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Integrated water resources management for emergency situations: A case study of Macau

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ABSTRACT

Integrated urban water management (IUWM) is a useful tool that can be used to alleviate water resource shortages in developing regions like Macau, where 98% of the raw water comes from mainland China. In Macau, scarce water resources deteriorate rapidly in emergency situations, such as accidental chemical spills upstream of the supply reservoir or salty tides. During these times, only the water from the two freshwater reservoirs in Macau can be used. In this study, we developed urban water management optimization models that integrated the raw water supply from the two reservoirs with various proposed governmental policies (wastewater reuse, rainwater collection, and water saving). We then determined how various water resource strategies would influence the urban water supply in Macau in emergency situations. Our results showed that, without imported raw water, the water supply from only the two Macau reservoirs would last for 7.95 days. However, when all the government policies were included in the model, the supply could be extended to 13.79 days. Out of the three non-conventional water resources, wastewater reuse is the most beneficial for increasing the Macau water supply, and rainwater collection also has great potential.

Introduction

The Macao Special Administrative Region, internationally renowned for its casinos and tourism, experiences water stress because of a lack of raw water combined with rapid economic growth in recent years. Although Macau has two storage reservoirs, the Macau main storage reservoir (MSR) and the Seac Pai Van reservoir (SPVR), it has virtually no conventional water resources, and 96% of the raw water supply comes from mainland China. Three water pipes transport raw water from the Zhuxiandong reservoir in Zhuhai to four water treatment plants in Macau (Fig. 1). The raw water in the Zhuxiandong reservoir is supplied from the Modaomen Channel by the HongWan pumping station. Non-conventional water resources, such as reused water and rainwater, are not widely exploited at present; Macau's wastewater reuse policy is still in its initial stages and the rainwater use rate was only 3.4% in 2012. The current, limited use of unconventional water resources maintains the fragility of the Macau water system, and means that it is particularly vulnerable in emergency situations, such as chemical spills and during the salt tide period.

Emergency situations in water supply systems have been reported by other researchers. Schade et al. (2015) reported that an industrial accident contaminated the public water supply of approximately 300,000 homes in and close to Charleston, West

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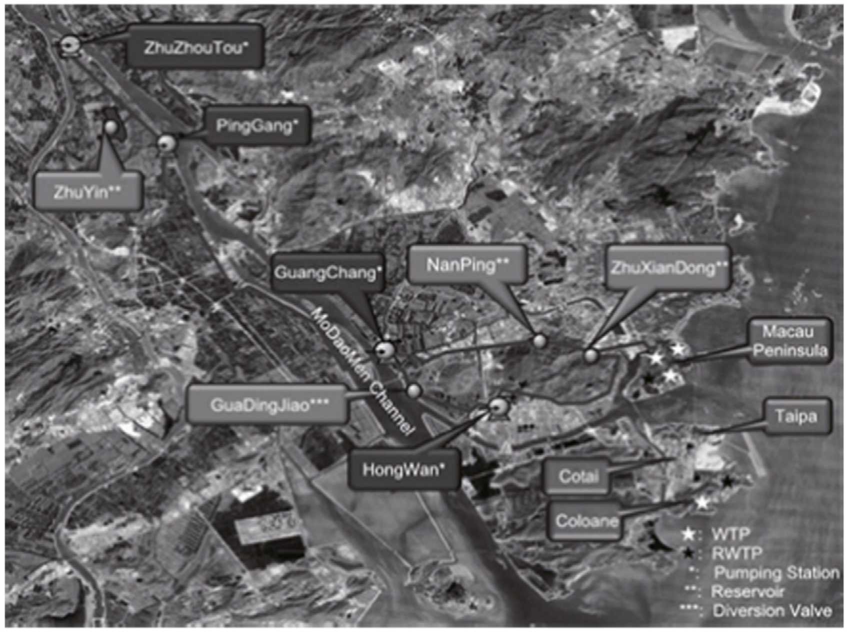

Fig. 1 – Raw water supply system of Macau.

Virginia. A fatal incident occurred in Longgang, a suburb of Shenzhen, when cyanide spilled into a sewer in 2007 and resulted in the death of two people. Macao Water Supply Company Limited also experienced a drill that chemical spill at the water treatment plant of the MSR in 2014. If the cyanide accidentally spills in the raw water from Modaomen Channel by the factory, the consequences could be disastrous, most of the fish and other aquatic organisms would die and the people around the river should evacuate immediately. Natural diffusion and dilution by environment itself would be the remedial way for serious cyanide spill. For Macau, it can mean that there may be no raw water in the water system except for the raw water in the two main Macau storage reservoirs. The severity of this kind of situation and the implications for daily life should be of concern to water users and the government; the safety and quality of the water supply should be a government priority. Another, unrelated problem is the salt tides that occur in urban water systems located in regions near tidal rivers. Vellinga et al. (2014) studied the discharge distribution and salt water intrusion in the Rhine–Meuse River delta network and found that the contribution of salt water to the total river flux strongly depended on the stage of the tide, but decreased rapidly upstream. The Macao Water Company and the government have moved the raw water intake from the Guangchang pumping station, to the Pinggang pumping station and the Zhuzhoutou pumping station, so that intake will be sourced further and further upstream. Furthermore, raw water has even been supplied from the Zhuyin reservoir to the Zhuxiandong reservoir (Fig. 1). In 2005, Macau residents rushed to purchase bottled water to neutralize the salinity of the water supply during a salt tide when the salt content reached 500 mg/L, which is twice the international standard.

In the situations given above (*i.e.*, chemical spills and salt tides), the number of days for which a normal water supply is available is a matter of great concern for water users and the government. Because the conventional water system has a limit on its available duration, Hamoda (2004) said non-conventional water systems have great potential and should be exploited. He figured that water reuse as non-potable water in agriculture is justified on agronomic and economic grounds. It will result in savings of fresh water and augmentation of water supply required for irrigation to overcome the shortage in food sufficiency. Besides, the reused water can also be used as potable water through the advanced treatment process. Government policies, such as wastewater reuse and rainwater collection, have been developed to enhance the non-conventional water resource supply in Macau. Water-saving policies can also strengthen the resilience of the water system. Methods like integrated urban water management (IUWM) are common and can help optimize the use of various water resources in urban water systems. This type of approach has been applied to alleviate water resource shortages and has been particularly successful in developing countries and in regions that have experienced high population and economic growth (Evans and Varma, 2009). Grit et al. (2015) studied IUWM and developed a method for identifying, bundling, and prioritizing measures that included resource orientation and cost-efficiency analysis. The IUWM method can be used to model and estimate the number of days that freshwater will last in emergency situations in urban water systems. Similar studies involving effective management of water resources in emergencies have focused on actions that using smart management coordinated various agencies. (Tiana et al., 2013). Rasekh and Brumbelow (2015) suggested that their optimized adaptive emergency response model could be a major component of an all-inclusive cyber-infrastructure to efficiently manage threats from contamination to urban water systems. The aim of this study was to model options that might enhance the overall efficiency of the water system by integrating aspects of governmental policies relating to the use of alternative water sources in emergency situations.

1. Materials and methods

The modeling in this study is similar to the one proposed in our previous studies (Gao et al., 2014). Urban water systems mainly comprise two parts: a water supply system and a water demand system. The water supply system includes various water resources, such as tap water, reused water, and rainwater, which supply water to meet, or stratify, the water demand system, while the water demand system includes the intermediate and end users of the water system, as four sectors: commerce, industry, households, and public supply. Optimizing the urban water system was reflected on the optimizing the water resources and emphasizes water-saving policies which can decrease the water demand.

The water supply system of Macau can be subdivided into four regions (Macau Peninsula, Taipa, Cotai, and Coloane) (Fig. 1). There are three water treatment plants (WTPs) in the Macau Peninsula, namely the Ilha Verde water plant, MSR plant, and MSR II plant with daily supply water capacities of 0.18, 0.06, and 0.06 × 10^6 m^3, respectively. An additional plant, the Coloane water plant in Coloane, can supply 0.06 million m^3 of water per day. With the exception of Cotai, the regions each have their own wastewater treatment plants. However, because of land limitations in the Taipa region, there are only two reuse water treatment plants (RWTP), one in the Macau Peninsula and the other in Coloane. The daily supply water capacities of the Macau Peninsula RWTP and the Coloane RWTP are 40,000 and 12,000 m^3, respectively.

Among the possible water resources, rainwater has most potential to enhance the efficiency of the water system because of its current low use rate. Historical data indicates that the heaviest average rainfall per month occurs in June (Table 1), however the maximum daily rainfall occurs in May (24.2 mm). Rainfall differs considerably between the rainy season (April to September) and the relatively dry season (October to March). The average daily rainfall in the rainy season is 8.6 mm while that in relatively dry season is only 1.2 mm. Unfortunately, salt tides frequently occur from October to March when the rainfall was low the preceding season. The salt tide affects the salinity of the raw water, which means that the water treatment cost is higher and there is a lower volume of available raw water, resulting in an overall decline in the water supply. Neutralizing raw water resources is an effective way to increase the number of days for which water is available. When the salinity of the original raw water from MSR and SPVR is 20 mg/L, the neutralization function is as follows:

$$C_s = \frac{C_1Q_1 + C_2Q_2}{Q_1 + Q_2}$$

In the water system, water demand is one of most important controls on the available days in emergency situations. Yearly data shows that most of the water demand (about 68%) is from the Macau Peninsula (Fig. 2). Because of the casino and tourism industries, the ratios of the commerce and household water demands are almost equal, and the sum of these two ratios comprises the majority of the water demand. The average daily water demands of each water user in each region were not shown in the annual data report but were needed to calculate the available days.

The link between the water supply system and water demand system is the pipe network, details of which are shown in Table 2. When the locations of the WTPs and RWTPs are combined, the pipe network shows that the Macau Peninsula is the core of the Macau water system because, regardless of whether it was for WTP or RWTP, the water demands of the Macau Peninsula and Taipa were only satisfied by the water plants in the Macau Peninsula. For simplicity, two options were considered for rainwater collection. The first option considers rainwater that is collected as an additional water resource in the MSR and SPVR water systems. The second considers rainwater that is collected and used by individual water users. The formulation between water demand $D_{k,i,e,f}$ and various water resources (including the water saving) $Q_{j,n,k,i,e,f}$ as follows; the leakage rate η_k is employed to fix the equation based on actual conditions of water resources, like its specific location and logic constraint, a.

0–1 parameter θ was introduced. The value 1 means supply–demand relationship is allowed and $Q_{j,n,k,i,e,f}$ is not equal to 0. The parameters i, j, k, n, e, and f respectively represent water user, water resource, region, region, pipe network type, and potable or non-potable.

$$D_{k,i,e,f} = \sum_j \sum_n \theta_{j,n,k,i,e,f} \cdot Q_{j,n,k,i,e,f} \cdot (1 - \eta_k)$$

The related cost formulation in this study only considers the operational expenditure $M^o_{j,n}$, transportation cost $M^t_{j,n,k}$, and water saving cost M^s. All of the costs s^g are the responsibility of the government in Macau.

$$s^g = \sum_j \sum_n M^o_{j,n} + \sum_j \sum_n \sum_k M^t_{j,n,k} + M^s$$

The models were set up for two types of emergency situation. While there are existing government policies that deal with chemicals, the impacts of these spills in water systems are sufficiently significant that the policies warrant more emphasis or even revision. A basic model that only considers raw water resources and other models (Model series A) that integrate various governmental policies have been developed to estimate the number of days the raw water system can last in

Table 1 – Average rainfall (in mm) from 2003 to 2012.

	Dry season						Rainy season					
Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.
Total rainfall	58.9	41.3	16.6	20.2	32.7	49.2	130.0	283.0	438.7	209.8	298.5	210.8
Rain event duration (in day)	5.8	4.5	4.0	6.4	9.6	11.1	11.7	13.4	18.1	15.6	15.2	12.3
Daily rainfall in a given rain day	10.2	9.2	4.1	3.2	3.4	4.4	11.1	21.1	24.2	13.4	19.6	17.1
Average daily rainfall	1.2						8.6					

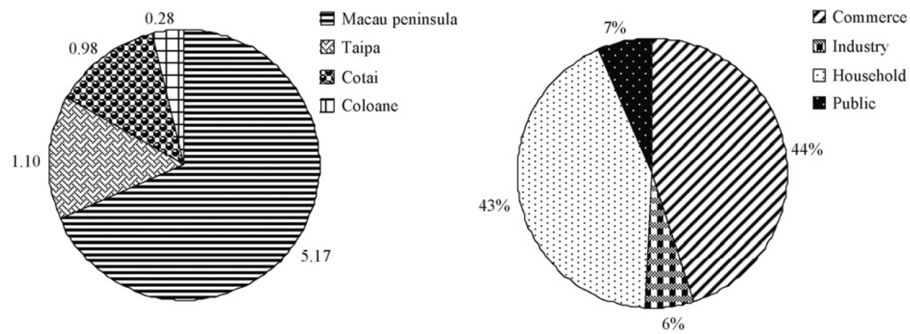

Fig. 2 – Water demand for each region and for each type of water user.

emergencies (Table 3). Those models use the maximum daily rainfall (24.2 mm), which can obtain the best result theoretically. While wastewater reuse and water-saving policies mostly rely on known and controllable factors, there is uncertainty in the rainwater collection policy because there is a large difference in rainfall amounts between the rainy and the dry seasons. The used efficiency of rainfall and floodwater resources can be analyzed, and their use can be optimized and improved with benefits for urban development (Chen and Huang, 2013). The performance of the integrated water system, including all the government policies and various possible rainwater use rates (*i.e.*, using 3.4%, 5%, 10%, 15%, 20%, 25%, 30%, and 40% rainwater) in the dry season and rainy season, was analyzed with model series B and C. Those two types of model series respectively apply 8.6 mm and 1.2 mm average daily rainfall. The raw water data in these two model series are from the MSR and SPVR. Thus, further analysis may provide insights into how the water system can be improved and optimized without adding additional raw water.

During a salt tide emergency, available days can be increased by integrating various water resources; for example, the raw water in the reservoir may be used to neutralize or dilute the water in the river that is affected by the salt tide instead of only using the reservoir freshwater. The water quality in the source area declines sharply during the salt tide period, which degrades the available water supply and threatens the water security of the whole city. The high water supply salinity affects people's taste, but might be harmful for the special crowd. Analysis of historical data indicated that the water supply salinity has, in certain periods, been as high as 500 mg/L, though the national standard is 250 mg/L. Model series D and E which respectively applied the above water supply salinity were used to analyze the performance of the water system, including all government policies and a range of salinity levels. The salinity levels used were 600, 700, 800, 900, 1000, 2000, 4000, and 8000 mg/L in model series D and 350, 450, 550, 650, 750, 1500, 3000, and 6000 mg/L in model series E. For example, model D600 was calculated for imported raw water with a salinity of 600 mg/L and a water supply salinity of 500 mg/L from the water treatment plant. Both model series D and E use the 1.2 mm average daily rainfall.

Table 2 – Pipe network of water plants.

	Macau Peninsula	Taipa	Cotai	Coloane
Ilha Verde Water Plant	√	√	√	–
MSR Plant	√	–	–	–
MSR II Plant	√	√	√	–
Coloane Water Plant	–	–	√	√
Macau Peninsula RWTP	√	√	√	√
Coloane RWTP	–	–	√	√

"√" represents "existing water supply"; "–" represents "no existing water supply".

The maximum days for which water is available is the number of days for which a normal water supply can be maintained until the daily water demand can no longer be met. We used an objective function to obtain the optimal solution. The x value represents the days water is available, while the function $f_i(x)$ represents the water remaining in the MSR or SPVR. The x value can be obtained by maximizing the function $F(x)$ to optimize the water system with various water resources:

$$\max\ F(x) = \sum_{i=1}^{2} f_i(x)$$

All the results were obtained with an objective function that maximized the amount of remaining water in two reservoirs. We used actual water demand data in 2012 and water supply data from the government plan. All the calculations were performed with Lingo version 11.0 (Lindo Systems Inc., Chicago, IL, USA) (Beutelspacher and Neubert, 1993). It is comprehensive tool designed to make building and solving linear, nonlinear *etc.* and integer optimization models faster, easier and more efficient. The constraint for the optimization model is the data collection. Enough data can divide the water system into more region, which lead to the result would be more accuracy and meaningful.

2. Results and discussion

The basic model indicates that, when only the raw water resource is considered, the water system in Macau can sustain 7.95 days of normal water supply without additions of imported raw water (Table 4). The other models that were used to analyze and optimize the integration of the various water resources in emergency situations from the policies were derived from the basic model. The remaining water, indicated in Table 4, was in the SPVR; the water system stopped because neither the Colone WTP nor the Colone RWTP could supply water to the Macau Peninsula and Taipa

Table 3 – Models that can be applied for various scenarios.

	Raw water from the two Macau reservoirs	Government policies			Rainy season	Dry season	Imported raw water from Mainland China	Water supply salinity	
		Wastewater reuse	Rainwater collection	Water saving				500 mg/L	250 mg/L
Basic Model	√	–	–	–	–	–	–	–	–
Model A1	√	√	–	–	–	–	–	–	–
Model A2	√	–	√	–	–	–	–	–	–
Model A3	√	–	–	√	–	–	–	–	–
Model A4	√	√	√	–	–	–	–	–	–
Model A5	√	√	–	√	–	–	–	–	–
Model A6	√	–	√	√	–	–	–	–	–
Model A7	√	√	√	√	–	–	–	–	–
Model B_g	√	√	√	√	√	–	–	–	–
Model C_h	√	√	√	√	–	√	–	–	–
Model D_m	√	√	√	√	–	–	√	√	–
Model E_l	√	√	√	√	–	–	√	–	√

"√" represents "considered in the model"; "-" represents "not considered in the model".
"g" and "h" represent "3.4%, 5%, 10%, 15%, 20%, 25%, 30%, and 40% rainwater use rates".
"m" represents "the imported raw water salinity 600, 700, 800, 900, 1000, 2000, 4000, and 8000 mg/L".
"l" represents "the imported raw water salinity 350, 450, 550, 650, 750, 1500, 3000, and 6000 mg/L".

region. The amount of rainfall in model series A was taken as the average maximum value during rainfall days, while the upper limit of the water saving was 10% of the water demand.

For chemical spill emergencies, the individual effects of government policies on the water system were ranked in decreasing order as follows: wastewater reuse, rainwater collection, and water-saving policies. Specifically, compared with the basic model, the individual effects of the rainwater collection and water-saving policies were similar, and only extended the duration of water availably by about one day. However, two additional days were achieved when only the wastewater reuse policy was added. This means that, once the water system was optimized, the extra increase in the supply water that resulted from implementing the rainwater collection policy was equal to the extra decrease in the water demand when the water-saving policy was considered. The wastewater reuse policy increased the capacity of the water supply system and reduced the wastewater discharge. The increase in the supply of water from wastewater reuse appears to be greater than that for the rainwater collection policy. In addition, the wastewater reuse policy can be applied to the additional water supply pipe network, which provides an opportunity to optimize the original conventional water network. For the cost, the government expenditure in model A1 was less than that in model A2 or A3. It could be the water saving subsidy from government is high than the cost of water reuse and rainwater collection. Therefore, the benefits for the water system from wastewater reuse are greater than the benefits from the other single-policy options.

Table 4 – Model results for chemical spill emergencies.

	Available days (day)	Remaining water (10^4 m^3)	Government expenditure (10^7 Macau dollars)
Basic model	7.95	6.18	1.10
Model A1	10.15	6.90	1.15
Model A2	9.12	1.18	1.18
Model A3	8.95	3.75	1.23
Model A4	11.82	6.12	1.27
Model A5	11.58	7.91	1.27
Model A6	10.15	0.76	1.33
Model A7	13.79	6.64	1.42

The results for pairwise combinations of policies were similar. The available days were almost the same in models A4 and A5, which shows that when raw water and reused water are considered in the water system, it makes little difference whether a policy of rainwater collection or water-saving is implemented. The available days for the combined policies of wastewater reuse and rainwater collection and rainwater collection and water-saving were 11.82 and 10.25, respectively. This indicates that the wastewater reuse policy was more effective than the water-saving policy. Comparison of the results of model A5 (wastewater reuse and water saving) and model A6 (rainwater collection and water saving) indicates that the wastewater reuse policy was more effective than the rainwater collection policy.

Table 4 also shows the relationships between the policies in the optimized water system. The difference (0.17 days) between models A2and A3 indicates the distinction between the rainwater collection policy and the water-saving policy. However, when the wastewater reuse policy is integrated into those two models, the difference between models A4 and A5 was 0.24 days, representing a slight extension of the available days. By including this policy, the difference between those two models increased by 0.07 days. Similarly, when the rainwater collection policy was introduced into models A1 and A3, the difference increased by 0.37 days. Further, when the water-saving policy was introduced into models A1 and A2, the difference increased by 0.30 days. Therefore, the introduction of the rainwater collection policy had a significant effect on the models that only considered the wastewater reuse and water-saving policies, but there was little effect from introducing the wastewater reuse policy into the models that only considered the rainwater collection and water-saving policies. The key to the different responses is the additional quantity of water resources. In models A1 and A3, the extra water resources from rainwater collection increased the added raw water resource for wastewater reuse. This effect, however, was not optimized for the water system. In contrast, no extra water resource was made available in models A2 and A3 when the wastewater policy was introduced, and there was little overall change.

Furthermore, when all the government policies were included in the model, the days water is available was extended to 13.65 days. The available days cannot be obtained by simple addition of the number of days for either the combined policy or the integrated policy. Compared with the basic model, the sum (4.37 days) of the differences in the available days for models A1, A2 and A3 was not equal to the difference between model A7 and basic model (5.84 days), which indicates the effect of optimization on integrated water resources in the water system. The differences between the individual results for models A4, A5, and A6 and those of model A7 were 1.97, 2.21 and 3.54 days, respectively. This indicates that the wastewater reuse policy was the most effective because the difference was greatest between models A6 and A7.

There is uncertainty associated with the rainwater use rate, as it may increase or decrease, depending on the water users. When the total technical rainwater use rate increased from 3.4% to 40%, the available days increased from 12.40 to 19.54 in the rainy season, and from 11.64 to 12.77 days in the dry season (Fig. 3). The line on behalf of the rainy season was almost linear, which means the increase of technical rainwater use rate nearly directly reflect on the available days with a stable increase value. It indicates that the rainwater resource did not perform well in the integrated water system. As the amount of rainwater collection increases, the water system can optimize the water resources in two ways: the WTP can use the rainwater collected from the storage reservoirs as additional raw water. For the whole supply water system, however, this quantity is too small, especially when the rainwater use rate is low. Second, the rainwater can be used as additional raw water in the RWTP when the rainwater is converted to wastewater after first satisfying the water demand. However, the RWTP capacity would reach its upper limit at a certain value of the rainwater use rate. The line for the dry season was relatively stable keeping a low value of available days no matter the increase of technical rainwater use rate because of the low rainfall during this season; thus, rainwater collection could not make an appreciable contribution to the water system.

As shown in Fig. 4, it is worthwhile to increase the rainwater rate because this considerably increases in the days that water is available during the rainy season. However, notably, the dry season coincides with the salt tide period. The main consideration for water users may be cost, which increases as the rainwater use rate increased. We examined the relationship between the actual rainwater use ratio and the technical rainwater use rate (Fig. 4). The technical rainwater use rate means the upper limit of rainwater use rate from water users. It is not less than the actual rainwater use rate equalling to the product of technical rainwater use rate and actual rainwater use ratio. In the optimized water system, the actual use ratio was 100% and the technical use rate increased in the dry season. In the rainy season, the curve dropped dramatically when the technical rainwater use rate was 10%, and reached a minimum when the actual use ratio was 82.14% and the technical use rate was 40%. To maximize cost-effectiveness, the government should enhance the technical rainwater use rate from 3.4% to 10%; the water supply could be extended by 0.26 and 1.20 days in the dry and rainy seasons, respectively. The rainwater collection policy should be revised because the policy has great potential to extend the available days.

For the salt tide scenario, with the same salinity difference, the larger difference between the water supply salinity and the raw water salinity in the reservoirs was determined by a larger total amount of raw water. More analyses are needed with different models to determine the effect of adding neutralized raw water to the water system. The results show that, relative to the salinity of additional raw water, the effect of a water supply with a salinity of 500 mg/L was better than that of a water supply with a salinity of 250 mg/L (Fig. 5). The curves showed the same decreasing trend and (1) maintained a high value of available days (58.65 days for model D600 and 38.88 days for model E350); (2) the available days dropped sharply when the salinity difference increased to 200 mg/L comparing the respective water supply salinity; and (3) converged steadily after the point at which the salinity of the additional raw water was 2000 mg/L. The amount of available days was always higher when the water supply salinity was 500 mg/L than when the water supply salinity was 250 mg/L. The government can consider the figure as a reference when they decide the salinity of the water supply in different salt tide situations. The results were controlled by the total amount of raw water, which was calculated by the neutralization function. The results for the additional raw water with salinities exceeding 3000 mg/L can be ignored because of the convergence of the curves.

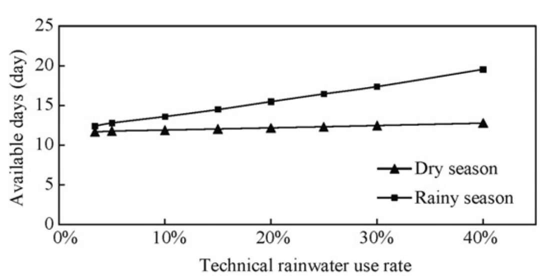

Fig. 3 – Modeling results for different technical rainwater use rates.

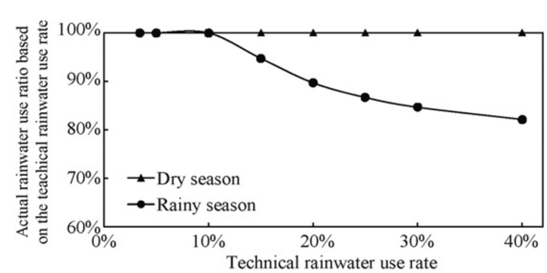

Fig. 4 – Modeling results of technical rainwater use rate *versus* actual rainwater use ratio.

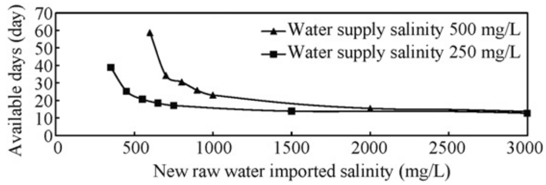

Fig. 5 – Model results for additional raw imported water with various degrees of salinity in the salt tide scenario.

The instability of the available days for the higher water supply salinity, which depends on the relationship between the two curves, is shown in Fig. 5. For each salinity difference of 100 mg/L in the two sources of raw water shown on the curves, the difference in the available days in the upper curve was always greater than the one in the lower curve. For example, there was a large difference in the available days (24.36 days) between models D600 and D700, while there was a small difference (13.60 days) between models E350 and E450. The number of available days remains the similar situation when the salinity of the additional raw water increases, as long as it remains below 2000 mg/L. In addition, when considering the same salinity and increases in the salinity of the imported raw water in two curves, we can obtain the same result. The number of available days therefore is unstable when the government uses a water supply with high salinity.

The results demonstrate the influence of different water resource scenarios and, so, can be used as a basis for revising related policy. Our study is significant because few studies have examined or considered emergency situations in integrated water systems. The modeling approach used here can also be applied to other emergency situations, such as burst pipes and sudden shutdowns of water plants.

3. Conclusions

In this study, we used a number of different models derived from a basic model that only considered the raw water supply from the MSR and the SPVR without any provision for additional raw water. Four series of models that integrated alternative water resources were used to optimize the urban water system for two types of emergency situations. The main findings from the model results are as follows: 1) Without additional raw water, and relying only on the two Macau reservoirs, the water supply can only last for 7.95 days. 2) When all the government policies are included in the model, the water supply can be extended to its theoretical maximum of 13.79 days. Out of the three policies, the wastewater reuse policy was the most beneficial for increasing the water resources in the Macau water system. 3) Even though the rainwater use rate was not completely effective in the dry season, the government still needs to revise the rainwater collection policy based on the increase in the rainwater use rate. 4) The number of days for which water is available can be extended by allowing an increase in the salinity of the water supply, although high salinity is inconvenient for water users and the number of available days is unstable. However, the available days during the salt tide period are always greater than the available days during chemical spills. Considering a wide range of factors indicated that a salinity of 250 mg/L would be suitable for the water supply.

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