Assessing the Impact of Reducing Agriculture Water Demand on Water Resource Management using Multi-objective Planning

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ABSTRACT

The amount of water supplied to agriculture is reduced during drought periods, as saved water is transferred to meet industrial or municipal requirements in Taiwan because the economic return of water used for agriculture is lower than that of water used for other purposes. However, the impact on the management of regional water resources of transferring the water from agriculture to other uses has never been systematically and quantitatively examined. Hence, this study develops a multi-objective planning model of water resource management to evaluate the trade-off among various supply objectives. The model integrates operating rules, linear programming (LP) and a multi-objective genetic algorithm (MOGA) to solve a regional conjunctive water allocation problem. Furthermore, this study investigates the trade-off relationship between agricultural and other water shortage using the proposed multi-objective model. The simulation results show a clear trade-off relationship between shortage index for agriculture and that for industry; it also demonstrates that the proposed model can solve a complicated multi-objective problem of regional water management. The computed trade-off curve, non-inferior solutions, is a valuable quantitative basis for compromising among various water demands in the future.

Keyword: water resource management, multi-objective programming, genetic algorithm

1. INTRODUCTION

The demand for water in Taiwan has increased markedly in recent years because of industrial growth and increasing living standards. However, environmental concerns have postponed further development of large water resource projects. Hence, the risk of drought damage in the dry season is increasing. During periods of drought, the supply of water to agriculture is reduced and the water saved is transferred to fulfill demand for water from other sectors because the unit return on water used to meet agricultural demand is less than that of water supplying to meet industrial or municipal requirements.

Recent papers on water allocation include the following. Alaya (2003) developed an optimization rule to estimate the necessary water release volume to meet two conflicting objectives - to meet the demand for irrigation water and to maintain the minimum volume of water that must be stored in the dam. The work, differently weighting these objectives, applies stochastic dynamic programming to solve the problem, but does not consider the competition between the demand for irrigation water and the public's demand for water under drought conditions. Yen and Chen (2001) simulated the conjunctive use of surface water and groundwater resources in south Taiwan, based on a forecast of demand for 2011. Three scenarios, of various supply priorities and demands for water from different sectors, were considered to guide the allocation of the water resources under different hydrological conditions and groundwater pumping constraints. The results show that the key factor that causes water shortages in south Taiwan is a lack of storage infrastructure. Furthermore, for all the scenarios, irrigation water was transferred to industrial sectors to reduce economic losses during drought. However, the study did not systematically and quantitatively considers the effect of the transfer of irrigation water to industrial sectors. Yang and Chang (2002) developed a multi-objective programming algorithm that integrates a multi-objective genetic algorithm (MOGA) with constrained differential dynamic programming (CDDP), to solve a problem of the conjunctive use of surface and subsurface water in southern Taiwan. They used a MOGA to generate various alternatives, system capacities, and the non-inferior set was obtained. A CDDP algorithm was embedded to compute the optimal releases of reservoirs for each alternative. However, the CDDP algorithm requires that all the variables in the problems must be continuous and differentiable. It can therefore, not be applied to a system of reservoirs that operate according to the rule-curves. Since reservoir operation according to rule-curve is the most common operating practice, this work proposes a multi-objective model for planning water resource systems that are operated according to rule-curves. The model integrates operating rules, linear programming and a multi-objective genetic algorithm (MOGA) to solve the multi-objectives planning problem of regional water allocation, and provides a trade-off curve of non-inferior solutions for various demands for water from various sectors.

2. METHODOLOGY

2.1 LP-based simulation model

A simulation model of the dynamic operation of a reservoir system that operates according to rule-curves, is developed. The model's core is to compute the available water and weighted demands for water, according to the rule curves at the beginning of each time step, and then to activate a linear programming model to determine the releases from each reservoir to meet the various demands for water in that time step. The procedure is repeated in the simulation. The simulation model can handle demand for water from various sectors (such as agriculture and the public), base flow and agricultural return flow. The model is reliable and efficient and can be applied to a large system of water resources.

2.2 MOGA

The genetic algorithm-based method has two advantages over traditional multi-objective programming approaches: first, it can generate both convex and concave trade-off curves; second, it can generate large parts of the optimal trade-off curve in a single iteration. The MOGA generates a wide range of alternatives (chromosomes) and ranks the alternatives according to fitness values. The alternatives evolve iteratively into a generation with higher fitness values for each alternative. The search is performed over a population of alternatives rather than over sequences of individual solutions, as in traditional optimal methods. MOGA directly uses information obtained from the fitness functions (objective functions), and applies probabilistic transition rules. MOGA has many attractive features, including its ability to solve NP-hard problems, its ease of interfacing with simulation models and being integrated into a hybrid system.

2.3 Integration of the MOGA and the simulation model

The proposed multi-objective planning model is developed by embedding the simulation model into the MOGA algorithm. In the MOGA procedure, an alternative (chromosome) assigns weightings to each water demand and, accordingly, constitutes a potential operating rule (rule-curve). The simulation model computes the operating policy of the release from the reservoirs in the water resource system, for each alternative (rule-curve). The value of each objective function, the shortage index of water demand herein, associated with each rule-curve, can be computed accordingly. The shortage indices of water demands compete with each other and are used to evaluate the fitness of the alternative. Pareto offline are generated by the following steps (Fig.1). (1) Code the variables (the discounting weights of the supply of water to meet the demands of the various). (2) Compute the releases from the reservoirs using the LP-based simulation model. (3) Evaluate the shortage indices of the demands for water for agriculture and by the public. (4) Generate a feasible solution set based on the shortage indices. (5) Determine the final Pareto offline using the procedures of elite, reproduce, crossover and mutation, which are incorporated into MOGA.

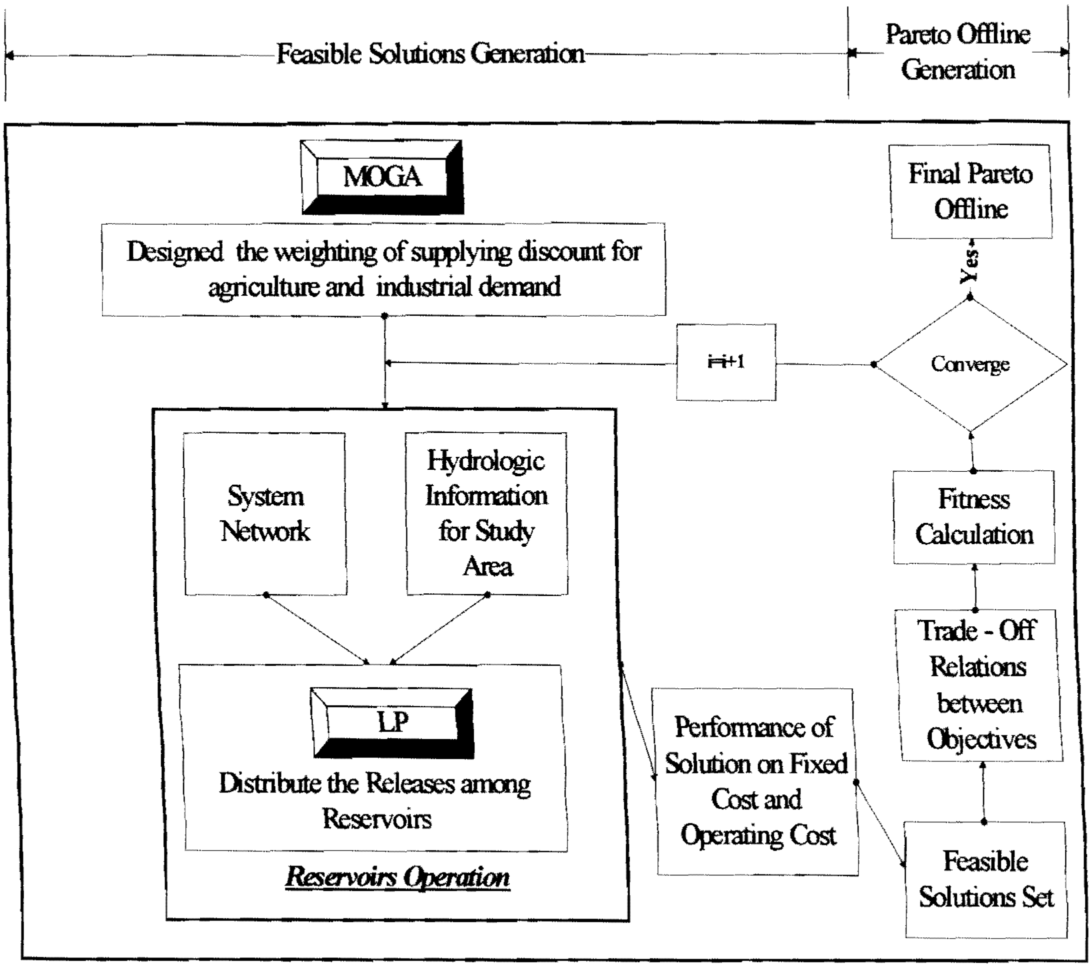


Figure 1. Method of Multi-Objective Planning for Conjunctive Use of Water Resources

3. APPLICATION

3.1 Study Area

Figure 2 shows three storage reservoirs and weirs constructed in the Tsengwen and Kaopin river basins. The Wushantou reservoir, with an effective storage capacity of $81.45*10^6$ m3 on the Guantein creek , and the Tsengwen reservoir with an effective storage capacity of $581.23*10^6$ m3 on the Tsengwen river, are the major facilities for supplying water to in the Tainan area. Just downstream of the Tsengwen reservoir, the Tongkou weir on the Tsengwen river diverts water to the Wushantou reservoir. Accordingly, the Tsengwen and Wushantou reservoirs are operated as serial reservoirs. The Nanhwa reservoir, with an effective storage capacity of $149.46*10^6$ m^3 on the Houchueh creek, distributes water to the Tainan and Kaohsiung areas. The Chiahsien weir on the Chyishan creek diverts the water to the Nanhwa reservoir. The Kaopin weir on the Kaopin river is the main water intake structure in the Kaohsiung area. However, the water authorities plan to lay pipes that connect Tainan to

Kaohsiung, allowing the residual water from the Kaopin weir to supply the Tainan area during the wet season, after the demand of Kaohsiung has been met. The Kaopin weir can conjunctively operate with the Tsengwen, Wushantou and Nanhwa reservoirs by co-supplying to the same demand area, Tainan, increasing operational efficiency in the two major river basins, Tsengwen and Kaopin. This work addresses the trade-off between the shortage indices of the demand of agricultural and public sector in 2011.

This model includes four demands-for water for agriculture supplied by Tsengwen and Wushantou, some of the water demanded by the public in the Chai-Yi area, public water demand in the Tainan area, and public demand in the Kaohsiung area. Table 1 details the situation.

Table1. Modeled demands

	Agriculture demand of Tsengwen and Wushantou	the portion public demand in Chai-Yi	public demand in Tainan	public demand in Kaohsiung
demand	$9*10^8$ ton/year	$1*10^5$ ton/day	$1.4*10^6$ ton/day	$1.16*10^6$ ton/day

The objective function in MOGA can be formulated as follows.

Objective function:

$$\vec{J} = \underset{\vec{L}}{Min} \ \vec{Z}(\vec{L}) = \underset{\vec{L}}{Min} \ (\vec{Z}_1(\vec{L}), \vec{Z}_2(\vec{L})) \quad (1)$$

Subject to,

LP-based simulation Model (2)

where $\vec{Z}_1(\bar{L})$ and $\vec{Z}_2(\bar{L})$ are the shortage indices associated with agricultural demand and public demand, respectively, and both are to be minimized. $\vec{L}$ is the decision variable (the rule-curve). The U.S. Army Corps of Engineers has proposed an SI of,

$$SI = \frac{100}{N} \sum_{i=1}^{N} \left(\frac{Sh_i}{T_i} \right)^2 \quad (3)$$

where N = number of periods; Sh_i = shortage volume during period i, and T_i = target demand during period i. The period over which reservoirs are operated for planning purposes is taken as one month herein. A year is divided into 12 periods.

In the simulation model, the optimal water distribution problem solved by LP in each time step is specified by the following equations.

$$Z = Min \left\{ \left(\sum_{i \in N_D} W_{SH,i} SH_i^t \right) + \left(\sum_{F \in N_F} W_{G,F} G_F^t \right) + \left(\sum_{j \in N_S} W_{SP,j} X_{SP,j}^t \right) + \left(\sum_{m \in N_{PI}} W_{PI,m} PI_{m,i}^t \right) \right\} \quad (4)$$

$$W_{SH,i} > W_{G,F} > W_{SP,J} > W_{PI,m}$$

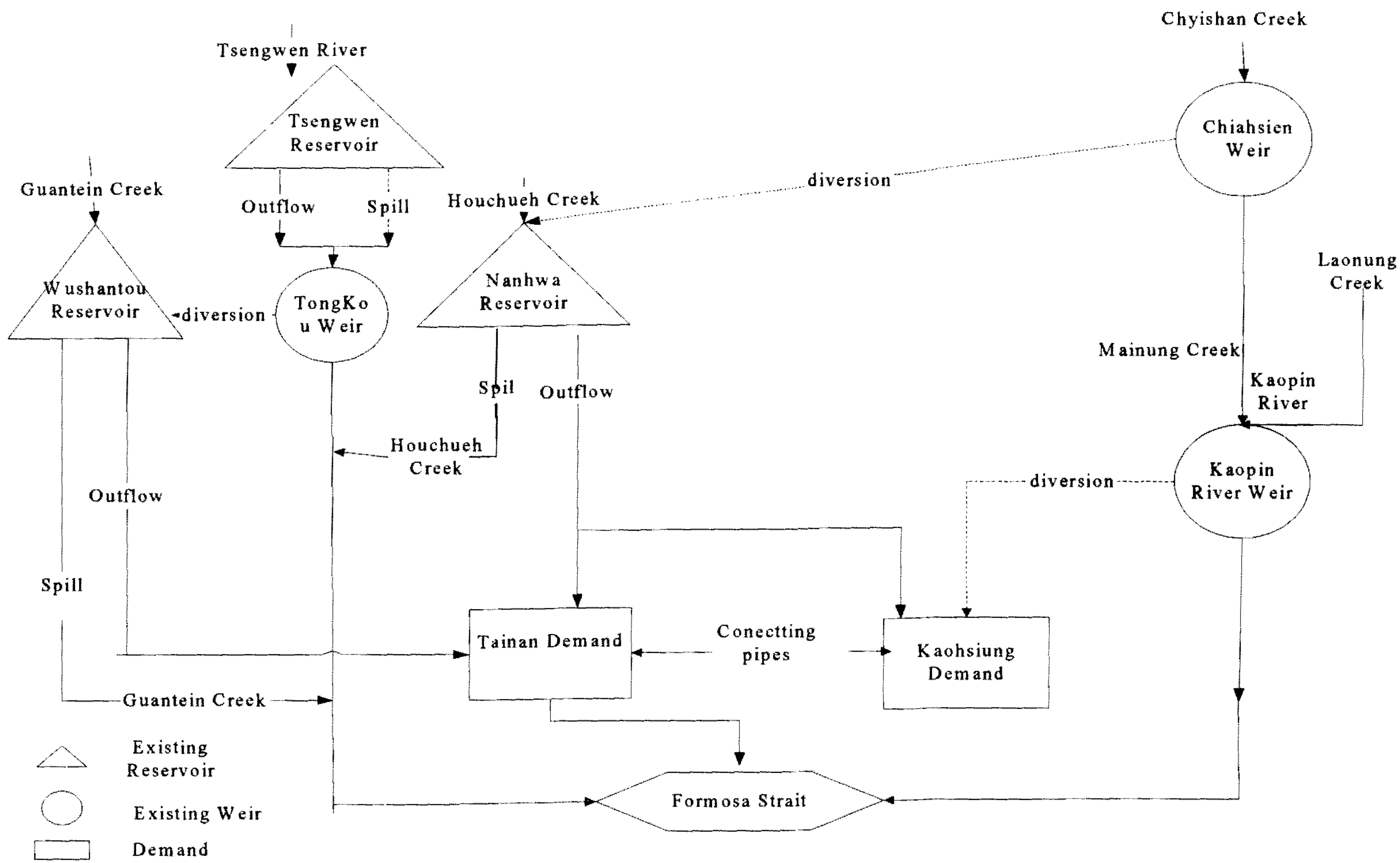


Figure 2. System Diagram of the Study Basin

subjected to
mass balance equations of each node
index balance equations of reservoirs
capacity constraints for water treatment plant and pipes where

SH_i^t : **shortage in meeting ith demand in period t.**

G_f^t : **slack variables in the equation for index balance in period t.**

$X_{SP,j}^t$: **overflow of jth reservoir in period t.**

$PI_{m,j}^t$: **discharge of jth two-way pipe in period t.**

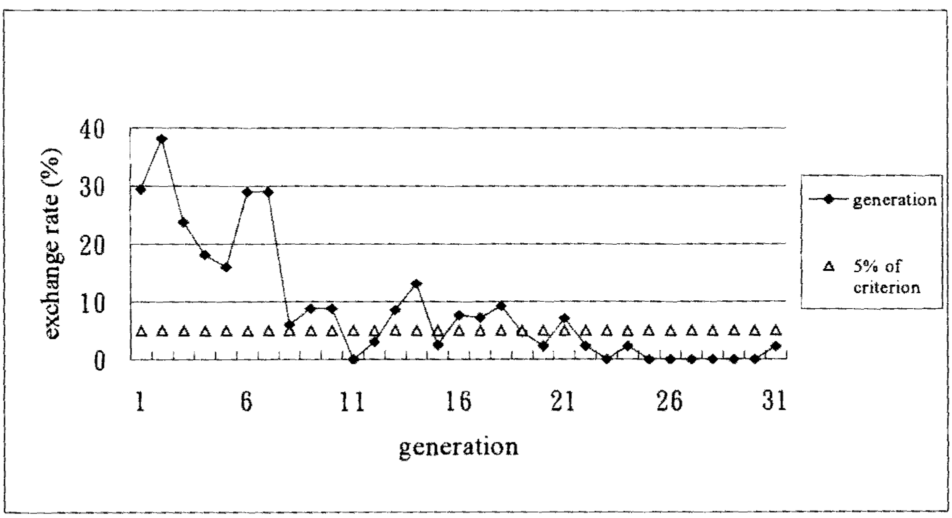
$W_{SH,i}$、$W_{G,F}$、$W_{SP,J}$、$W_{PI,m}$: **weighting of priorities.**

4. NUMERICAL RESULTS

The proposed model is applied to the problem defined by Eqs. (1) ~ (4). The model estimates the Pareto offline for the shortage indices of agricultural demand and public demand. The decision variables must be encoded as chromosomes before the MOGA can be applied. Each decision variable, the weighting value for the supply of water demand for agricultural when the volume of available water is in the buffer or inactive zones, is represented using ten binary bits. Three decision variables are involved, so a chromosome includes 30 bits. In the problem considered herein, the population in each generation is 100 chromosomes and the initial population is randomly generated. As shown in Fig.1, the LP-based simulation model is applied repeatedly within each generation to simulate the operation of the system according to the rule-curves represented by the chromosomes. The stopping criterion for MOGA is that the ratio of change of Pareto offline over ten consecutive generations should be lower than 5%. Figure 3 plots the decline of the rate of exchange from its initial value to the value of convergence. The final Pareto offline is obtained in generation 31.

Figure 3. Rate of Exchange vs Number of Generation

Figure 4 presents the initial and final population. The improvement represented by the final set of non-inferior solutions over the initial set is significant. Figure 5 shows the result of a non-inferior solution. The non-inferior curve can be a valuable reference in determining the



ransfer of water away from meeting agricultural demand in the future.

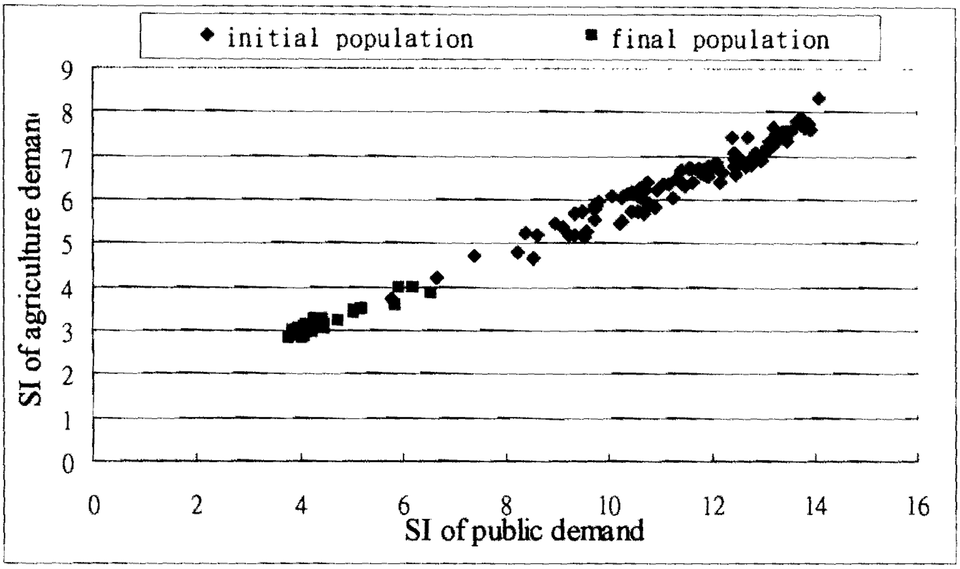


Figure 4. Initial population and Final population

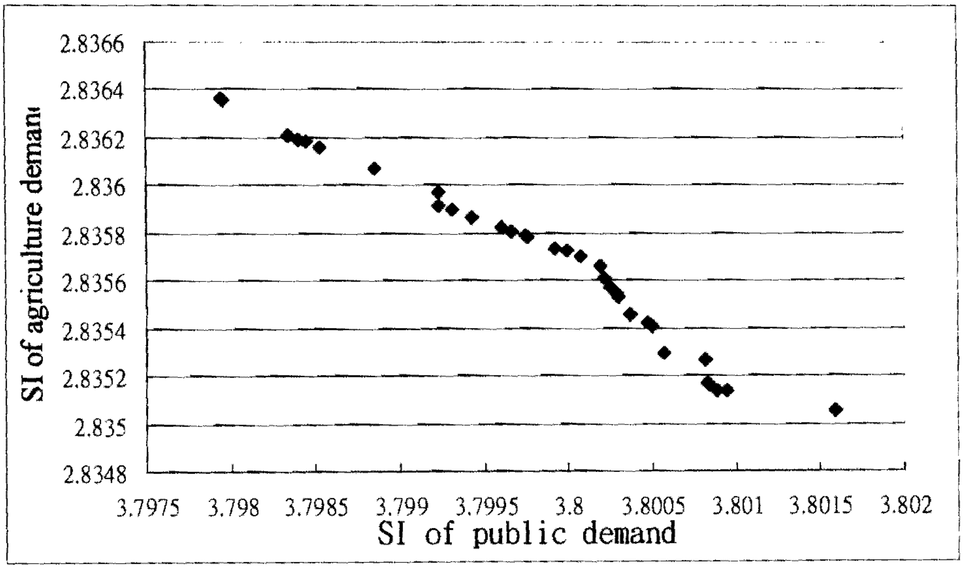


Figure 5. Non-inferior solutions

5. CONCLUSION

This study integrated operating rules, LP and MOGA into a regional conjunctive water allocation model that can solve a complex multi-objective problem. Unlike that obtained in single-objective optimization, the solution to this problem is not a single point, but a family of points known as a Pareto set. The model was applied to a real case of the allocation of water resources in southern Taiwan. The trade-off curve of the SI of agricultural demand for water against the SI of the public sector, was obtained. This trade-off curve is a valuable reference for governmental authorities when developing strategies for managing water resources

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