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EMERGENCY CONTROL SCHEME FOR UPSTREAM POOLS OF LONG-DISTANCE CANALS†

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ABSTRACT

An emergency control scheme is proposed for pools upstream of a canal experiencing flow obstruction incidents. In order to achieve a prompt and efficient transition process, operation strategies are set out. It is suggested to switch from a constant downstream depth operation method to a constant volume operation method under qualified conditions. Based on a balanced pool operation equation and a transitional time estimation equation, a two-step gate operation method is designed, which is compatible with the operation method of constant downstream depth and the mixed pool operation method of constant downstream depth and constant volume. The emergency control scheme is tested by simulations on the 561 km long Middle Route Project (MPR) of the South-to-North Water Diversion Project in China consisting of 30 pools. The constant downstream depth and mixed pool operation methods are examined. Results indicate that the control scheme operates well under the emergency situation of a flow obstruction incident. Canal flow moves promptly and effectively to the new steady state by switching to the constant volume method. Back and forth volume variation is avoided and a significant improvement is obtained in terms of transition time, while the times of check gate operation remain roughly the same. © 2018 John Wiley & Sons, Ltd.

KEY WORDS: canal system; emergency operation; constant downstream depth; constant volume; South-to-North Water Diversion Project; two-step check gate operation method

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RÉSUMÉ

Un plan de contrôle d'urgence est proposé pour les bassins en amont d'un canal victime d'obstruction d'écoulement. Afin de réaliser un processus de transition rapide et efficace, des stratégies d'opération sont définies. Une méthode de fonctionnement à profondeur constante en aval est suggérée pour passer à une méthode de fonctionnement à volume constant dans des conditions qualifiées. Basé sur une équation d'opération de réservoir à l'équilibre et une équation d'estimation du temps transitoire, une méthode d'opération de vanne en deux étapes est conçue, compatible avec la méthode de fonctionnement à profondeur aval constante et la méthode de réservoir mixte de profondeur et de volume constants à l'aval. Le système de contrôle d'urgence est testé par des simulations sur le projet de route moyenne (MPR) de 561 km de long du projet de dérivation d'eau Sud-Nord en Chine comprenant 30 réservoirs. Les méthodes de profondeur en aval constante et de fonctionnement à réservoir mixte sont examinées. Les résultats indiquent que le système de contrôle fonctionne bien dans la situation d'urgence d'un incident d'obstruction d'écoulement. L'écoulement au sein du canal passe rapidement et efficacement au nouvel état stable en passant à la méthode du volume constant. La variation de volume en va-et-vient est évitée et une amélioration significative est obtenue en termes de temps de transition alors que les temps de fonctionnement de la vanne de contrôle restent sensiblement les mêmes. © 2018 John Wiley & Sons, Ltd.

MOTS CLÉS: système de canal; opération d'urgence; profondeur en aval constante; volume constant; Projet de dérivation de l'eau du Sud vers le Nord; méthode d'opération de vanne de contrôle en deux étapes

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† Dispositif de commande d'urgence pour des piscines en amont de canal longue distance.

INTRODUCTION

With water being unevenly distributed and becoming increasingly scarce, many long-distance water delivery canal projects have been constructed around the world, such as the Central Arizona Project (CAP) and the California Aqueduct in the USA, the Narmada project in India, the Middle Route Project (MRP) of the South-to-North Water Diversion Project in China, etc. Long-distance canal systems are composed of cascade pools divided by regulating structures (usually check gates). Control is characterized by long time delays, strong couplings and nonlinear characteristics (Wahlin and Zimbelman, 2014). In past decades, canal automation techniques have been introduced to improve canal operations and numerous canal control methods have been developed. These techniques and methods were mainly designed for normal operational situations.

Emergency incidents such as physical destruction, flow obstructions, water pollution, etc. occur infrequently. If these incidents are not dealt with in a timely and proper manner, overtopping and additional severe incidents might occur. For emergency control, operating objectives and constraints are quite different from those of normal operating conditions. Water levels are temporarily permitted to encroach into the freeboard, and normal drawdown criteria are relaxed when facing the potential of more severe consequences. In addition, the utilization of waste-ways for protecting the canal system is permitted. Obviously, emergency control is much more challenging compared with normal control, especially for long-distance canal systems featuring coupled, delayed and nonlinear dynamics.

However, few studies have dealt with emergency control methods of canal systems. CAP (Springer and Graves, 1979), Narmada (Narmada Water Resources Water Supply and Kalpsar Department, Government of Gujarat, 2009) and MRP (Construction and Administration Bureau of South-to-North Water Diversion Middle Route Project (CABSNWDMRP), 2014) developed emergency operation plans and standard operating procedures for emergency operation, combining field experience with hydraulic simulation. CAP (Wahlin and Clemmens, 2016) and the Central Arizona Irrigation and Drainage District (Clemmens *et al.,* 2016) introduced a HEC-RAS based SCADA training tool to help train operators in a wide range of emergency situations. The MRP authority has sponsored numerous studies on water pollution incident control by means of water quality simulations and field testing (Tang *et al.,* 2016; Xu *et al.*, 2017). Nevertheless, many existing emergency control schemes are limited to general strategies and rough check gate operational rules. Control performance largely depends on the operator's personal experience and proficiency. Although hydraulic simulation is often utilized to aid decision-making, few canal automation methods are incorporated in control schemes. Pool operation methods, which determine a canal's recovery characteristics, are seldom discussed and improved in the emergency control study.

This paper describes an emergency control scheme study conducted for a canal impacted by flow obstruction incidents by means of hydraulic simulation and canal automation theory analysis. The research area is concentrated on pools upstream of the incident site. Emphasis is placed on assessing the feasibility of switching from a traditional constant downstream depth operation method to a constant volume operation method. Check gate control methods are developed to fulfil the pool operation methods.

The paper is organized as follows. First, emergency operation strategies for pools upstream of the incident site are elaborated and discussed. Second, response and recovery properties of the two pool operation methods are analysed. Qualified conditions of the switch between them are determined. Then, a compatible two-step gate operation method is designed for routing check gate flows. Lastly, the emergency control scheme, which contains a switchable pool operation method and a compatible gate operation method, is tested on MRP cases by numerical simulations.

EMERGENCY OPERATION STRATEGIES

For pools upstream of the incident site, the primary goal of the emergency operation scheme is to ensure the safety of the canal system. Furthermore, the negative impact on the operation of the canal should be reduced to a minimum. To meet such goals, a timely, efficient and effective emergency control scheme is essential. The following primary strategies should be adopted:

- hold the excess water in the upstream pools and bring the situation under control as early as possible. With the sudden shutdown of an incident pool, both flow rate balance and volume balance of upstream pools are impaired. Excess water causes rising water levels, the risk of overtopping, and water loss. It also leads to extra recovery and response time. Thus, all inflows of upstream pools should be controlled as early as possible;
- keep the continuous offtake delivery uninterrupted. Serving water users via offtakes is the basic mission of canal operation. During the whole transition process from the occurrence of the incident to the formation of the new steady-flow state, surplus discharge and volume are available in all upstream pools. The surplus discharge and volume are capable of supporting the continuous offtake water supply. In the meantime, the offtake water supply also helps to

relieve the pressure from the surplus water. In some cases, offtakes can also be temporarily used as a measure to remove excess water from the canal;
- make full use of in-channel storage and minimize water spills. Spills are highly undesirable in most canals due to water availability, cost or environmental concerns. Long-distance canals usually have a certain amount of inline or offline regulation capacity. In addition, extra storage can be acquired by permitting encroachment into the freeboard for a short time during emergencies. Therefore, the storage capacity of canal pools should be assessed and fully utilized when making an emergency control plan;
- avoid back and forth pool volume variation and speed up the transition process. During the transition process, discharge varies greatly from the initial value to zero (or a much-reduced value) and finally back to the initial value. For pools adopting a conventional constant downstream depth operation method, passive and back and forth volume variation comes with the variation of flow rate, which causes poor response and recovery characteristics along with additional operating costs. Operating procedures can be substantially improved by switching to a more efficient operation method (for example, constant volume) when possible.

POOL OPERATION METHODS FOR EMERGENCY CONTROL

The pool operation method determines how the water level varies in a canal pool and the recovery characteristics of a canal. Here, two commonly used pool operation methods are examined for emergency operation.

Single operation method of constant downstream depth

Constant downstream depth is the conventional operation method and is used in most canals (Buyalski *et al.,* 1991). The water level at the downstream end of a canal pool is kept constant, acting as a pivot point as the water level profile rotates about this point (Figure 1). The main advantage is that water can be delivered at maximum capacity. However, to keep the downstream depth constant, inflow must be changed by a greater amount than outflow until the new steady-state profile is achieved. Therefore, excessive time is required to either build up or deplete the storage when changing the steady-state rate of flow. This is known as volume compensation (Bautista and Clemmens, 2005).

For cascade pools applying this operation method (Figure 2), the time delay accumulates with an increase in the number of pools. In order to improve the response

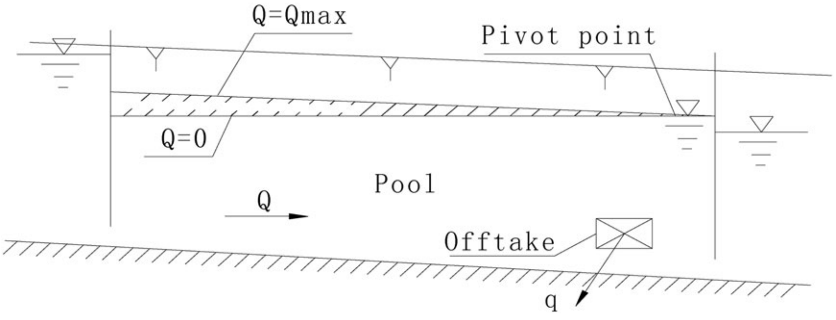

Figure 1. Constant downstream depth operation method.

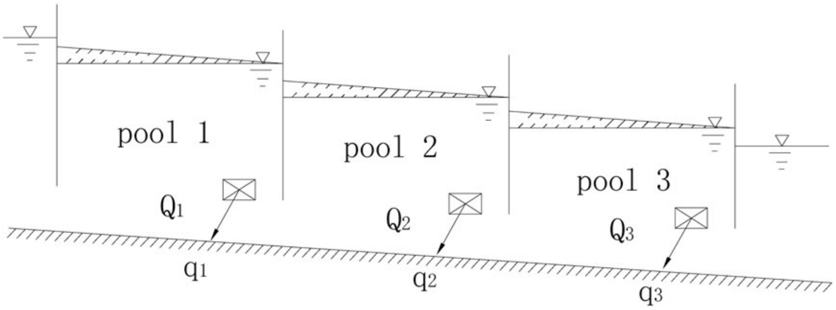

Figure 2. Cascade pools adopting constant downstream depth operation method.

characteristics of the canal, pool storage needs to be changed a certain period beforehand. Obviously, constant downstream depth is not an ideal method for emergency operation.

Mixed operation method of constant downstream depth with constant volume

The constant volume operation method is based on maintaining a relatively constant water volume in each canal pool. The water surface profile will rotate around a pivot point near mid-pool as the flow varies, as shown in Figure 3 (in fact the pivoted water surface often does not match the water surface profile) (Guan *et al.,* 2011). For any given flow change, the volumetric change in each of these wedges is equal and opposite. Thus the total volume of water in the canal system does not change significantly, and the flow condition in the entire canal system can change quickly. Nevertheless, this method is not always applicable for pools designed based on the constant downstream depth method because additional canal banks and lining are required at the downstream end of the pool.

Under certain circumstances, however, extra space is available, and the pool has the ability to switch between the two methods. For example, during the short duration of emergency operations, temporary freeboard encroachment is acceptable, as long as water level does not exceed the lining top. Additionally, for a newly constructed canal, target depth (set-point) at the downstream end of the pool is usually set below the design value, and extra space is available to cope with emergency situations. Some canals, like MRP, are designed with additional freeboard to accommodate enlarged flow. The CAP Canal was designed with extra depth downstream to accommodate rapid shutdown of the canal. The water level was allowed to exceed the lining height during emergency shutdown (WEST, 2014). For pools with different conditions, mixed operation methods will be applied (Figure 4).

The flow range permitted for switching methods should be identified before executing the gate operation order. Based on the characteristics of the constant volume method, the minimum margin of safety exists at the downstream end of a pool. This margin reduces with the reduction of flow rate. Therefore, the switch is permitted only for flow rates higher than a set value, which can be expressed as a range of permissible flow rates ($Q_{\min}$, $Q_{\max}$). $Q_{\max}$ is the design flow rate, Q_{design}. While $Q_{\min}$, which corresponds to the most unfavourable conditions of the switch, could be derived with relations depicted in Figure 5. In accordance with strategy 4 from the previous section, the volume under constant volume operation (expressed as V_{constant} in Figure 5) is kept equal to that

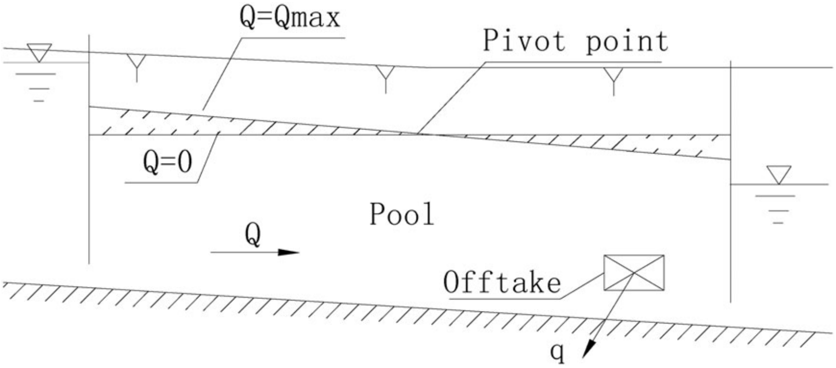

Figure 3. Constant volume operation method.

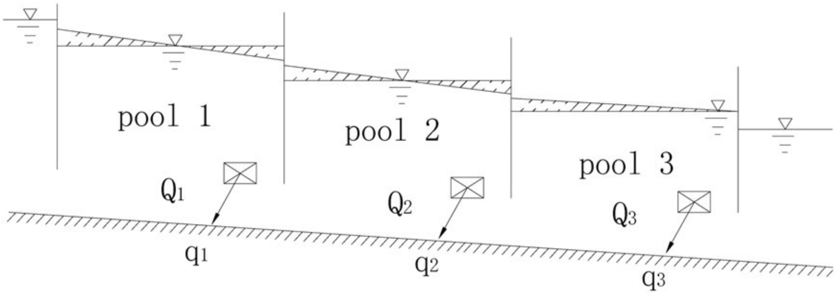

Figure 4. Cascade pools using mixed operation method (the first two use constant downstream depth method and the last one use constant volume method).

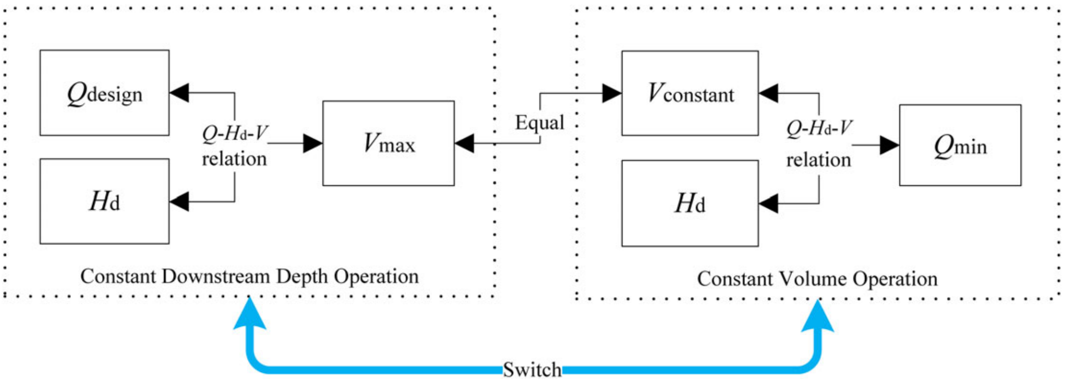

Figure 5. Switch relationship for the most unfavorable conditions. [Colour figure can be viewed at wileyonlinelibrary.com]

under constant downstream depth operation. Because the volume varies with flow rate, the maximum volume (expressed as $V_{\max}$ in Figure 5), which corresponds to the most unfavourable condition, is set equal to V_{constant}. Now that V_{constant} and H_{d} (water depth at the downstream end of the pool decided by freeboard) are given, $Q_{\min}$ can be determined with the 'Q–Hd–V' relation of steady-state flow (Henderson, 1966). In this way, the permitted range of ($Q_{\min}$, $Q_{\max}$) for a pool is determined to switch from constant downstream depth to constant volume operation.

TWO-STEP GATE OPERATION METHOD FOR EMERGENCY CONTROL

Based on the strategies and pool operation methods put forward above, a two-step gate operation method is designed that routes flows through gates in order to implement the pool operation methods. The gate operation method is designed to be compatible with the single constant downstream depth method and the mixed method. The desired flow routing is determined from the balanced pool operation equation (Equation (1)) and the transitional time estimation equation (Equation (2)).

Balanced pool operation equation

When the total outflow equals the total flow into the pool, the pool operation is balanced and Equation (1) exists:

$$QG_i = q_i + QG_{i+1} \tag{1}$$

where i = pool number; QG_i = pool inflow; q_i = offtake deliveries from the pool; QG_{i+1} = pool outflow at the downstream end.

Transitional time estimation equation

The time required to form a new steady-state flow can be estimated as

$$T_s = \frac{\Delta V}{\Delta Q} \tag{2}$$

where T_s = time to form the new steady-state flow; ΔV = storage volume variation before and after the steady state; ΔQ = change in flow.

Two-step gate operation routing

A canal consisting of three cascade pools is used to illustrate the routing process. In Figure 6 (a), the canal uses the single operation method of constant downstream depth in all pools. In Figure 6 (b), the canal uses the mixed operation method. Here, the first two pools apply the constant volume method, and pool 3 applies the constant downstream depth method. In both figures, ΔV is volume variation, QG is inflow discharge and q is offtake discharge.

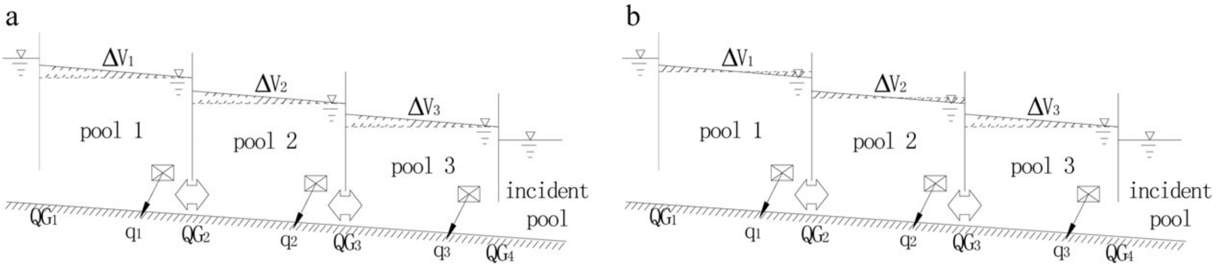

Figure 6. Pools upstream of an incident pool with single operation method (left) and mixed operation method (right).

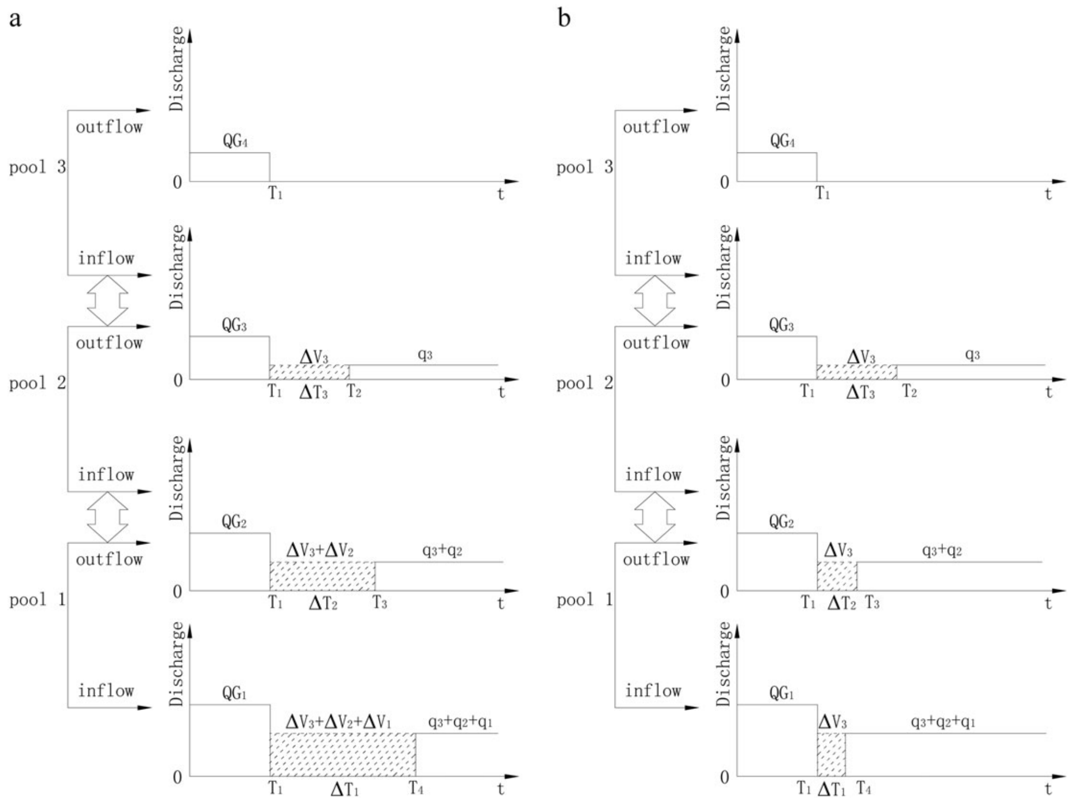

Figure 7. Checkgate flow routing for single operation method (left) and mixed operation method (right).

The two-step gate operation method can be addressed with the following procedures (illustrated in Figure 7 referring to Figure 6):

1) Execute the first step of gate operation. Close all the check gates simultaneously at the first moment an incident happens (i. e.T_1 in Figure 7). If the water level exceeds the freeboard, open a nearby waste-way gate immediately until the water level recedes;
2) Calculate the flow rate for the second step of gate operation (i. e. QG_i in Figure 7). QG_{N+1} is set to 0 for the shut-off of the tail gate. Apply Equation (1) to pools from i to N. QG_i is derived as

$$QG_i = \sum_i^N q_i \quad i = 1 \text{ to } N \tag{3}$$

3) Calculate the volume regulation for the second step of the gate operation (i. e. ΔV_i in Figure 7. Estimate the volume variation for a single pool itself (ΔV_{i0}) with Equation (3). For pools using the constant volume depth method, $\Delta V_{i0} = 0$. For pools using the constant downstream depth method, ΔV_{i0} is the storage wedge shown in Figure 1, which is the function of flow rate (Q) and downstream water depth (H_d). It can be obtained with the steady flow functions (Equation (4)). Then, taking the volume transferred to each downstream pool into account, volume regulation (ΔV_i) for pool i is derived with Equation (5):

$$\Delta V_{i0} = \begin{cases} 0, & \text{for constant volume operation} \\ f(Q_i, H_{di}), & \text{for constant downstream depth operation} \end{cases} \tag{4}$$

$$\Delta V_\mathrm{i} = \sum_i^N \Delta V_{i0} \quad i = 1 \text{ to } N \tag{5}$$

4) Determine the time for the second step of gate operation (i.e. time T_i in Figure 7, i = 2 to 4). First, calculate the volume regulation duration for pool i (i. e. ΔT_i) with Equation (6). Then add ΔT_i to T_1 to get T_i, as shown in Equation (7):

$$\Delta T_i = \sum_i^N \Delta V_i / \sum_i^N q_i \quad i = 1 \text{ to } N \tag{6}$$

$$T_i = T_1 + \Delta T_i \tag{7}$$

5 Execute the second step of gate operation. Convert QG_i to the appropriate gate opening determined from the check gate flow equation, and implement the gate opening regulation.

SIMULATION TESTS

Test canal

MRP is the largest water diversion project in China. It delivers water from the Danjiangkou Reservoir in South China to North China. A flow obstruction incident occurs in pool 31 of MRP (Figure 8). The upstream pools are 591 km long in total, and design flow rate is 350 $m^3\ s^{-1}$ at the upstream end and 260 $m^3\ s^{-1}$ at the downstream end. The test canal includes 31 check structures, 31 offtakes. There is no online reservoir. The bed slope is 0.00004. The Manning coefficient is 0.015. The canal is operated under the constant downstream depth method. Pools 1–24 have a freeboard of 1.4 m, and pools 25–30 have a freeboard of 1.2 m.

Identification of pools switchable to constant volume operation

Applying the two-step gate operation method for emergency control, the most unfavourable conditions, $Q_{\min}$, for adopting constant volume operation are identified from a steady-state flow program. Corresponding freeboard margins are derived (surplus freeboard margin = alert water level − design flow water level) and presented in Figure 9. Pools from 1 to 24 have a continuous surplus of freeboard margin. Consequently they are set to switch to constant volume operation during the emergency transition process.

Simulation method

The Saint-Venant equations are used to describe flow in the canals. Preissmann's implicit method is used to solve the equations. Prototype observed data are used to calibrate Manning's roughness coefficient and the check gate discharge coefficients (Cui *et al.,* 2014).

The upstream boundary condition is the water level in the reservoir and the downstream boundary condition is the inflow rate of the incident pool. It is defined to decrease from an initial 100 $m^3\ s^{-1}$ to 0 $m^3\ s^{-1}$ in 5 min after the incident happens (Construction and Administration Bureau of South-to-North Water Diversion Middle Route Project (CABSNWDMRP), 2014).

The simulation time step is set at 5 min. The deadband of check gate movement is set at 5 cm, which means only adjustments over 5 cm are executed. The water level deadband for triggering feedback control is 0.20 m. Canal operation time of 24 h has been simulated.

Simulation results and analysis

Simulation results are shown in Figures 10 and 11, which correspond to the method of constant downstream depth

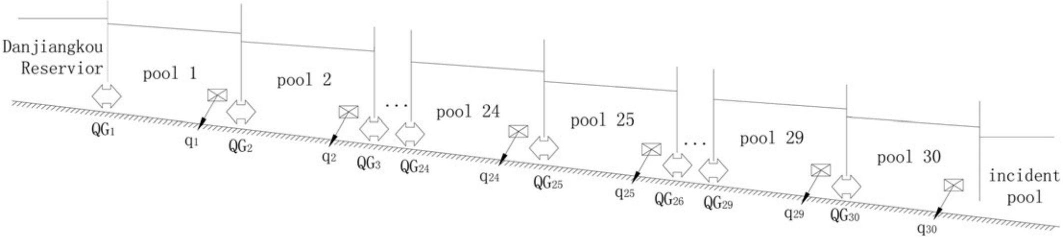

Figure 8. Schematic view of the test canal.

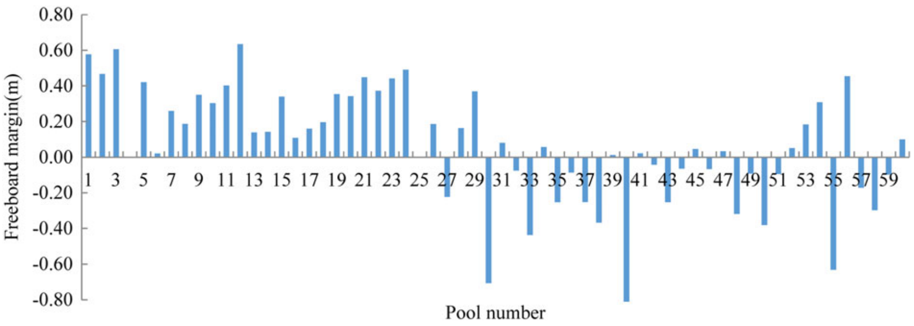

Figure 9. Surplus freeboard margin under constant volume operation with the most unfavorable condition. [Colour figure can be viewed at wileyonlinelibrary.com]

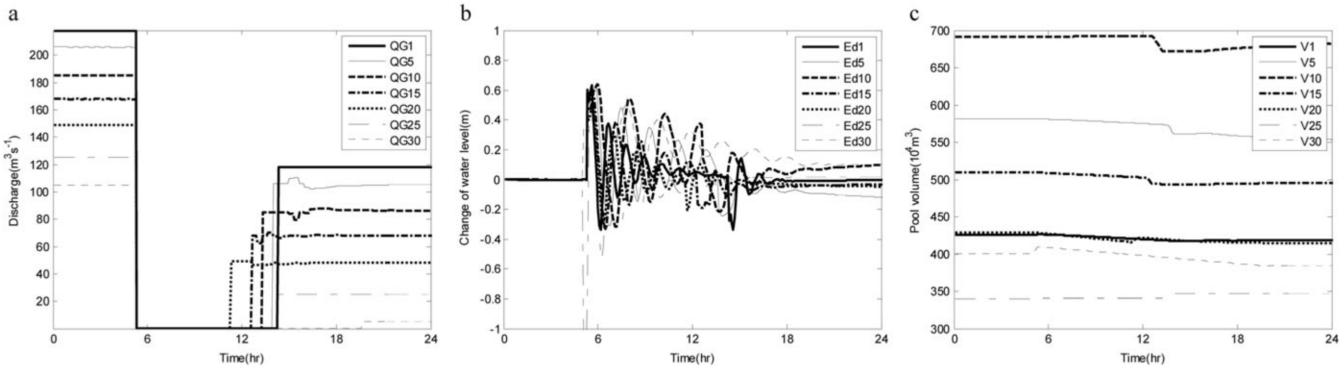

Figure 10. Simulation results for the test canal with single operation method.

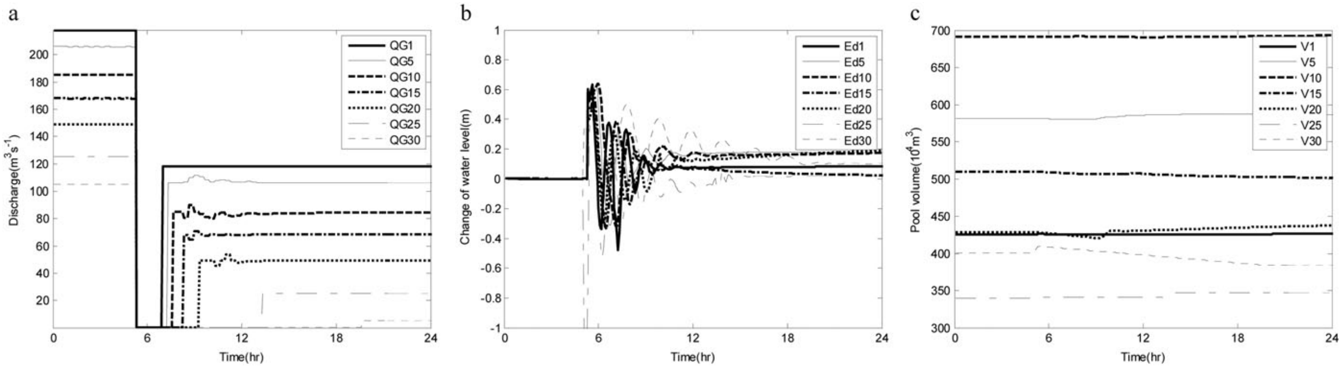

Figure 11. Simulation results for the test canal with mixed operation method.

and the mixed method of constant downstream depth and constant volume, respectively. For ease of visual interpretation, relevant curves are presented every five pools. The control performance indicators are shown in Table I.

Results show that both the single operation method and the mixed operation method fulfil the emergency control tasks. Canal flows transit promptly from initial steady-flow states to the new steady-flow states with water level errors inside the predefined deadband of ±0.20 m.

Pools 1–24 switch to constant volume operation during the transition process. Steady-state water levels increase about 0.20 m at the downstream end of pools. Maximum water level deviation is about 0.64 m, occurring when all check gates have just closed. Compared to the 1.4 m freeboard of these pools, sufficient safety margins are guaranteed under both the unsteady and steady states. Thereby, escape checks are not activated in either case.

Significant distinction exists between the two operation methods with respect to transition time. The mixed operation method takes approximately half the time of the single operation method. This reduction in time is the result of the constant volumes in pools 1–24 (Figure 11 (c)). Back and forth volume variation is almost eliminated. Thereby, it consumes little time during the transition period. No obvious difference in regulating times of check gates is observed between the two methods.

Table I. Performance indicators for the two methods

Pool operation method	Transient duration (h)	Check gate adjustment[a] (times)	Max water level steady-state error (m)	Max water level overshoot (m)	Escape checks initiation (times)
Single operation method	12	54	0.20	0.64	0
Mixed operation method	6	50	0.20	0.64	0

[a] Statistics based on Figures 10 and 11.

Optimized gate movement deadbands (China Institute of Water Resources and Hydropower Research (IWHR), 2016) are taken into account in both test cases. Results show that deadbands work well at preventing check gates from reacting frequently to minor requests (Figures 10 (a) and 11 (a)). However, deadbands induce constant water fluctuations (Figures 10 (b) and 11 (b)) and an error in steady-state water level and volume (Figures 10 (c) and 11 (c)).

In both cases, all upstream check gates are set to shut completely when responding to incidents downstream. The emergency control scheme also works when the gates are just partially closed, as long as inflows to the pools are less than the outflows and extra volume storage can be drained from the pools. Of course, the smaller the check gate opening, the shorter the transition time.

SUMMARY

Following the proposed operation strategies, an emergency control scheme for pools upstream of incident pools is presented. It is suggested to switch from the conventional operation method of constant downstream depth to a more efficient constant volume method under certain conditions. A two-step gate operation method is developed which can satisfy both the single and mixed pool operation methods. A case study of MRP demonstrates that the emergency control scheme can carry out the emergency operation task well. Canal flow transits promptly and effectively to the new steady state. By switching to the constant volume method, a significant improvement is made in terms of transition time, while the times of check gate operation remain roughly the same. The emergency control scheme makes full use of the canal's regulation capacities and reduces back and forth volume variation. It is especially meaningful for long-distance canals characterized by a large time delay.

ACKNOWLEDGEMENTS

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