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OPTIMIZING THE RULE CURVES FOR MULTI-RESERVOIR OPERATIONS USING A GENETIC ALGORITHM AND HEC-5

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SYNOPSIS

The model proposed in this paper integrates the Genetic Algorithm (GA) and the HEC-5 model, an extensively used reservoir simulation model. The HEC-5 distributes the releases among reservoirs according to both the rule curve of each reservoir and the principle of 'index balance', to fulfill the total demand. However, the HEC-5 is only a simulation model, and is incapable of computing the optimal rule curves. Therefore, this research develops a rule curve based management model (GHEC-5) by embedding the HEC-5 model into the Genetic Algorithm. In GHEC-5, a chromosome represents a potential combination of the operating zones; that is, a realization of the decision variables, for all the reservoirs. GHEC-5 then computes the fitness value for all the chromosomes by HEC-5 and improves the chromosomes through the GA. The shortage index (SI) is used as the objective function herein.

The GHEC-5 has been applied to the water resources system in southern Taiwan, including the Tsengwen river watershed and the Kaopin river watershed. Numerical studies demonstrate that the optimal rule curves obtained by GHEC-5 can improve significantly the system capabilities over those with the existing rule curves. Therefore, GHEC-5 can facilitate decision making concerning the optimal policy for regional water resource management.

INTRODUCTION

Reservoirs, the most important hydraulic facilities in a water resource system, can have a significant impact on regional water conservation. In practice, 'rule curves' generally regulate reservoir operations. Accordingly, determining the optimal rule curves is a critical factor in reservoir management. Rule curves are characterized by a set of operating zones and operating guidelines associated with each zone. These curves, including the operating zones, are normally determined by summing the repeated simulation results using historical or synthetic hydrological data (1). Adequate rule curves for complicated multi-reservoir systems may be difficult to obtain by using only simulations.

Simulation models are generally used to study the efficiency of the reservoir's operation. Among them, HEC-5, developed by the Hydrologic Engineering Center of the U. S. Army Corps of Engineers, (2) is one of the most widely used simulation models for a complicated multi-reservoirs system. The HEC-5 distributes the releases among reservoirs according to the predefined rule curve for each reservoir and the principle of 'index balance' to fulfill the total demand. Simulation models, such as HEC-5, are flexible and provide a detailed and realistic representation of a water resource system (3) but they require pre-determined rule curves.

A simulation model could be directly embedded into a management model to preserve the flexibility of the simulation models. In this case, the operating zones are the decision variables in the management model. Nevertheless, the problem will be difficult to solve by using conventional gradient-based optimization since a reservoir operation based on rule-curves contains discrete computations associated with the operating zones. A discrete dynamic program is hard to apply because the problems become non-separable when the operating zones are decision variables. Therefore, this study makes use of the Generic Algorithm, a combinatory algorithm, as the optimization procedure to resolve the optimal rule curves for the simulation embedded management model.

The genetic algorithm (GA), proposed by Holland, is a robust method for searching for the optimum solution of a complex problem and can compute the near global optimal solutions (4). The basic principle of the genetic algorithm is to simulate biological evolution, "the process of natural selection, survival of the fittest." This process has been successfully applied to many situations.

Wang (5) introduced a genetic algorithm in the field of hydrology, for function optimization and applied this algorithm to calibrate a conceptual rainfall-runoff model. McKinney (6) incorporated the genetic algorithm into the groundwater simulation model to solve three groundwater management problems: maximum pumping from an aquifer; minimum cost water supply development, and minimum cost aquifer remediation. Kuo (7) developed an irrigation simulation and optimization model, using the genetic algorithm, for decision support in irrigation planning. Mohan, S. (8) proposed the genetic algorithm to estimate the parameters of Muskingum models. According to the results, he obtained the genetic algorithm can estimate much more efficiently the parameters of Muskingum models than do conventional methods. Chen C.S., Wang N.B. (9) proposed a modified Muskingum model to simulate the flood more effectively. A genetic algorithm was also employed to obtain the parameters of C0, C1 and C2.

GA has also been applied in water resources planning. East and Hall (10) applied a GA to a four-reservoir problem, to maximize the benefits from power generation and irrigation subjected to constraints on the storage and the releases of the reservoirs. The study conducted by East and Hall showed the significant potential of GA in water resources systems optimization, and clearly demonstrated the computational advantages of GA over standard dynamic programming (DP). Fahmy et al. (11) also applied a GA to a reservoir system, and compared the performance of the GA with that of dynamic programming. The authors concluded that GA had potential in application to large river basin systems. Oliveira and Loucks (3) focused on the use of GA to derive the multi-reservoir operating policies. Instead of using rule curves, the operating policies are guided by sets of balancing curve. A real-coded GA computed the optimal balancing curves for the reservoir system and the individual reservoirs.

None of the authors mentioned above have adopted the GA with a simulation model directly embedded to compute the rule curves for a multi-reservoirs system. Therefore, this paper presents a rule curve based management model (GHEC-5) by embedding the HEC-5 model into the Genetic Algorithm. The proposed GHEC-5 is also applied to the water resources system in southern Taiwan, including the Tsengwen river watershed and the Kaopin river watershed, to demonstrate the significant improvements in the system.

MODEL DEVELOPMENT

Formulation

The Shortage index (SI), which reflects the water deficit, is used as the objective function in the GHEC-5 model. The SI was proposed by the U.S. Army Corps of Engineers and can be defined as,

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

Where N = number of periods; Shi = shortage volume during the period i ; Ti = target demand during the period i and $\sum$ indicates the summation of the indicated values for all periods. Ten days is usually taken as the period of reservoir operation for planning purposes in Taiwan. A month is divided into three periods (12). The shortage index has also been used in the United States to evaluate the potential water shortage for a specific reservoir capacity. Furthermore, it acts as a surrogate index for the socioeconomic impact of the water deficit, and is assumed to be proportional to the square of the deficit ratio.

Accordingly, the proposed formulation is as follows:

$$Minimize \sum_{i=1}^{m} SI_i(Sh_i(\vec{Z})) \qquad (2)$$

Subject to

$$Sh_i = HEC5((\vec{Z}), \vec{I}, T_i) \qquad (3)$$

Where

SI_i : Shortage index in the supply area i
Sh_i : Shortage volume in the supply area i
m : The total number of supply areas in the system
$\vec{Z}$: The set of rule curves (operating zones) for all reservoirs
$\vec{I}$: The inflows for all reservoirs, weirs and control points
Ti : The target demand of the supply area i
HEC-5(….) represents the computation of the HEC-5 simulation model

The HEC-5 Simulation Model

HEC-5 is one of the most widely used reservoir simulation models. It was developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, to simulate the operation of multipurpose, multi-reservoir systems for flood control, water supply, hydropower, and in-stream flow maintenance for water quality control. HEC-5 can be used to determine both reservoir storage requirements and operational strategies for flood control and/or conservation. Conservation or flood control reservoir storage and operation can be determined by iteratively analyzing the performance of reservoirs using different reservoir sizes (storage volumes) and control strategies. Individual reservoir storage for conservation (non-flood control) demands can be obtained by fulfilling a specified demand. The maximum reservoir yields can also be computed for a specified storage. Multi-reservoir operating policies are based on the rule curves of individual reservoirs, and the principles of index balance and equivalent reservoirs (1).

The program user assigns index levels for each reservoir for use in determining the priority of releases among reservoirs. A reservoir system is operated to meet specified operational constraints first, and then to keep the reservoir in balance. A reservoir system is in balance when all reservoirs are at the same index level. Index levels govern the priority for releases in the balancing of reservoir. The reservoirs at the highest levels at the end of the current period, assuming no releases, are given first priority for the current period (1).

The concept of equivalent reservoirs is used in determining the priority of reservoir levels among parallel reservoirs, or other subsystems in the case of a reservoir system which includes tandem reservoirs. Tandem reservoirs are reservoirs that are operated in conjunction with each other. The level of each reservoir in a subsystem is weighted by the storage in the reservoir to obtain a storage-weighted level for the subsystem of reservoirs (1).

Integration of the Genetic Algorithm and HEC-5

The genetic algorithm was first proposed by Holland based on the mechanisms of evolution. It is a computing procedure embodying important mechanisms of the adaptive process of natural systems. In the 1960s and 1970s, several evolutionary computing models were simultaneously developed. GA is becoming the most popular innovative method of computing due to its ability to solve complex problems, its simple interface, and its ability to be hybridized with existing simulation models (4). This study embeds the HEC-5 model into the Genetic Algorithm since HEC-5 is unable to compute the optimal rule curves. The proposed procedure can solve the optimal rule curves for multi-reservoir operation defined by equation (2) and (3). Figure2 illustrates the procedure of the algorithm. The algorithm has two key features. First, searching for the optimal rule curves is accomplished by the GA. Second, the HEC-5 calculates the releases of the system associated with the rule curves (chromosomes). The algorithm is described as follows.

Step 0: Initialization

GA requires encoding schemes that transform the decision variable vectors into a structure (chromosome) that permits genetic operations, including for example, reproduction, crossover, and mutation. These genetic operations will generate new sets of chromosomes (decision variables) with, on average, improved performance. The most common encoding schemes use binary strings, vectors of binary bits, as indicated in Fig 1. Each bit of the binary string is called a gene.

This step largely focuses on encoding the decision variable as a chromosome and randomly generating an initial population of that chromosome. A chromosome, a binary string, represents a possible design of the problem. The length of the binary string depends on both the number of bits required to represent a decision variable and the number of decision variables. For instance, the chromosome in Fig. 1 contains three decision variables, each represented by four bits. In this study, each decision variable represents a monthly value of a rule curve of a reservoir such that each chromosome represents a combination of the rule curves of all reservoirs.

0 0 1 0 0 0 1 0 0 0 0 1

Fig.1 Chromosome representation

Step 1: Evaluate the fitness for each chromosome

After the chromosomes (rule curves) of the initial population have been determined as in step 0, the release of the system in every period is calculated by the HEC-5 simulation model corresponding to each chromosome. This procedure is repeated for all chromosomes in each generation. Therefore, the HEC-5 is embedded in the GA to calculate the release of the system as indicated in Fig. 2. Finally, the release of the system for each chromosome is returned to the GA to evaluate its fitness. The shortage index of the system is defined as fitness in this study.

Step 2: Select the parent strings for reproduction

. The selection mechanism, tournament selection was adopted (13) in this study, plays a prominent role in driving the search towards superior individuals and maintaining high genotypic diversity in the population. GA selects parents from a population of strings based on the fitness. In each tournament selection, a group of individuals are randomly chosen from the population, and the fittest individual is selected for reproduction. The procedure is repeated until the number of chromosomes required for crossover is met. Accordingly, strings with above average fitness will have an above average probability of being selected as parents. The algorithm thus converges to a set of chromosomes with high fitness values.

Step 3: Perform crossover for reproduction

Crossover involves randomly coupling the newly reproduced strings and exchanging information within a pair of strings. Crossover aims to exchange gene information so as to produce new offspring strings that preserve the best material from two parent strings. In general, the crossover is performed with a certain probability (p_{cross}) ranging from 0.8~1.0 such that it is performed on a majority of the population. In this study, p_{cross} is set to1.0.

Step 4: Implement the mutation for reproduction

Mutation restores lost or unexplored genetic material to the population to prevent the GA from prematurely converging to a local minimum. A mutation probability (p_{mutat}) is specified so that random mutations can be made to individual genes. The value of p_{mutat} normally ranges from 0.01 to 0.05. This study takes p_{mutat} = .03. A random number with uniform distribution is generated. If this number is smaller than the mutation probability, mutation is performed. Otherwise, it is skipped. Notably, mutation changes a specific gene ($0 \rightarrow 1$ or $1 \rightarrow 0$) according to the specific probability in the offspring strings produced by the crossover operation.

Step 5: Perform termination

A new population is formed following step 4, which requires that fitness, as in step 1 be evaluated. The stopping criterion is based on the change of either fitness value or optimized parameters. The procedure stops if the user defined stopping criterion is satisfied or the maximum allowed number of generations is reached;

otherwise, step 1 is revisited for another cycle (another generation).

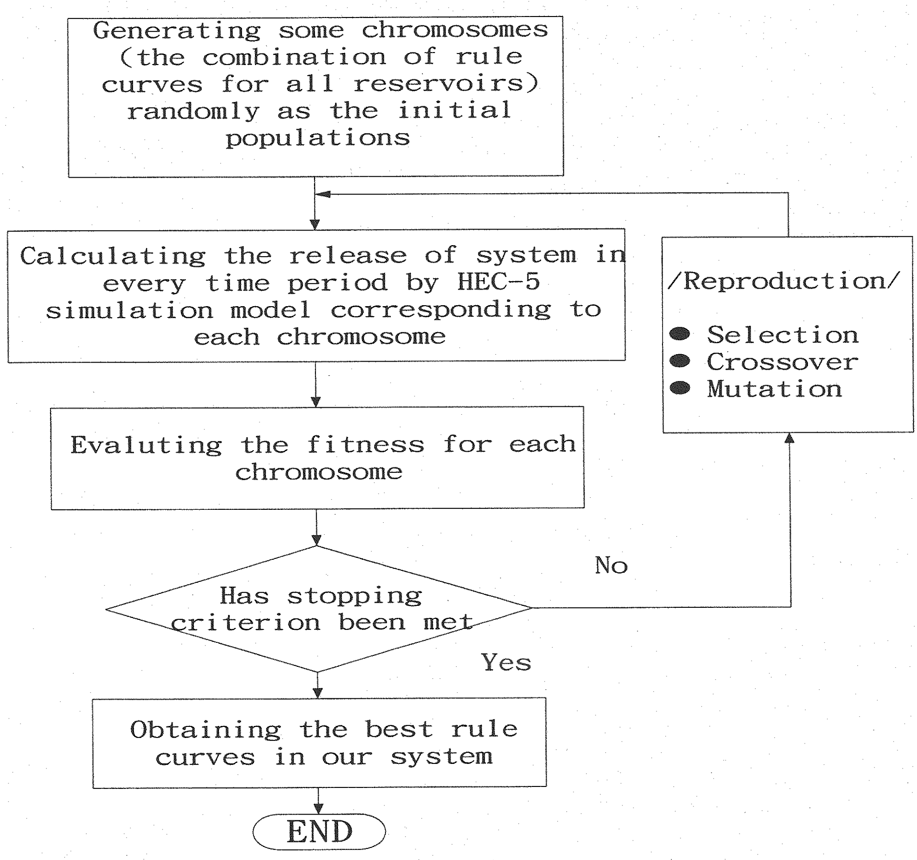

Fig.2 Flow chart for the GHEC-5 model

APPLICATION

The area which was studied (including the Tsengwen river watershed and the Kaopin river watershed) is located in the southern part of Taiwan covering a drainage area of 4,433 km^2. Major cities are Kaohsiung and Tainan. Figure 3 shows the area and its surrounding river system. Population growth, industrial development and rising in living standards have led to a significant increase in demand for water in recent years. According to predictions made by the Water Resources Planning Commission (14), there will be an increase in public water demand of 2,469,000 m^3/day by 2001 (869,000 m^3/day in Tainan, and 1,600,000 m^3/day in Kaohsiung). Although the reservoirs in the region will be able to satisfy the estimated demands in that year, water demand will outstrip the system's capabilities shortly thereafter. Following above predictions, the demand will reach 3,385,000 m^3/day by the year 2011 (1,390,000 m^3/day in Tainan, and 1,995,000 m^3/day in Kaohsiung), indicating a need to increase the capacity of the water resources system as well as improving the rule curves of all reservoirs.

As shown in Fig. 3, three storage reservoirs and weirs have been constructed in the Tsengwen and Kaopin river basins. The Wushantou reservoir with an effective storage capacity of 81.45*10^6 m^3, located on the creek Guantein, and the Tsengwen reservoir with an effective storage capacity of 581.23*10^6 m^3, located on the Tsengwen river, are the major water-supplying facilities for 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 two serial reservoirs. The Nanhwa reservoir which has an effective storage capacity of $149.46*10^6 m^3$ on the Houchueh creek, distributes water to the Tainan and Kaohsiung areas in the ratio of 42 to 38. The Chiahsien weir on the Chyishan creek diverts the water to the Nanhwa reservoir. The Kaopin weir on the Kaopin river is the major water intake structure for the Kaohsiung area. Figure 4, a system diagram, further illustrates the inter relationship of all the major water facilities. As indicated in Fig. 5, although the total yearly inflow volume for the Kaopin river basin is large, its temporal distribution is not uniform, and about 90% of the inflow on average occurs during the wet season (May to October). Since there is no storage reservoir on the Kaopin river basin as shown in Fig 4, the large residual flow from the Kaopin river in the wet season can not be stored for use during the dry season. A huge supply deficit may occur in Kaohsiung during the dry season if the Nanhwa reservoir and the Kaopin weir are used for supplying Kaohsiung. The effective storage capacity of the Nanhwa and Tsengwen reservoirs is too small to meet the demand during the dry season, and the inflow of Kaopin weir is not reliable. Therefore, the water authorities plan to build pipes connecting Tainan and Kaohsiung, allowing the residual water from the Kaopin weir to supply the Tainan area during the wet season, while the demand of Kaohsiung is fulfilled. The Kaopin weir can operate in conjunction with the Tsengwen, Wushantou and Nanhwa reservoirs by co-supplying to the same demand area Tainan, increasing operational efficiency for the two major river basins, the Tsengwen and the Kaopin.

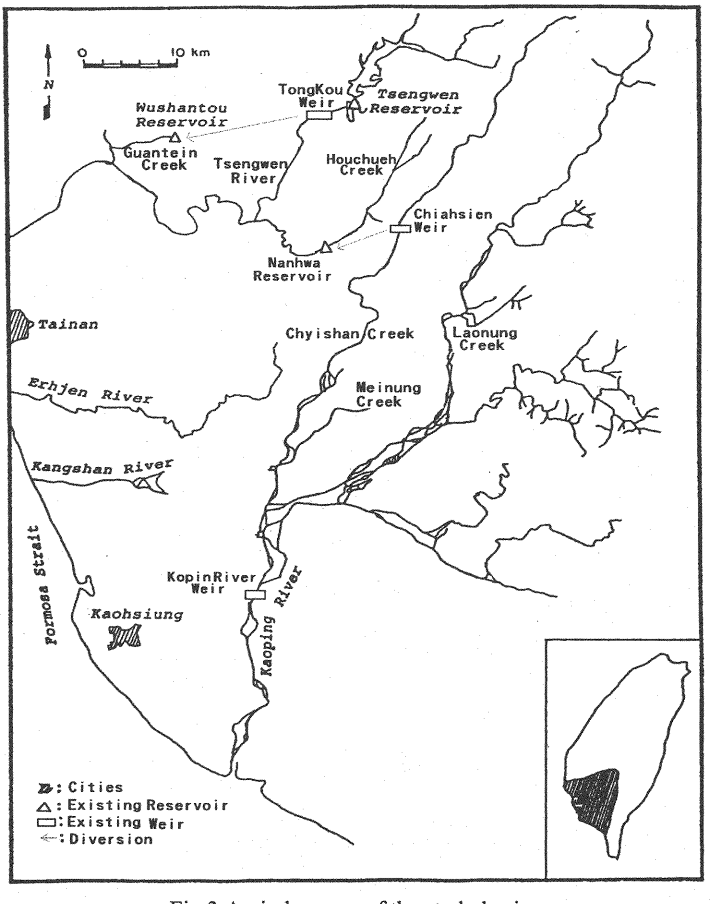

Fig.3 An index map of the study basin

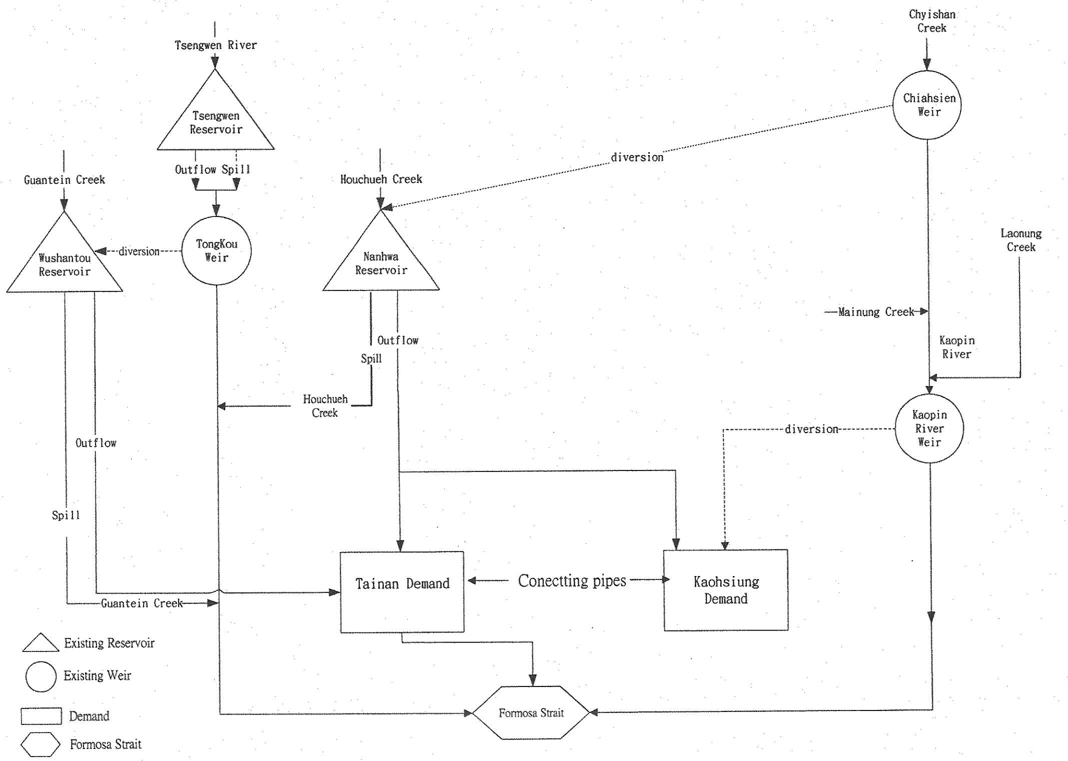

Fig.4 System diagram of the study basin

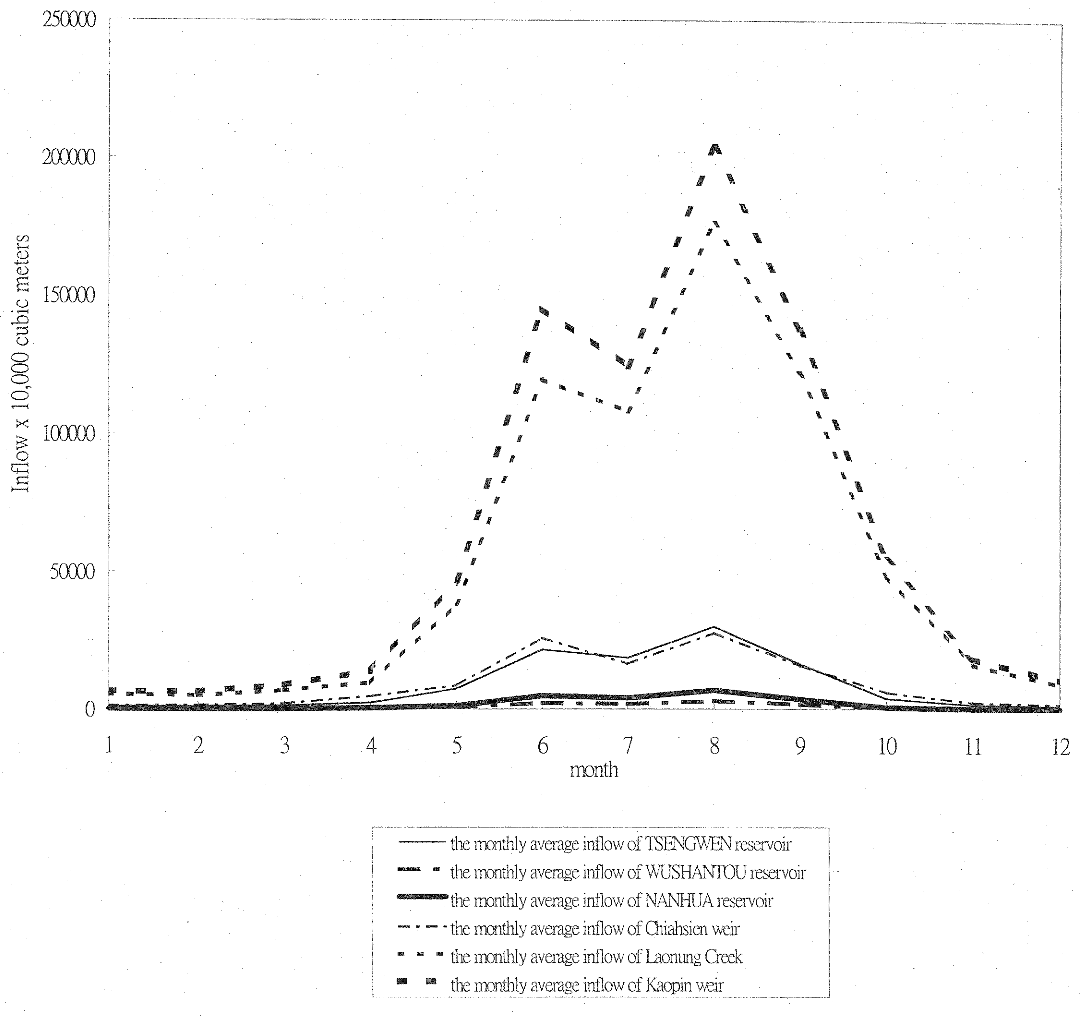

Fig.5 The monthly average inflow of all reservoirs and weirs

Problem Definition

This paper aims to define the appropriate rule curves of all reservoirs in the area to reduce the water deficit of Kaohsiung and Tainan area by 2011. Therefore, the upper and lower levels of the conservation zones, which may vary in time, are the decision variables of the problem. According to HEC-5, when the water level is in the conservation zone, all demands should be fulfilled. Above the upper level, the water in the flood control zone should be released as soon as possible. However, if the storage is below the lower level of the conservation zone, the release of the reservoir will only fulfill the curtailed demand. The three reservoirs are not treated equally because they have very different capacities. For the Wushantou and Nanhwa reservoirs, the upper levels of the conservation zone are maintained at the top of reservoir. Only the lower levels are the decision variables and may vary in time. Since the Tsengwen reservoir is the largest reservoir in the area, both the upper and lower levels of the conservation zone are decision variables. In this study, it is assumed that a time interval of one month for all variables. Hence, there are 12 decision variables for each zone level.

Since four zone levels are defined, 48 variables are associated with the three reservoirs. Although the rule curves, zone levels, vary monthly, the operating time-step in the model is 10 days.

According equations (2) and (3), the objective function and system dynamic for this problem can be formulated as follows.

Objective function

$$\text{Minimize } \{SI_{TN}(Sh_{TN}(\vec{Z}))+SI_{KS}(Sh_{KS}(\vec{Z}))\} \quad (4)$$

Subject to

$$\left(Sh_{TN}, Sh_{KS}\right) = HEC5((\vec{Z}), \vec{I}, T_{TN}, T_{KS}) \quad (5)$$

Where

SI_{TN} : shortage index for Tainan
SI_{KS} : shortage index for Kaohsiung
Sh_{TN} : shortage volume for Tainan
Sh_{KS} : shortage volume for Kaohsiung
$\vec{Z}$: the combination of rule curves for the three reservoirs
$\vec{I}$: the combination of inflows for the three reservoirs, weirs and control points
T_{TN}: the target demand in Tainan
T_{KS}: the target demand in Kaohsiung
HEC-5(….) indicates the computation of the HEC-5 simulation model

Computational Consideration

GHEC-5 is applied to the problem defined by equation (4) and (5). The model computes the optimal rule curves, zone levels, for all the three reservoirs. The decision variables must be encoded as a chromosome before the GA can be applied. Each decision variable, the zone level for a specific month, is represented by four binary bits. Since there are 48 decision variables, a chromosome contains a total of 192 bits. In our problem, the population for each generation has 250 chromosomes and the initial population is randomly generated. As indicated by Fig 2, the HEC-5 model is used repeatedly within each generation to simulate the operation of the system according to the rule curves specified by the chromosomes. Our stopping criterion for the GHEC-5 is that the optimal fitness values in ten consecutive generations are the same. The computations are implemented on a PC PENTIUM III 733 MHz, using Microsoft Windows 98. The CPU time per case study is 36 hours on average. Figure 6 shows the decrease of the optimal fitness values within a generation with respect to the progress of generations.

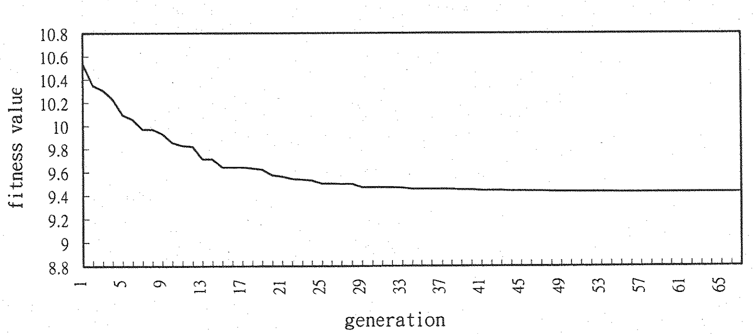

Fig. 6 The optimal fitness values varying with generations

Numerical Results

Table 1 describes four cases, which are implemented to demonstrate the capability of GHEC-5 and explore the advantages of applying the optimization model by comparing it to the simulation model HEC-5. The cases are formulated according to the system configurations and solution schemes. Two system configurations are considered; one with and one without the pipes connecting Tainan to Kaohsiung. The GHEC-5 and HEC-5 are used to solve the same problem for each system configuration, and the results compared. Much residual water from the Koaping weir can supply the Tainan area through Kaohsiung during the wet season when the pipes are laid. Accordingly, when the pipes are present, the water resource system in the studied area can be more efficiently operated, and the SI indices are smaller for both demand areas, than when there are no pipes. All the case studies are based on hydrological data from 1959 to 1996. The water demands for the two target areas in 2011, are 1,390,000 m^3/day and 1,995,000 m^3/day for Tainan and Kaohsiung, respectively.

Table 2 shows the values of shortage indices in all cases, revealing several important results. First, the connecting pipes can significantly increase the operating efficiency as indicated by the reduction of SI values for both HEC-5 (case 1 and case 2) and GHEC-5 (case 3 and case 4) models. The SI value is reduced from 5.08 in case 1 to 2.76 in case 2 for Tainan and from 13.84 to 7.93 for Kaohsiung using the HEC-5 model. The SI value falls from 3.10 in case 3 to 1.72 in case 4 for Tainan and from 12.06 to 7.71 for Kaohsiung, using the optimization model (GHEC-5). Second, the GHEC-5 can reduce the water deficits in the two demand areas for the two distinct system configurations, and shows a significant reduction in Tainan. Comparing the cases without pipes, the SI index falls from 5.08 in case 1 to 3.10 in case 3 for Tainan and from 13.84 to 12.06 for Kaohsiung. Comparing the cases with pipes, the SI index falls from 2.76 to 1.72 for Tainan and from 7.93 to 7.71 for Kaohsiung. Regardless of whether the pipes are connected, the decrease in SI value is significant for Tainan but relatively small for Kaohsiung. These results show that reducing the deficit in future water supply to Kaohsiung is difficult, even when the optimization scheme (GHEC-5) is applied. This phenomenon is further clarified by the system configuration shown in Fig. 4. The major water resources of Tainan originate in the Tsengwen and Wushantou reservoirs which together have a large volume. Therefore, improving the rule curves of reservoirs can increase significantly the reservoir release and reduce the water deficits in Tainan. The primary regulated water resource of Kaohsiung is the Nanhwa reservoir. Kaohsiung shows a high SI value, even though the operation is defined by GHEC-5 and is rule-curve based optimal. Figures 7 and 8 further explain the findings. Figure 7 shows that the Nanhwa reservoir is full at the high reservoir level in the wet season, but is almost empty at the low reservoir level during the dry season. During the dry season, however, the water deficit in Kaohsiung is the highest as indicated by Fig. 8. Therefore, Figures 7 and 8 together indicate that the reservoir capacity is insufficient to regulate the Kaoping rivers to supply enough water for Kaohsiung during the dry season. These findings are evidences that a new water facility on Kaoping river is required to reduce the water deficits in the Kaohsiung area.

Figures 9 to 11 illustrate the optimal rule curves for the three reservoirs with the pipes connecting Tainan and Kaohsiung. Figure 10 indicates that there is no conservation zone in April (dry season) for the Tsengwen reservoir, and all the zone limits are very low, demonstrating that the Tsengwen reservoir functions as a flow through channel in that month. The situation can be explained as follows: Since the flow rate is very low in the stream during the dry season, the Wushantou alone has a high enough capacity to store and regulate the water. Futhermore, the two reservoirs are operated in series, and the water of Tainan is directly supplied from the Wushantou but not from the Tsengwen, as shown in Fig. 4. Therefore, the stream flow should be stored in the Wushantou if possible to regulate the release to Tainan during the dry season. In light of above reason, the Tsengwen must release the water to the Wushantou for avoiding the shortage of Tainan as far as possible during the dry season. So the meaning of "as a flow through channel" is lacking of storage function for Tsengwen in this situation.

Collecting the chromosomes that have a fitness value close to optimal leads to another interesting phenomenon. GA can uniquely obtain a set of near optimal solutions. This capability helps in studying the sensitivity of the objective function to the decision variables near the optimal solution. Figure 12 shows the collection of ten rule curves (chromosomes) of the Nanhwa reservoir whose fitness value is closest to optimal. In Fig. 12, the dark lines represent the envelopes at the bottom of conservation zone. The wide range of envelopes during the wet season implies that SI values are insensitive to the operation of Nanhwa at that time since during the wet season, the demand for water in Kaohsiung is already met by the Kaoping weir. The general policy of reservoir operation is, "no demand, no release", and to save as much water as possible, unless the water level is above the upper limit of the conservation zone. With no requirement for releasing the water, the bottom of the conservation zone has no operational effect on the operation. In other words, the operation is insensitive to the bottom of the conservation zone. This fact is indicated by the wide range of envelopes during the wet season shown in Fig. 12.

In summary, the case studies have demonstrated that the proposed method, GHEC-5, can deal with a complicated water allocation problem, and can help to clarify the important aspects of the system configuration and hydrological condition.

Table.1 List of study cases

Considered Factors / Case No.	Solution Schemes	System Configuration
Case 1	HEC-5	Without pipes
Case 2	HEC-5	Pipes connected
Case 3	GHEC-5	Without pipes
Case 4	GHEC-5	Pipes connected

Table.2 Summary of case results

SI Value / Case No.	Tainan	Kaohsiung
Case 1	5.08	13.84
Case 2	2.76	7.93
Case 3	3.10	12.06
Case 4	1.72	7.71

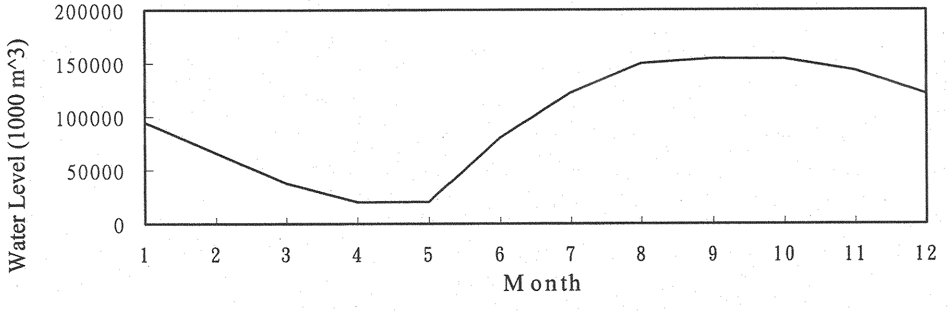

Fig. 7 Water level of the Nanhwa reservoir

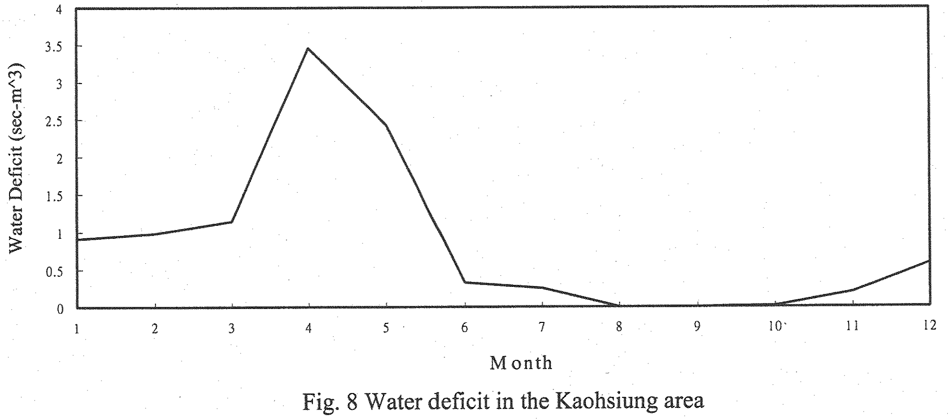

Fig. 8 Water deficit in the Kaohsiung area

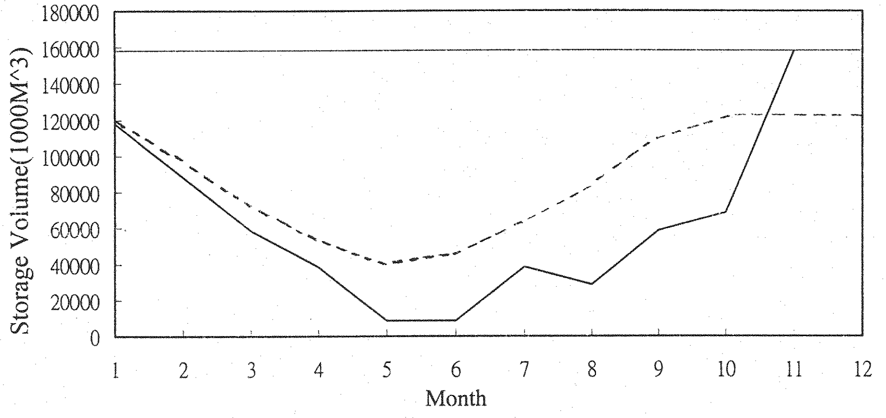

Fig.9 Rule curves of reservoir Nanhwa under conjunctive use
(The upper rule curve is the top of the reservoir; the lower curve is optimal)
----- current rule curves
___ optimal rule curves

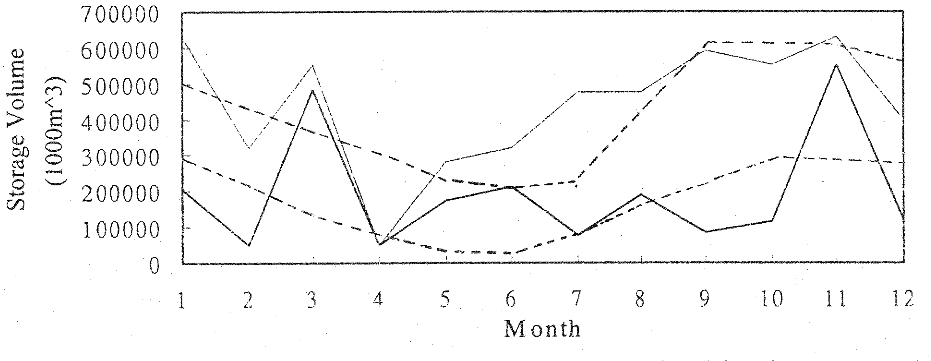

Fig.10 Rule curves of reservoir Tsengwen under conjunctive use
(The upper rule curve is optimal; the lower curve is optimal)
----- current rule curves
___ optimal rule curves

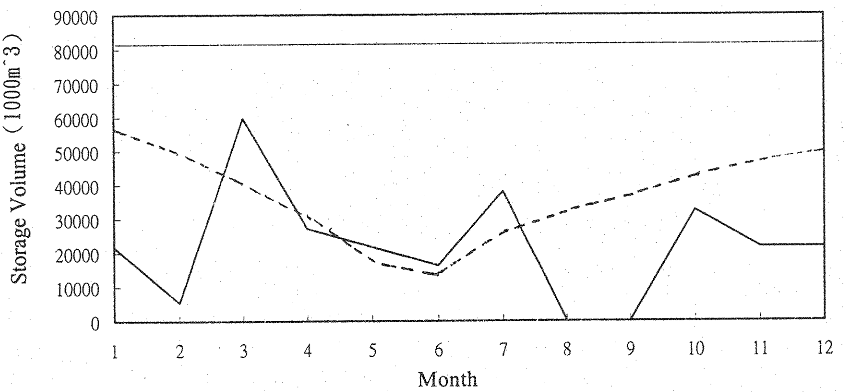

Fig. 11 Rule curves of reservoir Wushantou under conjunctive use
(The upper rule curve is constant; the lower curve is optimal)
----- current rule curves
___ optimal rule curves

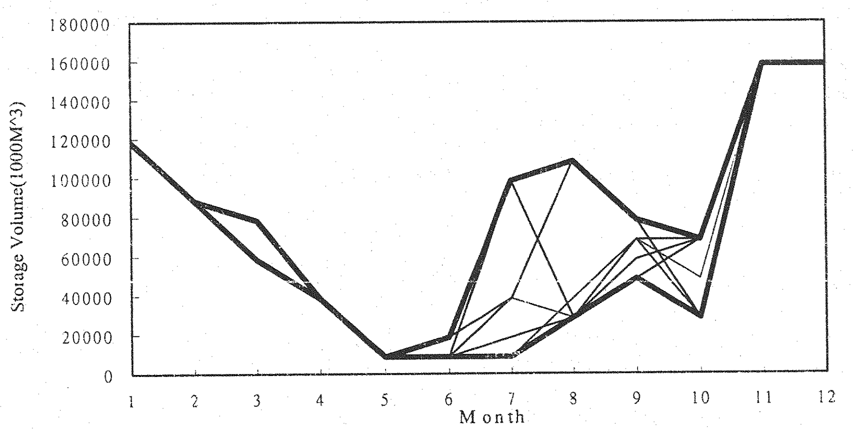

Fig. 12 The envelopes of the best ten rule curves of the Nanhwa reservoir

CONCLUSIONS

This study demonstrates the feasibility of integrating GA with a rule-curves based simulation model to resolve the optimal rule-curves for multi-reservoir operation. Embedding a simulation model leads to a more practical and flexible management model since it can very closely simulate the operating practice of reservoirs. The results of this study also show that by applying the GHEC-5 model, analysis can shed light on the important aspects of the system configuration and hydrological conditions. Findings clearly demonstrate the advantage of changing the system configuration by using pipes to connect demand areas, and the need for a new water supplying facility for Kaohsiung. The case studies also show the flow-through feature of the Tsengwen reservoir in the dry season and the insensitivity the water supply of Kaohsiung to the operation of Nanhwa during the wet season. The limitations of HEC-5 are also applied in the GHEC-5 model. Therefore, it is feasible to adopt the procedure proposed, and to develop a problem-oriented simulation model whenever the system of interest is complicated and implementation is cost effective.

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APPENDIX 1 – RESERVOIR STORAGE SPACE AND RULE CURVE

Reservoir systems may be grouped into two generation purposes: conservation and flood control. Conservation purposes include water supply, low-flow augmentation for water quality, recreation, navigation, irrigation and hydroelectric power. Flood control is simply the retention or detention of water during flood events for the purpose of reducing downstream flooding. This study focuses only on surface water reservoir systems for conservation.

Generally, the total reservoir storage space in a reservoir consists of three major parts: (I) the dead storage zone, mainly required for sediment collection, recreation; (II) the active storage, used for conservation purposes, including water supplies, irrigation, navigation, etc.; (III) the flood control storage reserved for storing excessive flood volume to reduce potential downstream flood damage. In general, these storage spaces could be determined separately and combined later to arrive at a total storage volume for the reservoir. Base on this characteristic, the active storage can be separate into two parts, Buffer Zone and Conservation Zone. On the other hand, the Flood Control Storage Zone and the Conservation Zone can be combined to one when the flood control is neglected for reservoir operation. The Dead Storage Zone and the Buffer Zone can be combined to one when the dead storage is neglected for reservoir operation.

The total reservoir storage space in a reservoir is usually divided into four parts, Dead Storage Zone, Buffer Zone, Conservation Zone and Flood Control Zone, in HEC-5. The operation rules of those four zones are as follows:

1. If the storage is in Dead Storage Zone, there is no release from a reservoir.
2. If the storage is in Buffer Zone, not all demand can be meet.
3. If the storage is in Conservation Zone, all demand can be fulfilled.
4. If the storage is in Flood Control Zone, the water should be released as soon as possible.

Rule curves in this study indicate the boundary of storage of Conservation Zone throughout the year. The upper rule curve is the top of Conservation Zone and the lower rule curve is the top of Buffer Zone. On the other hand, the range of each zone is changed by month.

APPENDIX 2 – INDEX LEVEL AND INDEX BALANCE

Release priorities between reservoirs are an important reservoir operating criterion which must be specified for most system operations. To illustrate the technique used in computer program HEC-5, the following example has been prepared. Assume the information shown below in Table 3 is known for each of two reservoirs which constitute a reservoir system. Figure 13 shows the various reservoir levels graphically.

Table. 3 The storage levels of two reservoirs

Reservoir Number	Top of Dead Storage Zone (accumulative storage volume)	Top of Buffer Zone (accumulative storage volume)	Top of Conservation Zone (accumulative storage volume)	Top of Flood Control Zone (accumulative storage volume)
1	20	30	40	50
2	30	40	60	70
Index Level	1	2	3	4

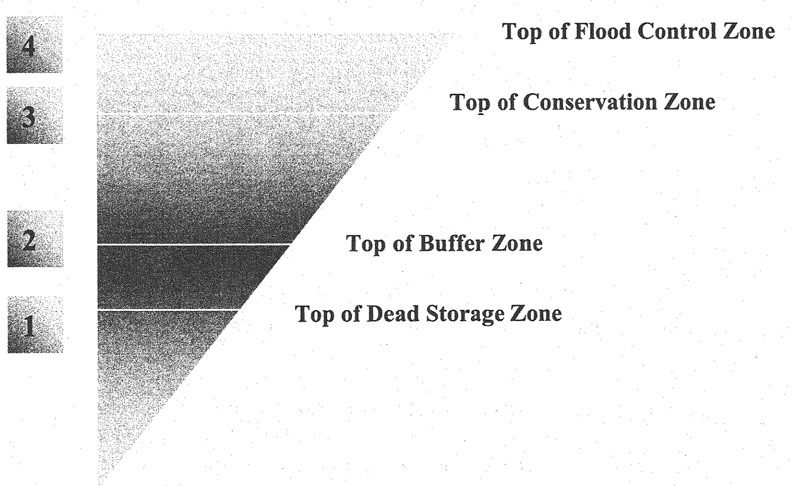

Fig. 13 Reservoir storage levels

Where

$$\text{Index level} = \text{Base Index} + S/TS$$

When the water level of a reservoir is between the top of Dead Storage Zone and the top of Buffer Zone, Base Index = 1.

When the water level of a reservoir is between the top of Buffer Zone and the top of Conservation Zone, Base Index = 2.

When the water level of a reservoir is between the top of Conservation Zone and the top of Flood Control Zone, Base Index = 3.

S : the storage volume of a reservoir in the specific zone.
TS : total storage volume in the specific zone.

Suppose that it is desired to determine the amount of release for the same demand to make from reservoirs 1 and 2 and those storage in reservoirs 1 and 2 at the end of the previous time period are 25 and 56. The index levels of reservoirs 1 and 2 are 1.5 (basic level = 1, S = 5 and TS = 30-20 =10, so index level = 1 + (5/10) = 1.5) and 2.8 (basic level = 2, S = 16 and TS = 60-40 =20, so index level = 2 + (16/20) = 2.8). Therefore, a release for the demand would be made from reservoir 2 and not from reservoir 1 because the index level of reservoir 1 is below the reservoir 2. Following the rule of index balancing, the useful release of the reservoir2 is the storage from the index level of 2.8 fallen into the index level of 1.5.

APPENDIX 3 – EQUIVALENT RESERVOIRS

For example, consider a situation in which two parallel reservoirs are upstream from a third, as shown in below Figure 14.

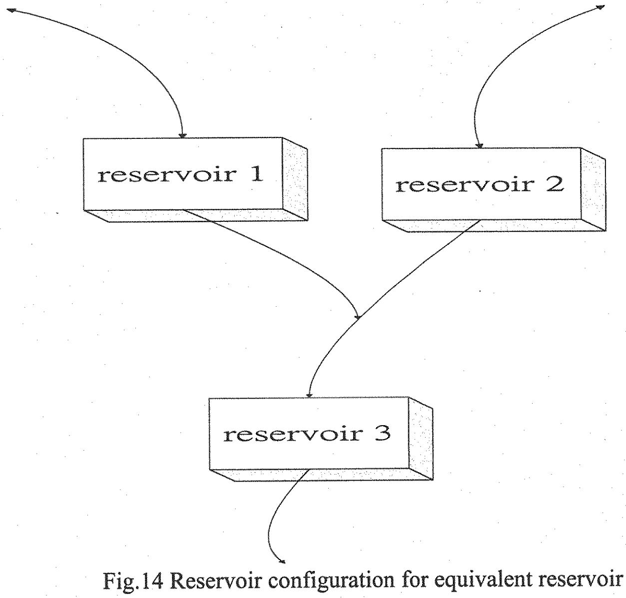

Fig.14 Reservoir configuration for equivalent reservoir example

Table. 4 Equivalent reservoir level-storage characteristics

Index Level	Reservoir 1 (accumulative storage volume)	Reservoir 2 (accumulative storage volume)	Reservoir 3 (accumulative storage volume)	Equivalent Reservoir (accumulative storage volume)
4	40	20	8	68
3	30	15	6	51
2	20	10	4	34
1	10	5	2	17

Suppose that it is desired to determine the amount of release to make from reservoirs 1 and 2 and that storage in reservoirs 1, 2 and 3 at the end of the previous time period are 35, 12.5 and 3, respectively. For these storages, the equivalent reservoir storage is 50.5 and the equivalent level is 2.97. The levels of reservoirs 1, 2, and 3 are 3.5, 2.5 and 1.5, respectively. The criterion used in the computer program is that releases will be made from an upstream reservoir if its level is above the greater of the level of downstream reservoir or the equivalent reservoir level. Therefore, a release would be made from reservoir 1 and not from reservoir 2 because the level of reservoir 2 is below the equivalent reservoir level.

APPENDIX 4 – NOTATION

The following symbols are used in this paper:

N	= number of periods ;
Shi	= shortage volume during the period i ;
Ti	= target demand during the period i;
$\sum$	= indicates the summation of the indicated values for all periods ;
SI_i	= shortage index in the supply area i ;
Sh_i	= shortage volume in the supply area i ;
M	= the total number of supply areas in the system ;
$\vec{Z}$	= the set of rule curves (operating zones) for all reservoirs ;
$\vec{I}$	= the inflows for all reservoirs, weirs and control points ;
HEC-5(....)	= represents the computation of the HEC-5 simulation model ;
T_{TN}	= the target demand in Tainan ;
T_{KS}	= the target demand in Kaohsiung ;
SI_{TN}	= shortage index for Tainan ;
SI_{KS}	= shortage index for Kaohsiung ;
Sh_{TN}	= shortage volume for Tainan ;
Sh_{KS}	= shortage volume for Kaohsiung.

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