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An Optimization Model for Crucial Key Pipes and Mechanical Reliability: A Case Study on a Water Distribution System in Taiwan

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Abstract This study develops a new method to calculate the water distribution system's mechanical reliability and locates crucial pipes by using the minimum cut-sets method, exhaustive enumeration method and an optimal allocation model. First, a full domain optimization model was established to analyze the water distribution system. Next, the minimum cut-sets method and exhaustive enumeration method were used to discover the water distribution system's key pipes. At last, water distribution system's mechanical reliability can be calculated. The major contributions are that we can use optimal allocation model to locate crucial pipelines in the water distribution whose failure will severely impair the source-demand connectivity. Besides, we can calculate water distribution system's mechanical reliability. Thus we can offer these results for hydraulic construction funds consulting. The developed methodology is applied to a water distribution system in Hsin-Chu, Taiwan.

Keywords Optimal allocation model · Minimum-cut-set-theory · Mechanical reliability · Water distribution system

1 Introduction

Due to its social, economic, environmental and hydrologic factors, to reduce the risk and the damage caused by floods and drought is by no means unimportant in Taiwan. Further, the over development of high technology in Taiwan has also affected the stability and reliability of water supply. It is thus necessary and important for Taiwanese authorities to examine the use of water resources and the management of water distribution system (WDS).

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However, with the decrease of reservoir water saving and the difficulty of expanding new water resources, the primary task concerning the stabilization of regional water demand and water supply is to analyze the optimal allocation of regional water resources and water distribution system. This lessens the loss resulted from water shortage. In addition, technological and industrial water demands also make industrial fields have less tolerance on water shortage. Thereupon, it is important to investigate water supplying reliability of key pipes in water sources as well as public water system and to search for possible solutions.

Through the discussion of Hsin-Chu case, this study hopes to pave ways for calculating mechanical reliability of water distribution system and the optimal allocation of public water system and water resources. We also hope that this study enables readers and the authorities concerned to reach better understanding about future supply of water resources.

In the following discussion, we provide brief conceptual analyses of relevant literature about mechanical reliability.

To understand the reliability of the water distribution system is an important topic of water resource allocation. The probability distribution functions of system capacity was researched by Shamir and Howard (1981, 1985) at first. Then some analytical methods to estimate the reliability of water system capacity was proposed by Hobbs (1985) and Wagner et al. (1988). They proposed two algorithms for the connectivity of uncapacitated series-parallel network and general capacitated network of the water distribution system. For calculating the reliability, Park and Liebman (1993) embedded the required reliability level in the design model. They constrained the shortage of each node in the network to certain specified fractions of demand. In another study conducted by Keisler et al. (1990), they discussed certain degrees of redundancy in water distribution network where the network can sustain any single component failure.

Assessing the failures mechanism of a pipe requires date related to each failure event. Cullinane (1989) categorized hydraulic and mechanical failures of water distribution system. A famous method (minimum cut-set method) to understand mechanical and hydraulic failures of small water distribution system was employed by Su et al. (1987). Besides, the methodology was applied by Yang et al. (1996a, b) to the concept of source-demand connectivity to large scale regional water distribution network. Their approach looked at the effect of link failures on source demand connectivity, which is a measure for the mechanical reliability of water distribution network. Recently, Park et al. (2008) use maximized log-likelihoods method to model the failure rate and estimate the economically optimal replacement time of individual pipes in a water distribution system.

1.1 Methodology Development

Research methodologies of this study are concluding two parts, i.e., (1) the optimal allocation model of water distribution system, and (2) exhaustive enumeration method with the combination of optimal allocation model and minimum cut-set method for the search of key pipe reliability. The analysis procedure is shown as Fig. 1. In order to calculate the mechanical reliability of the water distribution system, this study establishes a full domain optimization model to analyze water

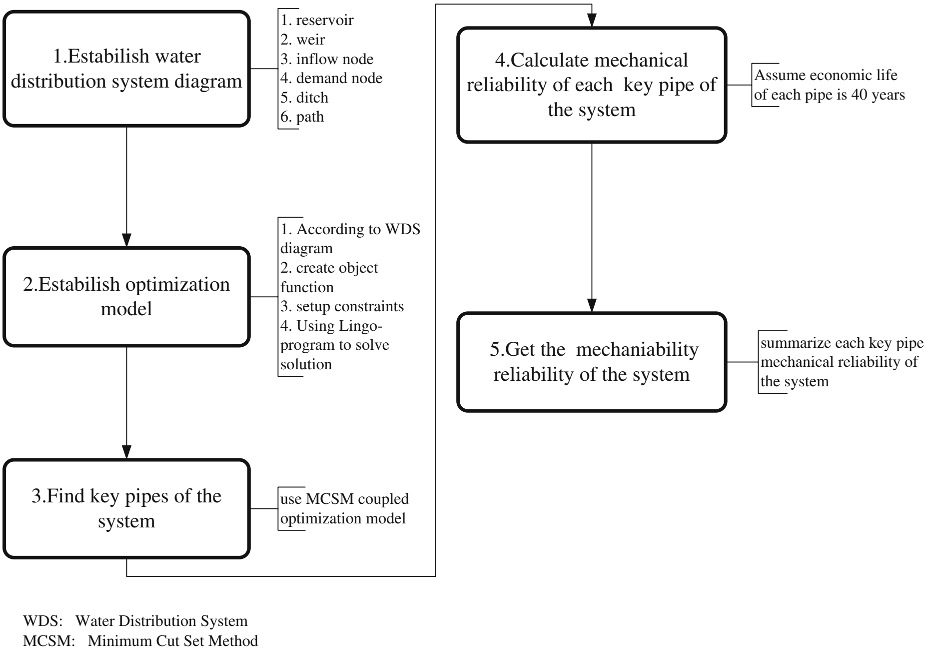

Fig. 1 Mechanical reliability analysis procedure

distribution system based on the water resources data. Next, this study applies the simulation process and exhaustive enumeration method optimal allocation model for the analysis of key pipes. After all, according to the life cycle of each key pipe, we can get each pipe's mechanical reliability as the reciprocal of the life cycle of each key pipe. Finally, we can calculate water distribution system's mechanical reliability by summing up all the mechanical reliability of each pipe of the water distribution system.

1.2 Optimization Model—Linear Programming Method

In the following discussion, we provide brief conceptual analyses of relevant literature about optimization model.

In the last decade, new techniques such as Linear programming method, Genetic Algorithms, artificial neural networks and fuzzy logic have been applied to optimization. Labadie (2004) presented the most comprehensive state-of-the-art review on the use of optimization techniques for reservoir operation. Besides, since 1978, Liu (1978) simplified the mass balance equation. Via the selection of different time, he turned the linear programming model into a single-variable formula. Kuczera (1989) developed a network linear model and applied it to multiple reservoir systems for efficient operation. Chang and Yih (1990) applied a stochastic linear programming model to the study of agricultural water demand. To explore the best water-releasing strategy for reservoirs and the inflow amount in any given situation at any given period of time, the distribution and usage of agricultural water in Taiwan's Chiu-Chiu lower stream supplied by Sun-Moon Lake was adopted by Chang as the case for study. Crawley and Dandy (1993) focused on the simulation of surface-water rights by applying the linear programming method. To understand actual water supply under different policies of water resource distribution, Chou and Huang (1998) established a united operation model to analyze surface water and groundwater in south Taiwan. Drawn on different hydrology situations and different strategies of water resource distribution, their study found that water amount can be modified and simulated when the quality of water is in stable situation. Hsu and Cheng (2002) developed a generalized network flow optimization model for long-term supply–demand analysis of basin-widewater resources planning. The decision variables are reservoir storage and water supply for public and agricultural uses. The objective function to be minimized is formed by summing the products of the decision variables which are multiplied by their corresponding cost coefficients. Hsu and Cheng's developed model was applied to a river basin located in northern Taiwan. Their result showed that water shortage computed by the optimization model is smaller than that computed by the simulation model. In another study conducted by Tu et al. (2003), they developed a mixed integer linear programming (MILP) model to operate multipurpose and multi-reservoir system. The MILP model featured both traditional reservoir rule curves and hedging rules and was applied to a multi-reservoir system in south Taiwan.

This study holds the view that the analysis and assessment of water distribution system should start from the investigation of link-pipes in each water treatment plant so that researchers are able to establish a key pipe model for feature analysis of key pipes. With the data collected, authors of this study conduct a simulation analysis for the optimization. Water supply systems in this study include dams, rivers, ditches, pipes, weir, etc. In addition, water demands for agricultural and public purposes are also part of water supplying concerns. To reach the goal of optimal allocation for water resources and public water system, this study draws on studies of Tsai and Hsu (2002), Tu et al. (2003) and Tsai (2003), where they discussed the optimization model (i.e., the simulation model of ten-days optimization or the simulation model of a full-domain optimization). Recently, Sahoo et al. (2006) developed a linear programming and fuzzy optimization models to optimize the economic return, production and labor utilization. The models keep all the three objectives at the same priority to obtain the comprised solution in a fuzzy environment. Reca et al. (2008) used several meta-heuristic techniques to estimate the optimal solution of the minimum network investment in the water distribution system. Sechi and Zuddas (2008) developed a water resources management model by using the hypergraph optimization approach to solve reservoirs design problems. Liu et al. (2010) developed a model for the optimal allocation of water resources in saltwater intrusion areas by using a genetic algorithm. The formulizations of the optimization model are discussed below:

This study, in order to demonstrate the needs relationship of water resources, divides water resources into five types of node (i.e., reservoir nodes, demand nodes, weir nodes, inflow nodes, and common nodes.) It is shown in Fig. 1. In Fig. 2, the authors present a flow network diagram, which uses the arrow line model (i.e., reservoir storage, conserved water quantity, reservoir overflow, path and pipe links) to connect these nodes. These nodes are also numbered and shown in Fig. 2.

The optimization model established for this study includes object function and constraints. The process of formulization and notations used are explained below.

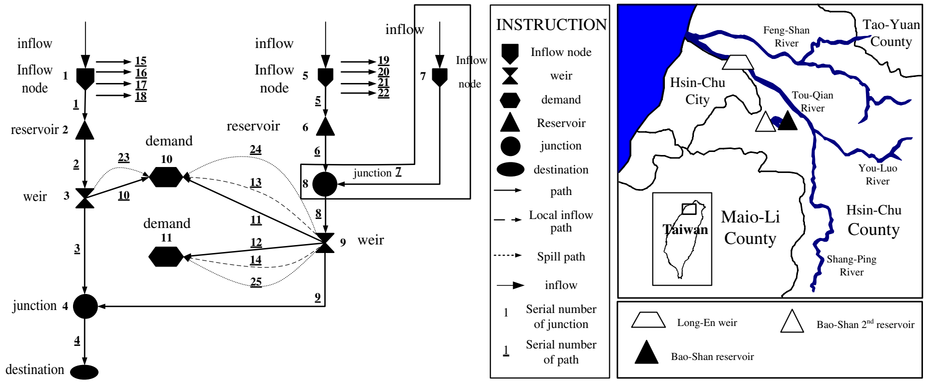

Fig. 2 Water distribution system diagram and nodes diagram

1.2.1 Objective Function

This study maximizes the object functions of source demands from local inflow, reservoir release, reservoir storage, and reservoir overflow, as a way to develop the optimization model. These object functions are arranged in an order and into a compound object function by the weighting factor method, where the arrangement is determined by the absolute value of the weighting factor. The object function is represented as Eq. 1:

$$Max\left(\sum_{i\in A_L} c_{i,t}^{L}\cdot x_{i,t}+\sum_{i\in A_S} c_{i,t}^{S}\cdot x_{i,t}+\sum_{i\in A_C} c_{i,t}^{C}\cdot x_{i,t}+\sum_{i\in A_R} c_{i,t}^{R}\cdot x_{i,t}\right) \tag{1}$$

In the above equations, $C_{i,t}^{L}$ represents the weighting factor pertaining to the water supply node of side inflow during time span t. $C_{i,t}^{S}$ represents the weighting factor concerning water supply node of reservoir overflow during time span t. $C_{i,t}^{C}$ represents the weighting factor about the arrow line of water saving during time span t. $C_{i,t}^{R}$ represents the weighting factor about the water supply node of reservoir release during time span t. Where $x_{i,t}$ represents the flow-quantity of the pipe i during time span t.

1.2.2 Constraints

Constraints include the reservoir node, inflow node, weir node, demand node, general nodes, and other quantity limit constraints such as water distribution flow quantities and water reservation flow quantities.

In Fig. 3, the inflow node and weir node are nodes 1, 5, 7 and 3 and 9. General nodes are nodes 4 and 8, which are the nodes for junction or link nodes. Regarding the balancing equation for inflow, weir and general nodes, we use mass balance theorem to represent it, which is shown as Eq. 2:

$$\sum_{\substack{h_j=j\\ i\in A}} X_{i,t}-\sum_{\substack{f_j=j\\ i\in A}} X_{i,t}=\sum_{\substack{g_j=j\\ k\in I}} Q_{k,t}^{i}, \qquad \forall j\in\{N_I\cup N_T\cup N_G\},\forall t\in T \tag{2}$$

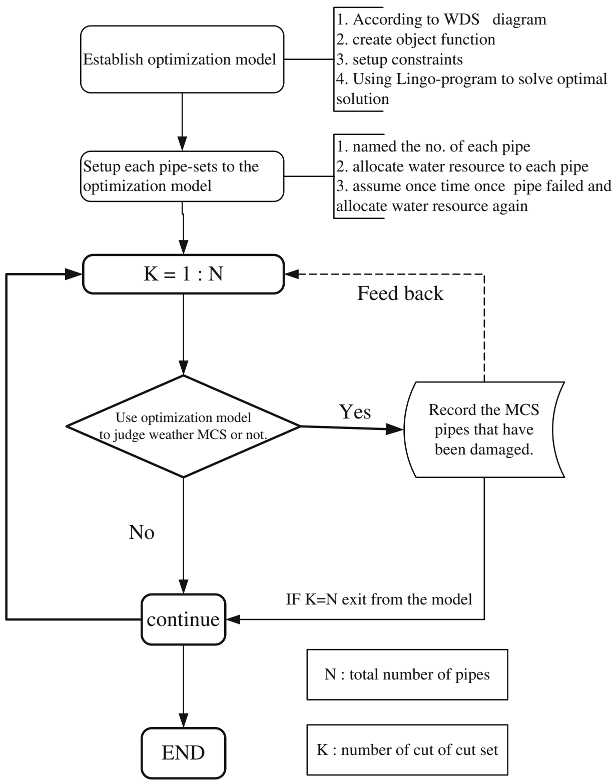

Fig. 3 Flow chart of minimum cut-sets searching

Where $x_{i,t}$ represents the flow-quantity of the pipe i during time span t, $Q^i_{k,t}$ represents the inflow, N_T is the weir node set, N_G is the general node set, N_I is the inflow node set. h_i is the terminal point of flow-quantity, f_i is the start point of flow-quantity, g_k is the water reservation of the node k, i is the water supply flow-quantity of water distribution system, j is the node of the water distribution system.

Water acquired from the source of water demand node may include reserved reservoir water, partial inflow between the reservoir node and the weir node, and the possible overflow (e.g., surface water) caused by the full load of dam. In Fig. 2, nodes 10 and 11 are water demand nodes and the needed water for use may come from partial inflow (i.e., flow-quantities 13 and 14), water release (i.e., flow-quantities 10, 11, and 12), reservoir release (i.e., flow-quantities 15–18, flow quantities 19–22) and weir overflow (i.e., flow-quantities 24, 25). The relevant equation is shown as Eq. 3:

$$\sum_{\substack{h_i = j \\ i \in A_L}} x_{i,t} + \sum_{\substack{h_i = j \\ i \in A_S}} x_{i,t} + \sum_{\substack{h_i = j \\ i \in A_R}} x_{i,t} \leq D_{j,t}, \quad \forall j \in N_D, \forall t \in T \tag{3}$$

Where $x_{i,t}$ represents the flow-quantity of the pipe i during time span t, $D_{k,t}$ represents the demand node in the water distribution system, h_i represents terminal point of flow-quantity, A_L represents flow-quantity set for connecting partial inflow and water demand nodes, A_R represents flow-quantity set for connecting all the dams and water demand nodes, A_S represents flow-quantity set for connecting all the overflow and water demand nodes, N_D represents water demand node set in the water distribution. j represents node in the water distribution system, T is the total number of time periods.

In the optimization model, the totality of water selection amount from the partial inflow should be less than its inflow, which can be represented as Eq. 4:

$$\sum_{\substack{r_i = l \\ i \in A_L}} X_{i,t} \le \sum_{\substack{q_k = l \\ k \in I}} Q_{k,t}, \qquad \forall l \in I_L, \forall t \in T \tag{4}$$

Where $x_{i,t}$ represents the flow-quantity of the pipe i during time span t, $Q^p_{k,t}$ represents the partial inflow, r_i is the local inflow set of the water demand node, q_k is the local inflow set of the inflow, A_L is the flow-quantity set for connecting partial inflow and water demand nodes, I_L is the partial inflow sets, T is the total number of time periods.

In terms of the optimization model, all the water distribution and reservation flow-quantity have capacity limit, which can be shown as Eq. 5:

$$x^{\min}_{i,t} \le x_{i,t} \le x^{\max}_{i,t}, \quad \forall i \in A \, \forall t \in T \tag{5}$$

Where $x_{i,t}$ represents the flow-quantity of the pipe i during time span t, $x^{\max}_{i,t}$ is the upper bound of $x_{i,t}$, $x^{\min}_{i,t}$ is the lower bound of $x_{i,t}$, A is the water amount flow-quantity set.

1.3 Exhaustive Enumeration Method

Exhaustive enumeration method is a methodology to compute all the results in the domain. Besides, it means a way to find out all the solutions in the computing fields. This study uses this method to combine minimum-cut-set method to find out all the key pipes in the water distribution system.

1.4 Minimum-Cut-Sets Method

Beside the optimization model in the Section 1, this study adopts the minimum-cut-sets method to analyze mechanical reliability. In terms of water distribution system, the objective of employing the minimum cut set method is to inspect the connection status between water sources and water demands. Its methodological procedures are briefly described in the below. The methodology of MCSM can be find detail in reference literature (Yang et al. 1996a, b).

To analyze the interrelationship in a water distribution system, it need transformed into a network representation fist. A network representation of a water distribution system involves a large number of nodes and link, which means a lot of types of facilities in the system.

The cut-set refers to the pipe connection in water distribution system. If one of the pipe sets is out of order, it may bring disorder to the water distribution system. Such disordered pipe sets is called the cut-set. Among the disordered pipes, water supply can be continued if any of the pipes is restored. The sets for these water supply pipes are called minimum-cut-sets. When one of the water demand points can no longer supply water (i.e., unable to distribute water from the water supplying point to the water demand point) due to pipe damage, it is called mechanical damage. The probability of mechanical damage refers to the occurrence at least one mechanical damage.

Based on the definition of minimum-cut-sets, it is necessary to discover cut-sets from all the pipes so that the minimum-cut-set can be discovered out of the cut-sets. Assuming that there are N_l connections in the water distribution system, there should be S_N kinds of possible connections. S_N can be represented in the Eq. 6:

$$S_N = \sum_{i=1}^{N_l} Com \begin{pmatrix} N_l \\ i \end{pmatrix} \text{ Com is notation of combination} \tag{6}$$

The minimum-cut-sets mean the pipe sets that cause the least pipe damage which may cause damage in the water distribution system. By applying the above concept and the probability of pipe damage, we are able to calculate the mechanical reliability.

The minimum cut-set method involves the generation of a number of component failure events whose effects on the system are determined one at a time. In addition, cut-sets are directly related to the modes of system failure and can be used to identify situations in which a system may fail. A minimum cut-set for a source-demand pair is defined as a set of links, when all links of the set fail simultaneously will disrupt the connectivity of the specified source node to the specified demand node.

In the identification of the minimum cut-sets for a specified source-demand pair, only the links in the associated subnetwork are considered. The associated subnetwork to be examined for a source-demand pair is all the links connecting these two links. The subnetwork can be identified by a combined use of forward and backward network search algorithms.

Nevertheless, prior to analyzing the mechanical reliability, the optimization model should be developed (i.e., the global optimization model for water distribution system as discussed earlier). By applying the optimization model and the minimum-cut-sets concept, we are able to identify all the mechanical minimum-cut-sets. It is represented in Fig. 3:

In the flow chart shown as Fig. 3, N is the sum of all pipes in the same system and k refers to the number of damaged pipes in the pipe set (k = 1,2,3…N). We step by step work on the simulation of damage by employing the optimization model to pipe sets of the water distribution system.

Whenever the simulation result shows that damaged pipe sets are also minimum-cut-sets. The optimization model would record pipe sets to be minimum cut sets until K = N. Further, the result we obtain from minimum-cut- sets pipes of the water distribution can be applied to the calculation of mechanical reliability.

1.5 Mechanical Reliability

The identification of minimum-cut-sets discussed above helps researchers identify the minimum-cut-sets in each water distribution system. It also helps researchers calculate the occurring probability of each cut-set. By calculating the damaging probability (P_f) of pipe sets in each water distribution subsystem and by assuming the damaging probability of each subsystem as an individual matter, the damaging probability is the sum of the probability of all the individual matters. If the breakdown probability of a system is defined as P_f, the mechanical reliability (R_m) for water supplying stability is $1 - P_f$. It is represented in the Eq. 7:

$$R_m = 1 - P_f \tag{7}$$

Mechanical reliability (R_m) refers to normal water supplying rate in water distribution systems. The probability of mechanical damage (P_f) refers to the occurrence at least one mechanical damage in the system. In the minimum cut sets of water supplying system, damages are represented by C'_1, C'_2,..., and C'_n, and the damaging probability can also be represented by $P_f(C'_1)$, $P_f(C'_2)$,..., and $P_f(C'_n)$. Mechanical damaging probability P_f, is represented as Eq. 8:

$$P_f = P\left(C'_1 \cup C'_2 \cup ... \cup C'_n\right) \tag{8}$$

Besides, the mechanical reliability for water supplying stability is shown as Eqs. 9 and 10:

$$R_m = 1 - P_f = 1 - P\left(C'_1 \cup C'_2 \cup ... \cup C'_n\right) \tag{9}$$

Or

$$R_m = 1 - \left[(-1)^{1-1} \sum_{i=1}^{M} P(C_i) + (-1)^{2-1} \sum_{i=2}^{M} \sum_{j=1}^{i-1} P\left(C_i \cap C_j\right) + ... (-1)^{M-1} P(C_1 \cap C_2 \cap ... \cap C_n)\right] \tag{10}$$

In the Eq. 10, M_c means the total cut-sets for the system; C_1, C_2..... mean mechanical damages; $P(C_1)$, $P(C_2)$..... mean the probability of damages; R_m refers to the water supplying reliability.

2 Application of Methodology

This study develops its optimization model of water distribution system water to the case of Hsin-Chu (which is located in northwest Taiwan). The study further discusses the mechanical reliability and key pipes in Hsin-Chu area. The objective of this study is to provide useful information for the development of future water resources and key pipe protection.

2.1 Description of Study Area

This study selects Hsin-Chu, Taiwan as the case for the study of optimization model. In Hsin-Chu, water sources mainly come from Tou-Chian River and Feng-Shan River, where the irrigation facilities encompass Bao-Shan Reservoir, Bao-Shan 2nd Reservoir, Long-En Weir, Zao-Shu-Pai Weir, etc. In terms of water treatment plants in this area, there are Shin-Zhu-1st Treatment Plant, Shin-Zhu-2nd Water Treatment Plant, Nan-Ya Water Treatment Plant, Yuan-Dong Water Treatment Plant, and Bao-Shan Water Treatment Plant. As for the irrigation districts in Hsin-Chu, there

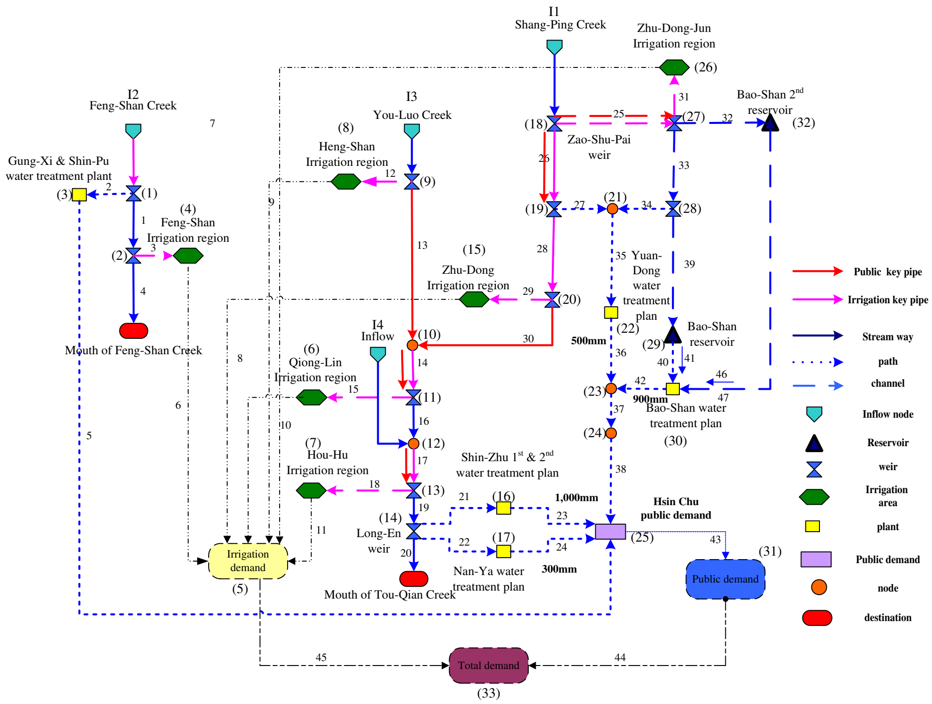

Fig. 4 Water supplying system in Hsin-Chu

are Feng-Shan, Qiong-Lin, Hou-Hu, Heng-Shan, Zhu-Dong, and Zhu-Dong-Jun. This study collects data from each water resource facility and creates the water system of Hsin-Chu in Fig. 4.

This study adopts data collected during years 1971 to 2006 for analysis. Data sources are based on Hsin-Chu's water resource data, reservoir water evaporation and capacity limit, public and agricultural water demands, water treatment plants and pipe water transport limit. Relevant information is shown in Fig. 4.

3 Results and Discussion

3.1 Analysis Result—Key Pipes

This study employs the minimum-cut-sets method exhaustive method and optimization model, for the analysis of water distribution system in Hsin-Chu area

After getting results about the minimum-cut-sets on Hsin-Chu's water distribution system, we then can proceed to the identification of key pipe sets. Key Pipes means the crucial pipes of the water supply system. It's the important key about water supply system can supply water resource or not if these pipes can work normally or not. This enables us to understand the influence of key pipe damage on the water supply system. This study analyzes Hsin-Chu's need of water demand and water supply in the year 2006. Drawing on its status quo of water demand, we discuss possible influences of pipe damage on water supply.

This study finds that the distribution system of public water in Hsin-Chu may be seriously affected when certain pipe sets are damaged. To analyze in detail, pipes sets numbered x13, x14, x17, x25, x26, and [x13, x30] are key pipes for Hsin-Chu's public water demand and pipe sets numbered x1, x3, x12, x14, x15, x17, x18, x25, x26, x28, x29, x31, and [x13, x30] are key pipes for Hisn-Chu's irrigation water demand (shown in Fig. 4). When these pipes are damaged and fail to work normally, the distribution system of public water in Hsin-Chu will be seriously affected. Water cannot be transported successfully when key pipes are damaged. We therefore suggest the authorities concerned consider this research as reference resource for future prevention of water shortage.

3.2 Analysis Result—Mechanical Reliability

It is necessary to identify the minimum cut-set pipes and the damaging probability for Hsin-Chu's water supply system prior to identifying the mechanical reliability. Due to the fact that pipe links in Hsin-Chu are disorganized, aligned with both new and old ones, this study according to the piping it is usual 40 years of lifetime and 20 years for pumps. The damaging probability of each pipe set can be calculated via the inverse of pipe lifespan. The damaging probability of each pipe in a 10-day-period is $1/(36 \times 40) = 0.0006944$. The probability that two pipes get damaged at the same time is $0.0006944 \times 0.0006944 = 0.000000482$. The rest may also be deduced by analogy. Due to the fact that the probability that three pipes (or more than three) get damaged at the same time is relatively low, this study focuses on analyzing the damaging condition of two pipes (and the below) in lieu of the damaging probability. The analysis is shown in Table 1. Based on Table 1, we learn that the total

Table 1 The damaging probability of minimum cut-sets pipes in Hsin-Chu area

Serial numbers	Minimum cuts (irrigation)	Destroy probability	Minimum cuts (public)	Destroy probability
1	[1]	0.0006944	[13]	0.0006944
2	[3]	0.0006944	[14]	0.0006944
3	[12]	0.0006944	[17]	0.0006944
4	[14]	0.0006944	[25]	0.0006944
5	[15]	0.0006944	[26]	0.0006944
6	[17]	0.0006944	[30,13]	0.000000482
7	[18]	0.0006944		
8	[25]	0.0006944		
9	[26]	0.0006944		
10	[28]	0.0006944		
11	[29]	0.0006944		
12	[31]	0.0006944		
13	[30,13]	0.000000482		
Total destroy probability (P_f)	0.00833		0.00347	
Summation (P_f)	$0.00833 + 0.00347 = 0.0118$			

damaging probability (P_f) in Hsin-Chu area is: $P_f = 0.00833 + 0.00347 = 0.0118$. The mechanical reliability in Hsin-Chu area is represented below:

$$R_m = 1 - P_f = 0.9882 = 98.82\%$$

As the result shows, Hsin-Chu's mechanical reliability $R_m = 98.82\%$. This implies that there is no much need for the authorities concerned to ameliorate the mechanical reliability of water supply system in Hsin-Chu area at present.

4 Conclusions

The study successfully applied the developed model to regional water distribution system in north Taiwan. This study demonstrates the applicability and utility of the proposed methodology. The optimization model of water supply developed in this research and the results obtained from this study can be used for the allocation of water resources at any certain region in any certain year. Meanwhile, key pipes for water supply purpose can also be identified through calculation when we integrate the optimization model of water supply with the minimum cut-sets approach. Besides, we recommend the use of multi-pipes instead of single pipe for water transportation since they can lessen the possibility of damaging minimum cut sets. We hope this study provide useful information for authorities concerned in the consideration of budget issues on pipe maintenance. Results discussed above are of great assistance for practical affairs such as the allocation of water resources and the maintenance of optimal operation of pipes.

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