" signal in Shihmen and an "orange" signal in Feitsui, were taken: (1) to suspend all irrigation water, (2) to cut public water supply by 20% or even tighter restrictions if needed, and (3) to give full water supply to the HSIP.

[42] As illustrated in Table 9, it is quite obvious that the pertinent authorities appeared to be insensitive and indecisive to the drought threats compared with the effective responses via the developed early warning system. The slow response caused the resignation of a minister and consequently caused a jittery attitude toward reservoir operation. In addition, the unforeseen arose; that is, a dysentery outbreak due to polluted water, feeble performance of the tech stocks due to concerns over water deficit, and debates on when to start a water rationing program and how to allocate reservoir's water efficiently. If the authorities could have made a prompt and proper decision for fallow farmland by the end of February 2002, the cost and public criticism would have been less.

[43] A keen judgment of fallow farmland was quickly made after such an impressive and bitter lesson in 2002. By the end of January 2003, on the basis of the current operating rules, the drought assessment yielded signals of (O, O, O, O, O, O) along with $D = 4$ and $(S|Q_i) = (3, 3, 3, 4, 4, 4)$. A highly potential drought prompted the authorities concerned to seriously consider options for fallow farmland, and eventually the government decided to impose a fallow project analogous to the "orange" alert level for the next growing season, i.e., 25,000 ha of farmland in the Shihmen area. A total of NT$1.2 billion was estimated for compensation. Nonetheless, a possible water crisis in 2003 was defused. The timely decision for the fallow project was worth the cost.

[44] With regard to the effect of attribute weight on the drought status assessment, Tables 6 and 10 show the weight impact associated with 1- and 3-month-long accumulated reservoir inflow, respectively. The former obviously has a smaller weight, as compared with the attribute of reservoir storage. The weighted average judgment vector (**Z**) in each month of the 2002 drought example is really influenced by weight change. However, the drought status (D) does not change significantly because the determination of drought status is based on the rule of $\sum_{i=1}^{n} \mathrm{z_i} > 0.5 > \sum_{i=1}^{n-1} \mathrm{z_i}$, rather than z_i.

[45] Overall, rules for long-term reservoir operation are indeed too rigid to manage drought alerts. So an appropriate decision making under uncertainty for a real-time reservoir operation becomes a challenging task. It is important and helpful to have an early warning system for drought management concerning when to renew the operational mode. In this study the proposed drought early warning system has definitely proved its applicability to the real-time reservoir operation. Whether joint operation or independent operation, the system can aid the water authorities concerned on how to take a decisive step while confronting drought threats.

5. Conclusions

[46] This paper has presented a newly developed early warning system for drought management. Accounting for the past hydrologic inflows, present reservoir storages and future water consumption, the five-level, color-coded system, ranging from "green" (very low risk of water deficit) to "red" (very high risk of water deficit), will allow management to make proper decisions in response to potential drought severity. The directions to the reservoir

Table 10. Sensitivity of Drought Severity Due to Weight Change (Independent Operation in 2002)

	Shihmen Reservoir						Feitsui Reservoir					
	Jan.	Feb.	March	April	May	June	Jan.	Feb.	March	April	May	June
Weight of inflow	0.14	0.22	0.28	0.29	0.35	0.46	0.19	0.22	0.18	0.14	0.19	0.26
Weight of storage	0.86	0.78	0.72	0.71	0.65	0.54	0.81	0.78	0.82	0.86	0.81	0.74
Past 1-month-long inflows, $\times 10^6$ m^3	28.99	27.49	25.05	25.13	23.75	42.67	29.43	39.61	21.35	20.41	20.33	38.81
Exceedence probability	0.81	0.83	0.91	0.92	0.93	0.93	0.98	0.93	0.98	0.98	0.95	0.91
Current water level *M*	231.42	223.37	214.82	204.84	198.98	204.43	156.07	153.17	144.3	133.91	122.38	119.44
Effective storage, %	57.0	38.0	22.2	8.8	3.1	8.3	64.5	58.5	42.0	26.0	10.7	7.6
Membership of level 1	0	0	0	0	0	0	0	0	0	0	0	0
Membership of level 2	0	0	0	0	0	0	0.810	0.785	0.823	0.172	0	0
Membership of level 3	0.814	0.545	0	0	0	0	0	0	0	0.687	0.405	0.074
Membership of level 4	0.186	0.455	0.533	0.412	0.300	0.624	0.038	0.151	0.035	0.028	0.500	0.900
Membership of level 5	0	0	0.467	0.588	0.700	0.376	0.152	0.065	0.141	0.113	0.095	0.026
Drought severity *D*	fairly severe (3)	fairly severe (3)	severe (4)	very severe (5)	very severe (5)	severe (4)	slightly severe (2)	slightly severe (2)	slightly severe (2)	fairly severe (3)	severe (4)	severe (4)

operators on what to do at each alert signal are included as well. By receiving more helpful information from the warning system for drought assessment the decision makers will enlarge their understanding toward natural uncertainty and make a timely decision on the real-time reservoir operation. An appropriate response can lower the threat of drought appreciably, and the warning level will then be turned back to normal. The drought warning system has been applied experimentally to the two major reservoirs in northern Taiwan with satisfactory results.

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