Chapter

Emergency Operations of Sudden Water Pollution Accidents

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Abstract

Emergency operation technologies can help to make reasonable operation measures of hydraulic structures, which are important to control the scope of the effect arising from an event and reduce the harm caused thereby. The main canal of MRP is divided into three parts in case of sudden water pollution accidents: the accident pool, the upstream section of the accident pool, and the downstream section of the accident pool. For each part, the target and strategy for emergency operation technologies are discussed. With regard to an accident pool, multiple kinds of check gate closing methods, synchronous, asynchronous, identical speed, and different speed are put forward; for the upstream section, a new method of equal-volume operation is introduced; and for the downstream section, three emergency operation methods are proposed. The simulation result of case study shows that the methods raised in this chapter can be used to determine suitable emergency operation measures.

Keywords: emergency operation technologies, gate closing methods, equal-volume operation, accident pool, upstream section, downstream section

1. Introduction

When a sudden water pollution accident happens, control structures including check gate, pumping station, and dam can be utilized for emergency operation to reduce the harm caused thereby [1]. Regarding sudden water pollution accidents that are unforeseeable in the MRP, safety and stability are the ones of the key problems to which most attention are paid in an emergency regulation process. The main response characteristic parameters which reflect the safety and stability of a water transfer system are the response duration time from the transition of the steady water state to an emergency state of an open channel, as well as the change range and change speed of the water level in the channel during such response duration. The factors that affect these response characteristic parameters mainly include flow, check gate closing mode and time, and the use of drainage gate. Therefore, it is necessary to develop a complete set of operation rules to achieve safe and stable operation of a channel under emergency conditions. In addition, in order to make the operation process of the channel go with the aforesaid rules, emergency conditions often lead to great changes in the operating conditions of the channel. At present, the mainly conventional control algorithm of a channel is PI control algorithm. The control condition generally is a small change in water diversion and restores to the original water diversion process after lasting for a not very long period of time; or water diversion experiences a small change, but fails to restore to the original water diversion process [2]. In case of an emergency, the operating conditions of a channel pool undergo great changes.

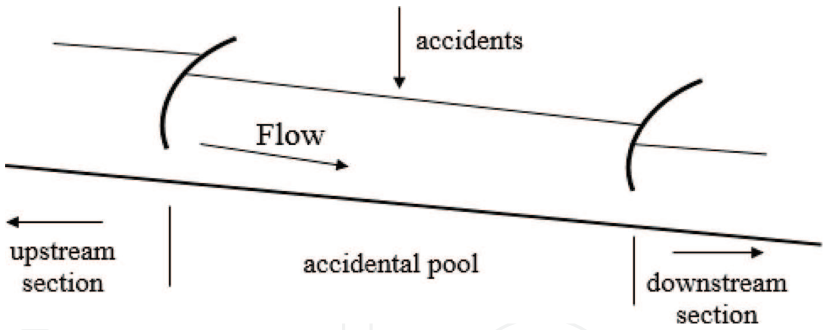

Figure 1.
Schematic diagram of subsections of main canal of MRP.

For this, the main characteristics of the channel, such as the lagged effect of the upstream of the channel on the downstream, as well as the cumulative impact of flow on the water level, will change [3]. At this time, it is difficult to achieve emergent adjustment by using a conventional automatic control system. Therefore, an automatic check gate control algorithm should be used for a change in an emergency to meet the fast smooth transition from a conventional process to an emergent process and then to a conventional process.

2. Target of emergency operations

In case of a sudden water pollution accident in the main canal in the MRP, channels are divided into three parts: accident pool, the upstream section of the accident pool, and the downstream section of the same, for which, joint emergency operations will be carried out (**Figure 1**).

2.1 Overall operation strategies

In case of an emergency, related operation strategies should be developed at the first time. All check gate operation rules should fulfill the strategies. The following control strategies are put forward by referring to the control strategy of some large water transfer project and the experience of water diversion:

2.1.1 Reduce excess flow and storage volume as soon as possible to control the development trend of an event

In the event of an emergency, cut off the accident section or reduce the flow of water that transfers downstream. If excess flow and storage volume occur in all channel pools at the same time, and if their reduction is not done as soon as possible, the channel pools will suffer overflow and water loss. Therefore, all upstream check gates of the accident section should have their flow reduced or even cut off. Not only should the “excess flow” be reversed but also the “excess storage volume” should be reduced.

2.1.2 Do not affect water supply at upstream turnouts as far as possible

Because the water volume in upstream pools tends to increase rather than decrease after an emergency, there is adequate water supply to the turnouts. Therefore, after the emergency, operation measures should not interfere with the water supply at upstream turnouts.

Use the regulation and storage capacity of channels and try not to waste and abandon water so as to reduce economic losses.

2.1.3 Maintain storage volume in channels when in normal water diversion

Maintain the volume of the canal pools as much as possible at the volume storage which the pools have in normal condition, so as to reduce the repeated adjustment of the storage volume and the operation and management costs.

A general water supply channel adopts a constant downstream depth mode. The response and the recovery characteristics of this mode lead to repeated adjustment of storage volume before and after channel pool flow switching, not only increasing the costs of operation and management but also taking a lot of time in storage volume regulation. Comparatively speaking, equal-volume operation has no defects. Therefore, equal-volume operation should be applied if a channel satisfies the condition for using an equal-volume operation mode.

2.1.4 Regulate the flow and storage volume in the channel so as to reduce the time of contingency transition state

Some research shows that the channel response and recovery time of synchronous gate operation is shorter than that of asynchronous gate operation, and synchronous operation should be preferred in emergency phase.

2.2 Gate operation rules

According to the channel pool where a water pollution event occurs and the control strategy thereof, a whole channel can be divided into accident pool, the upstream section of the accident pool, and the downstream section of the same. Use different operation rules for different control strategies.

2.2.1 Control rules for drainage gate

The first main purpose of using a drainage gate is for clipping peak and reducing the maximum backwater height of a check gate; the second is for regulating the upstream water level of the check gate during fluctuation of the water level in the channel so as to make them come near to the target water level. The use of drainage gate, however, also results in water waste. Therefore, the drainage gate is not opened generally. It is only opened when the water level endangers the safety of a project. A warning level indicator is used here to judge whether to adopt drainage gate, and it is used when the warning level is above the warning level.

Drainage gate control rules for an accident pool: when the upstream water level of drainage gate is higher than the warning level, the drainage gate is used; when the volume stored in the channel pool comes near to the target volume, the drainage gate should be closed rapidly. After the water surface of the accident pool becomes steady, then decide whether to reuse the drainage gate to abandon water, according to the level of the accident. If water body in the channel pool fails to realize self-purification or too long duration of self-purification which has an effect on downstream water supply, the drainage gate should be reused to discharge polluted water body into a temporary water pool or an abandoned lake by the channel section for treatment. Close the drainage gate and restore water supply after the channel pool is drained.

Drainage gate control rules for the upstream section of an accident pool: when the upstream water level of all upstream check gates is above the warning level, use the drainage gate; for a channel section without drainage gate, when the upstream water level is above the warning level, do not close the check gate temporarily for current calculation. The purpose is for clipping peak and reducing the maximum backwater height of a check gate; the second is for regulating the upstream water level of the check gate during fluctuation of the water level in the channel so as to make them come near to the target water level.

The drainage gate is not used for the downstream section of the accident pool, because the downstream section is where inflow water is smaller than outflow water. When a reasonable check gate operation process is used, the situation that the upstream water level is above the warning level will not happen basically. Moreover, the drainage gate will not be used in order to keep water supply at the downstream section as much as possible.

2.2.2 Control rules for turnout

Turnout control rules for an accident pool: the turnout closes rapidly as the check gate closes rapidly to reduce the impact of polluted water diversion.

The turnout at the upstream section of the accident pool does not involve emergency scheduling, keeping original normal scheduling opening, and ensuring normal water supply at the upstream section.

Turnout control rules for the downstream section of an accident pool: the flow of all turnouts at the downstream section is controlled according to the reduction ratio of the flow of the downstream check gate of the channel.

2.2.3 Control rules for check gate

Check gate control rules for an accident pool: the two check gates should be closed rapidly to prevent clean water of the upstream channel pool from entering the accident pool and to avoid polluted water body from flowing into the downstream channel pool.

Check gate control rules for the upstream section of an accident pool: a relevant operation plan should be developed according to a water level control target in order to ensure normal water supply at the upstream section.

Check gate control rules for the downstream section of an accident pool: the check gate should be closed gradually depending on a water level control target.

3. Emergency regulation algorithm

3.1 Accident pool

The objective of gate emergency operations in the accident pool (**Figure 2**) is to confine the pollutants within the accident pool, and then the polluted water can be

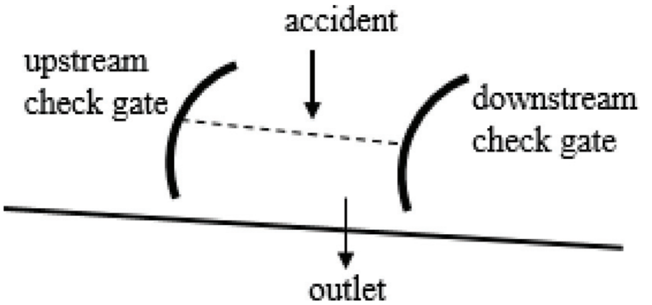

Figure 2.
A schematic of the accident pool.

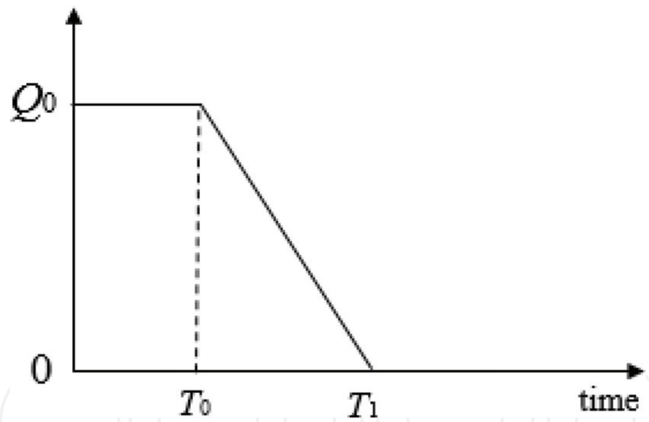

Figure 3.
The emergency operation of a gate.

Number	Mode	When the gate starts closing (T_0)	Closing time ($T_1 - T_0$)
1	Synchronous with the same speed	$T_{0up} = T_{0down}$	$(T_1 - T_0)_{up} = (T_1 - T_0)_{down}$
2	Asynchronous with the same speed	$T_{0up} \neq T_{0down}$	$(T_1 - T_0)_{up} = (T_1 - T_0)_{down}$
3	Synchronous with different speeds	$T_{0up} = T_{0down}$	$(T_1 - T_0)_{up} \neq (T_1 - T_0)_{down}$
4	Asynchronous with different speeds	$T_{0up} \neq T_{0down}$	$(T_1 - T_0)_{up} \neq (T_1 - T_0)_{down}$

Note: Up, upstream check gate; down, downstream check gate.

Table 1.
Closing modes of the two check gates and their features.

treated with other measures, for example, adsorption. In this situation, the discharge of the two gates in the initial and final state is known, but it remains unknown when the gate starts closing and how long it takes from the initial discharge to the final discharge (**Figure 3**). Therefore, there are four closing modes for the two check gates, as shown in **Table 1**.

3.2 Upstream section of accident pool

3.2.1 Adjustment of operation mode

3.2.1.1 Existing operation mode and its defects

Emergency Scheduling Plan for Sudden Events under Main Route of South to North Water Diversion Project (Q/NSBDZX G014-2014) points out that the regulation method of the upstream section of an accident pool should be performed according to the control principle of constant downstream depth; and that the opening of check gates should be adjusted real time depending on the actual water level.

Constant downstream depth operation is an operation mode to keep relative steady the downstream water depth of each channel section. When the flow in the channel section changes, the water surface profile will rotate around the pivot point at the downstream end of the channel section, as shown in **Figure 4**. Wedge volume between different steady flowing water surface profiles is formed therefrom. When

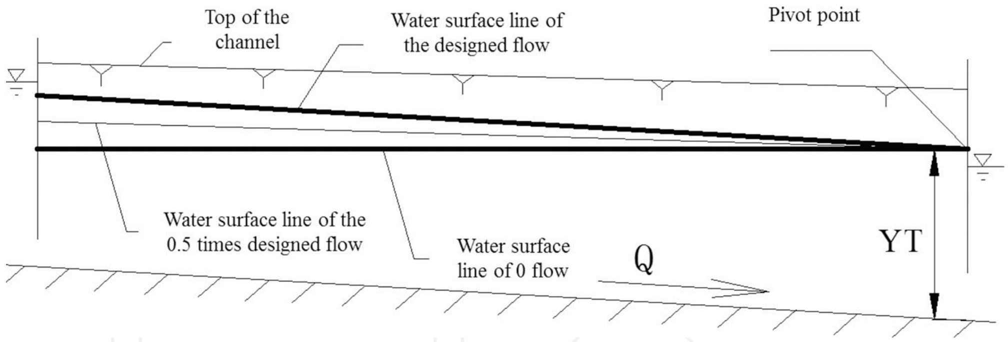

Figure 4.
Operation mode of constant downstream depth.

the flow increases, so do the water surface slope and wedge capacity volume; on the contrary, when it decreases, so do the water surface slope and wedge volume [4].

At present, constant downstream depth is set as the operation mode used for emergency regulation. This mode features high capacity of water transfer but poor response and recovery characteristics, so it needs to be improved further.

3.2.1.2 Feasibility analysis of using equal-volume operation mode under emergency regulation

On the basis of analysis of equal-volume operation mode features, this section demonstrates the feasibility of using equal-volume operation mode under emergency regulation in three steps: Step (1) determines the most unfavorable condition of equal-volume operation; Step (2) analyzes the free board margin; and Step (3) determines the flow interval suitable for equal-volume operation under the main route project.

3.2.1.2.1 Equal-volume operation mode and its features

Equal-volume control features "water retention capacity." When in equal-volume operation mode, the volume in a channel section keeps unchanged at any time. When flow transits from one steady state to another one, water surface rotates around the pivot point by the middle point of the channel section. Sometimes, the equal-volume operation mode is also referred to as "a synchronous operation mode," because this mode keeps a steady volume by synchronously controlling upstream and downstream check gates. The change of wedge volume in the channel section appears at both sides of the middle pivot point of the channel section, as shown in **Figure 5**. Providing a given flow change, the changes of wedge volume at

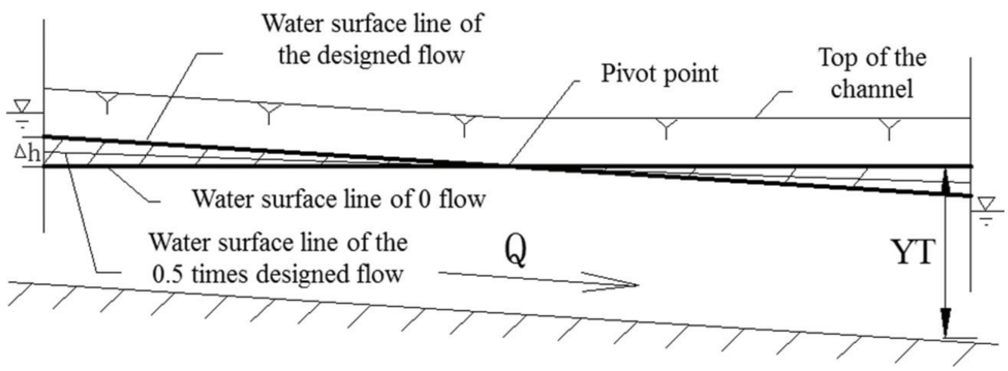

Figure 5.
Equal-volume operation mode.

the both sides of the pivot point equals and are different in direction. When the flow goes down, so does the upstream wedge volume, and the downstream wedge volume goes up; when the flow goes up, the upstream wedge volume goes up, and the downstream wedge volume goes down.

Advantages of equal-volume operation: the volume in the channel pool keeps unchanged during operating condition switching. Therefore, the equal-volume operation can change the state of water flow in the whole channel system rapidly. This is particularly suitable for operating conditions.

3.2.1.2.2 Judgment of the most unfavorable operating condition of equal-volume operation

When analyzing the feasibility of the equal-volume operation, identify and test the most unfavorable operating condition.

During normal water transfer in the MRP, constant downstream depth mode is used and changed to the equal-volume operation mode during an emergency. In order to ensure fast, smooth switching, water makeup from adjacent channel sections, or to ensure water discharge should not be performed before such switching. For this, the volume in a channel during equal-volume operation should be equal to that of constant downstream depth operation.

In the constant downstream depth mode, the water volume stored in the channel changes with the flow: the greater the flow is, the volume is more and the operation safety margin of the corresponding channel is smaller. Similarly, the safety margin at the time when this operating condition is switched to equal-volume operation is the smallest. Therefore, when equal-volume operation is under test, the volume should be the one with the design flow of constant downstream depth.

If volume is the same, the water surface profile of equal-volume operation is not unique, but rotates with flow change, among which the most unfavorable situation is the horizontal water surface profile corresponding to zero flow. This is because that the water surface profile at the downstream position of the channel section (i.e., the upstream water surface profile of downstream check gate) comes nearest to the top of a dike. For this reason, the test flow for equal-volume operation mode is zero.

Based on the above analyses, the most unfavorable operating condition of the equal-volume operation is that the flow is zero, with a volume equal to the one under the design flow of constant downstream depth. Because of subcritical flow in the open water conveyance canal, the average of the water surface profile is a backwater-type water surface profile. The corresponding upstream water level of check gate can be based on the corresponding relation among channel section flow, upstream water level of check gate, and volume and is determined by using a trial method.

3.2.1.2.3 Calculation of engineering safety margin for equal-volume operation

Under the most unfavorable operating condition of equal-volume operation, the rising maximum of the water level in all channel pools occurs upstream of check gate. First, by using a constant uniform flow program for calculating water surface profile, and via section integral, the volume V_0 is obtained according to the upstream water depth H_d of check gate corresponding to the design flow and the constant downstream depth of all channel pools. Second, take the volume in a channel pool, V_0 as a target and zero flow as a known condition, set different upstream water depths of check gate, and perform trial calculation by using a dichotomy until the respective H_{d1} is determined, that is, the upstream water depth

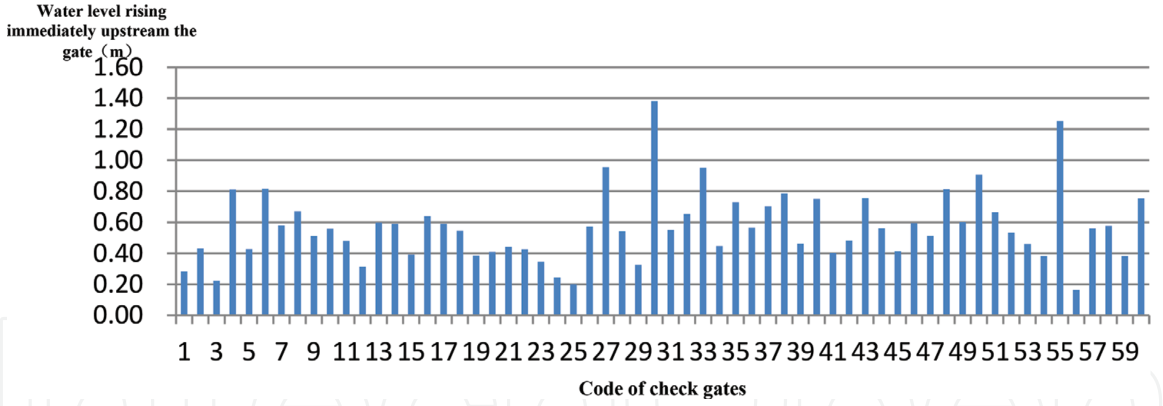

Figure 6.
Rising value of upstream water depth of check gate under equal-volume operation compared with constant downstream depth (the most unfavorable operating condition).

of check gate in each channel pool of the middle route under the most unfavorable operating condition of equal-volume operation. Calculate the water level rising value (**Figure 6**) and engineering safety margin under the most unfavorable operating condition of equal-volume operation (**Figure 7**).

From these figures, we can see that the first 25 channel pools have sufficient margin to implement equal-volume operation, while more channel pools at the right section have no sufficient margin.

3.2.2 Emergency regulation algorithm

Emergency regulation algorithm module can be divided into a feedforward control module and a feedback control module as a whole, as shown in **Figure 8**.

The feedforward control module is based on the water diversion quantity and volume of a channel before and after a channel accident; determine the operation plan for upstream check gates from the channel head to the accident section in combination of the plan for water diversion at dividing gate, in a bid to ensure safe, smooth transition between normal operation and emergency operation, reduce water abandoned by drainage gate as soon as possible, and cut the operation cost. The main decision-making basis for feedforward control module is overall water amount balance relation of a channel, without detailed calculation of factors such as

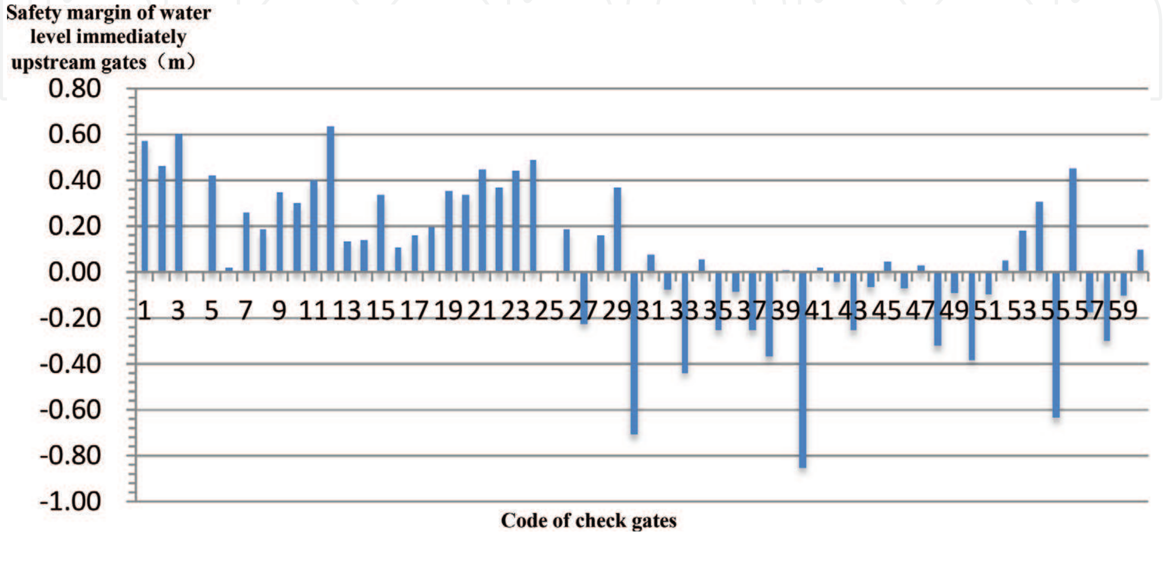

Figure 7.
Safety margin of upstream water depth of check gate under equal-volume operation (the most unfavorable operating condition).

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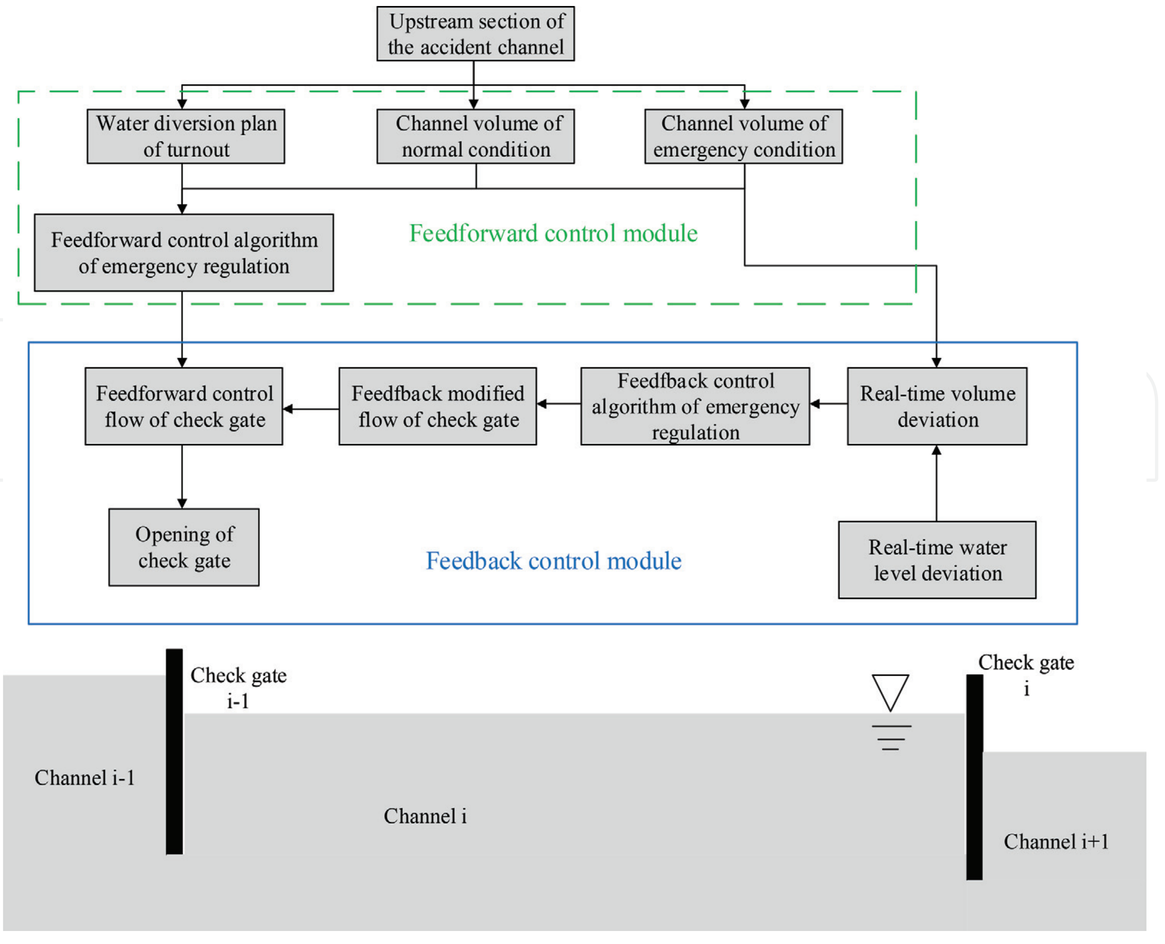

Figure 8.
Construction of emergency integrated control module at upstream of accident section of the middle route project.

check gate mechanical dead band, channel hydraulic model, sensor measuring error, etc. The purpose is "rough regulation."

The purpose of the feedback control module is to eliminate the water level control deviation arising from various types of perturb factors during a whole transition. By using a water level sensor, the module performs real-time measurement of the deviation in the upstream water level of check gate and converts it to a volume deviation; after that, it realizes the correction of feedforward control flow of check gate by changing the flow of water entering the channel, maintaining a target water level within a preset reasonable range.

3.2.2.1 Feedforward control

The channel adopts conventional constant downstream depth operation mode, constant downstream depth, and equal-volume operation mode. The emergency integrated feedforward control module differs, so do the respective tradition process and control effect. This research carried out calculation, analysis, and comparison depending on different operation modes of the middle route project.

3.2.2.1.1 Constant downstream depth

For easy explanation, assume that there is a generalized canal with three channel pools in series as shown in **Figure 9**, and that the accident section lies at the most downstream. In the figure, DV1–DV3 stand for the decrease of the volume in each channel pool before and after emergency control (i.e., normal

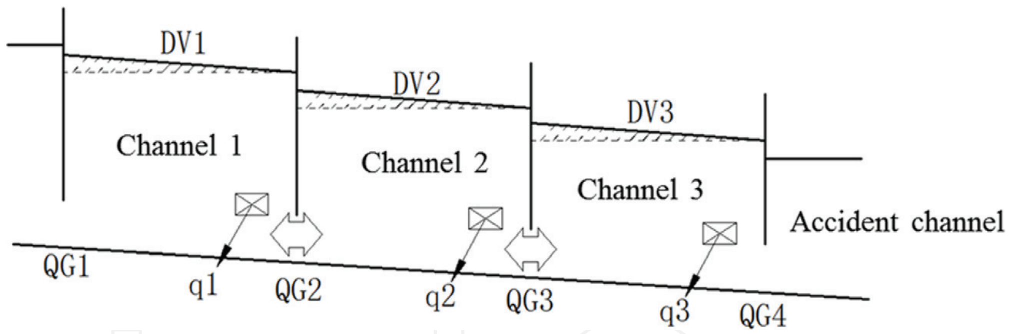

Figure 9.
Channels emergency regulated and controlled by using constant downstream depth operation.

operation and emergency operation); QG1–QG4, the flow of inflow or outflow check gate of each channel pool; q1–q3, the flow at the dividing gate of each channel pool.

On the basis of overall operation strategies and measures of the MRP, an integrated feedforward control module is designed in the constant downstream depth operation mode of the whole route. The detailed process description is shown in **Figure 10**.

1. After an accident occurs, rapidly close all check gates at the upstream accident section at the first time; if the water level is above the warning level, open the drainage gate until the water level falls back to the design level.

2. Determine a new target flow after emergency operations of inflow of each channel pool. Depending on the balance relation between inflow and outflow of channel pool, from the adjacent channel pools at the upstream accident section, accumulate the flow of all downstream turnouts to the upstream direction, taking the total flow as a new target flow after emergency operations of inflow check gate of this channel pool.

3. Calculate the regulation target value of volume in each channel pool. (1) Calculate the regulation target value of volume before and after emergency response of single channel pool. According to a new target flow after emergency operations of inflow check gate of each channel pool, calculate the volumes before and after emergency operations of each channel pool, respectively, by using a calculation program for constant nonuniform water surface profile of conventional open channel; the regulation target value equals to the difference of the two volumes; (2) calculate the regulation target value of accumulated volume of channel pools in series. Starting from adjacent channel pools at the upstream accident section to channel head, accumulate the regulation target value of single channel pool volume, channel pool by channel pool, and then obtain the regulation target value of accumulated volume of channel pools in series, and take it as the target volume for emergency operations of each channel pool.

4. Calculate the time when inflow of each channel pool is reduced. (1) Starting from the upstream channel section adjacent to accident section to upstream direction, accumulate the flow of dividing gates channel by channel, and then obtain the accumulated flow for emergency operations of each channel pool. (2) Divide the target volume for emergency operations of each channel pool by the accumulated flow for emergency operations of each channel pool, and then we obtain the change transient time of emergency operation volume in each channel pool.

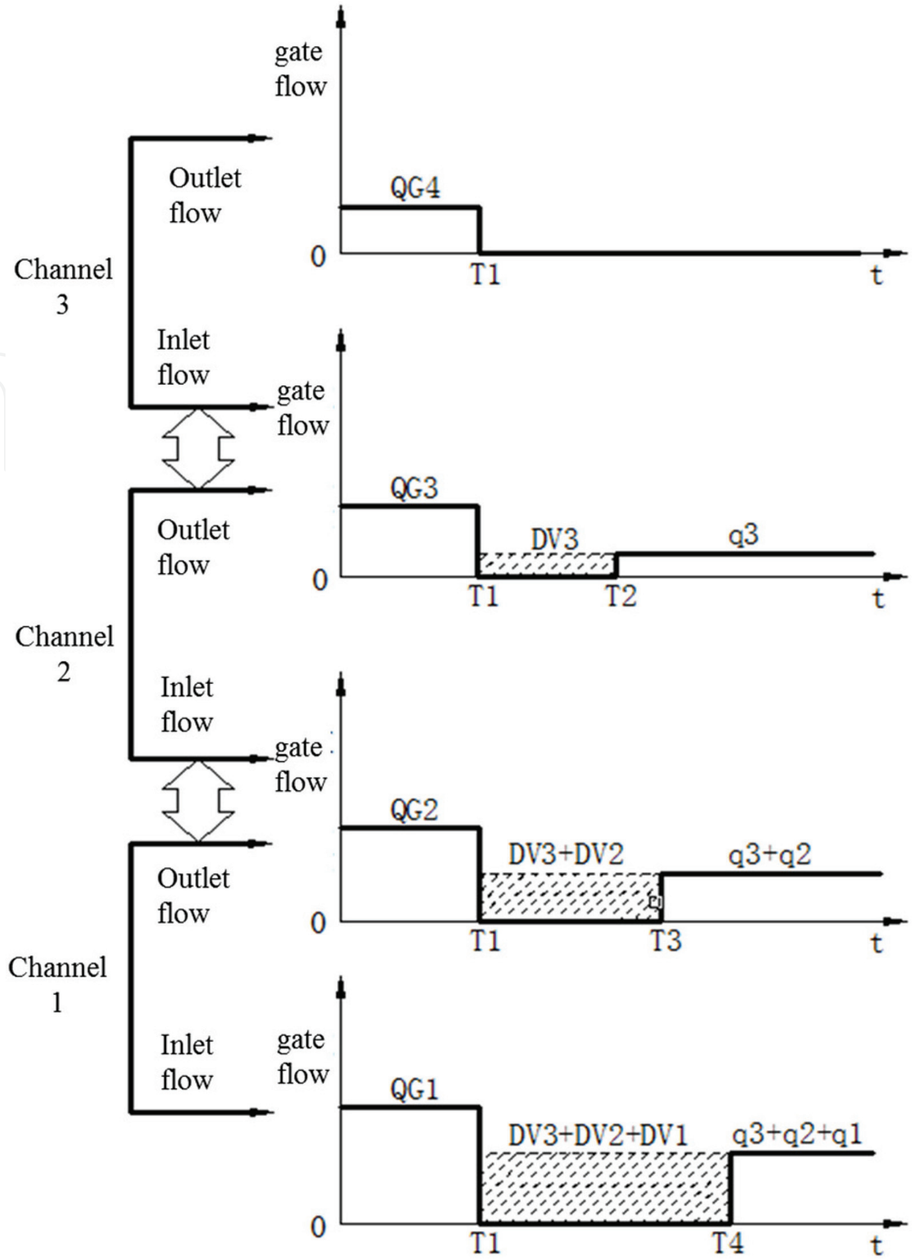

Figure 10.
Schematic diagram of emergency control mode by using constant downstream depth operation mode.

5. Carry forward with time and make implementation, respectively, according to the new target flow after emergency operations of inflow check gate of channel pool determined in Step (3), as well as the time when inflow of each channel pool is reduced (determined in Step (4)).

3.2.2.1.2 Constant downstream depth + equal-volume operation

For easy derivation and explanation, assume that there is a generalized canal with three channel pools in series as shown in **Figure 11**, and that channel pools 1 and 2 use the equal-volume operation mode. In the figure, DV1–DV3 stand for the decrease of the volume in each channel pool before and after emergency control; QG1–QG4, the flow of inflow or outflow check gate of each channel pool; q1–q3, the flow at the dividing gate of each channel pool.

On the basis of overall operation strategies and measures of the MRP, integrated feedforward control module is proposed by combining constant downstream depth

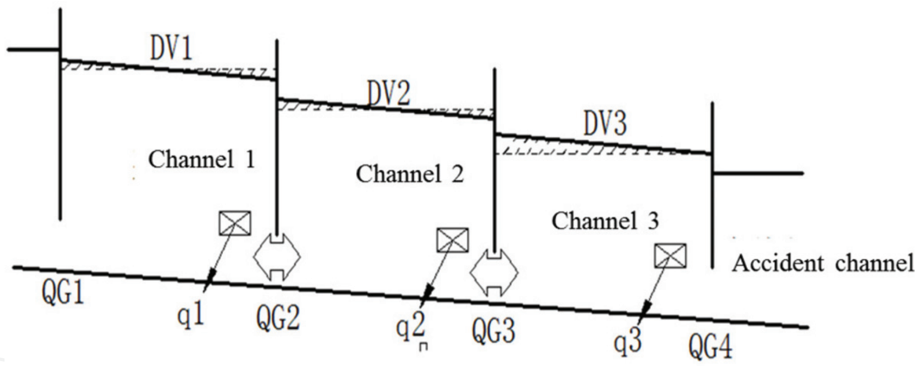

Figure 11.
Channels emergency regulated and controlled by using equal-volume operation.

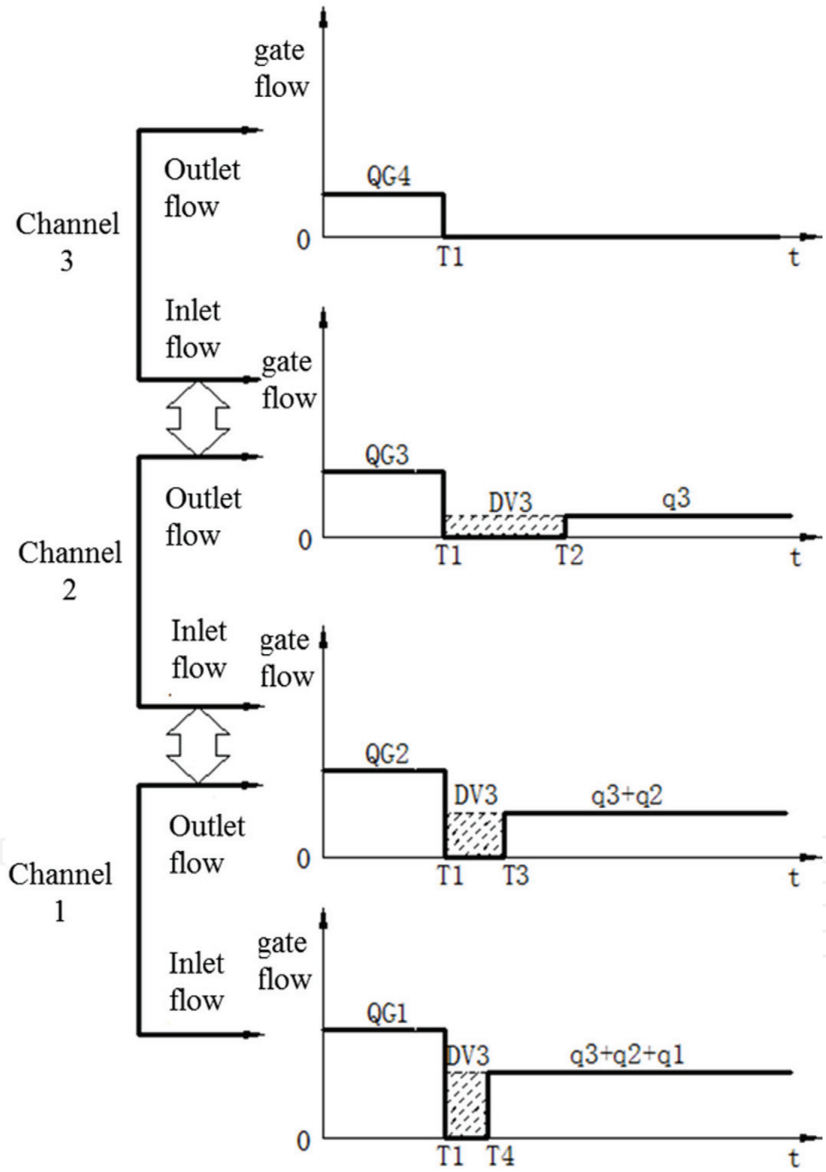

Figure 12.
Schematic diagram of emergency channel integrated control mode by using constant downstream depth operation mode.

and equal-volume operation mode. For the description of the detailed process, refer to **Figure 12**:

1. After an accident occurs, rapidly close all check gates at the upstream accident section at the first time. If the water level is above the warning level, open the drainage gate until the water level falls back to the design level.

2. Determine a new target flow after emergency operations of inflow check gate of each channel pool. Depending on the balance relation between inflow and outflow of channel pool, accumulate the flow of all downstream dividing gates channel section by channel section from the adjacent channel pools at the upstream accident section to the upstream direction, taking the total flow as a new target flow after emergency operations of inflow check gate of this channel pool.

3. Calculate the regulation target value of volume in each channel pool. (1) Calculate the regulation target value of volume before and after emergency response of single channel pool. For channel pools using equal-volume operation, let the regulation target value of volume in a single channel pool equal to 0. By adopting the channel pool using constant downstream depth operation and according to a new target flow after emergency operations of inflow check gate of each channel pool, calculate the volumes before and after emergency operations of each channel pool, respectively, by using a calculation program for constant nonuniform water surface profile of conventional open channel; the regulation target value equals to the difference of the two volumes; (2) calculate the regulation target value of accumulated volume of channel pools in series. Starting from adjacent channel pools at the upstream accident section to channel head, accumulate the regulation target value of single channel pool volume, channel pool by channel pool, and then obtain the regulation target value of accumulated volume of channel pools in series, and take it as the target volume for emergency operations of each channel pool.

4. Calculate the time when inflow of each channel pool is reduced. (1) Starting from the upstream channel section adjacent to accident section to upstream direction, accumulate the flow of dividing gates channel by channel, and then obtain the accumulated flow for emergency operations of each channel pool. (2) Divide the target volume for emergency operations of each channel pool by the accumulated flow for emergency operations of each channel pool, and then we obtain the change transient time of emergency operation volume in each channel pool.

5. Carry forward with time and make implementation, respectively, according to the new target flow after emergency operations of inflow check gate of channel pool determined in Step (3), as well as the time when inflow of each channel pool is reduced (determined in Step (4)).

3.2.2.2 Feedback control

Feedback control is also called closed-loop control. It adjusts the input quantity of a controlled object by measuring the deviation between the state of the controlled object and the target state and makes the state of the controlled object meet actual demands. During the design of feedback control algorithm, perform in-depth analysis of the dynamic response characteristics of the controlled object, and then on such basis, design the control algorithm and calibration control parameters in order to improve the performance of the controller as much as possible. For example, reduce the response process of the controlled object and the fluctuation range of the controlled parameters, improve the stability of the controlled object, and so on.

In the field of channel control, PID feedback control algorithm is the algorithm that is applied most. This algorithm is characterized by simple structure, good stability, reliable operation, convenient adjustment, etc. [5]. The dynamic response characteristics of PID control algorithm are closely related with control parameters of the control algorithm. These parameters will change with time because of uncertainty of channel roughness, cross-section size, check gate overflow coefficient, etc., and for sediment deposition, aquatic weed growth, and other reasons. Therefore, the setting of controller parameters is very critical to control performance and safe operation of a water conveyance system. There is a lot of work to do for such setting. At present, there are three kinds of commonly used methods: theoretical analysis, empirical trial method, and on-line setting method.

In order to reduce controller setting workload, this research proposes a feedback control algorithm based on dynamic volume correction thinking. The core of the algorithm is real-time dynamic correction of volume in each channel pool to make the volume of the channel pool the same with that at the target water level. For the principle, see **Figure 13**. The specific process of implementation of dynamic volume feedback correction is as follows:

1. Perform real-time monitoring of upstream target water level of check gate $Z_{\text{up}}(i,t)$. If the deviation of the water level from the target value is more than water level dead band, then the feedback control algorithm for correcting channel pool volume will be triggered.

2. Calculate the real-time volume deviation ΔV by using the following method: calculate constant water surface profile depending on the current upstream water level and target value of check gate, respectively, determine the current volume of the channel pool and its target volume via integral, and then we obtain the real-time volume deviation ΔV via subtraction between the two volumes.

3. Calculate volume correction process parameters including volume correction duration $\Delta\tau$ and respective correction flow ΔQ_{volume}. See Formula (1). For the determination of ΔQ_{volume}, we should consider multiple constraint conditions. For example, respective flow passing through check gate should be more than 0, but less than the design flow of channel, etc.

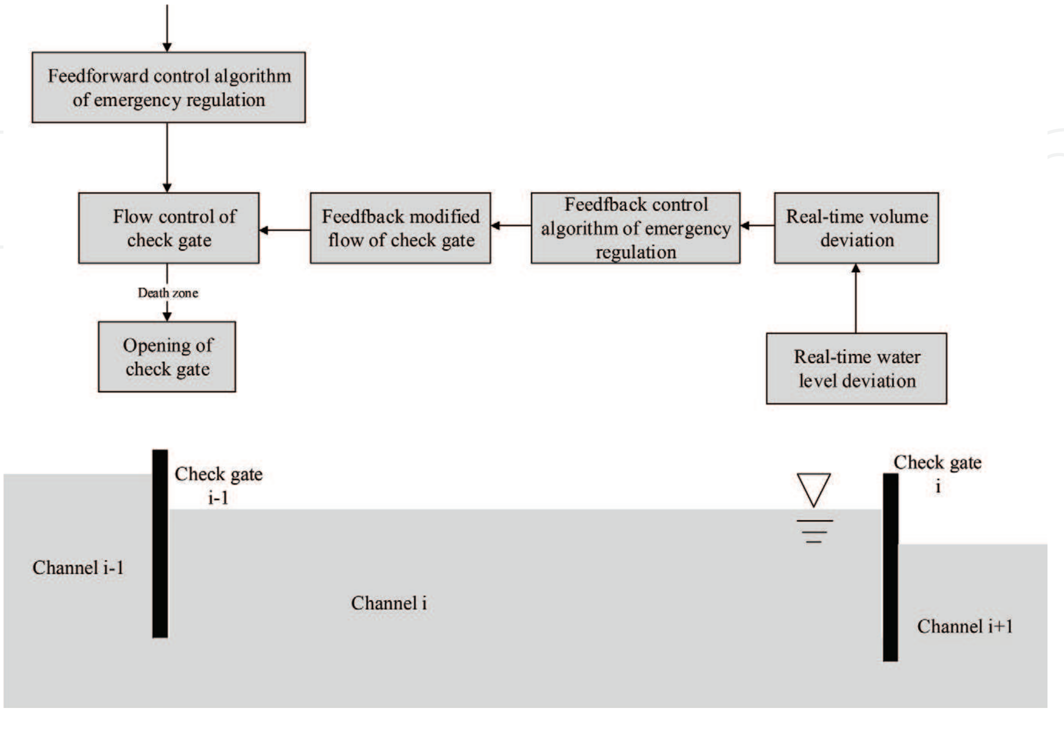

Figure 13.
Schematic diagram of emergency feedback control of upstream accident section.

$$\Delta Q_{\text{volume}}(i,t) = \Delta V(i)/\Delta\tau(i) \tag{1}$$

where $i = 1 \sim N$, and N is the number of channel pools; ΔQ_{volume} is the volume compensation flow; ΔV is the volume variation during volume compensation; $\Delta\tau(i)$ is the duration used by the volume compensation process of channel pool i.

4. The action that check gate implements volume correction for the corrected control flow of check gate $Q_{\text{gate}}(i,t)$, see Formula (2). For reverse calculation of check gate opening $Gate(i,t)$ by using check gate overflow formula, see Formula (3) and (4), where $Z_{\text{up}}(i,t)$ and $Z_{\text{down}}(i,t)$ are the upstream and downstream water levels of check gate, respectively. Compare them with check gate motion dead band (DB) and then determine whether to output check gate action (see Formulas (4) and (5)).

$$Q_{\text{gate}}(i,t) = \Delta Q_{volume}(i,t) + Q_0(i,t) \tag{2}$$

$$Gate(i,t) = \text{f}^{-1}\left(Q_{\text{gate}}(i,t),\ \ Z_{\text{up}}(i,t),\ \ Z_{\text{down}}(i,t)\right) \tag{3}$$

$$DG(i,t) = Gate(i,t) - Gate(i,t-1) \tag{4}$$

$$Gate(i,t) = \begin{cases} Gate(i,t) + DG(i,t) & if\ \ DG(i,t) \geq DB \\ 0 & if\ \ DG(i,t) < DB \end{cases} \tag{5}$$

5. Following the completion of this volume correction, go back to Step (1) and realize dynamic rolling correction.

It is important to note that in order to speed up the transition process of volume feedback regulation, the action of volume correction of each check gate (refers to ΔQ_{volume}) should be passed to all upstream check gates so as to make all upstream check gates operate synchronously, jointly completing volume feedback regulation.

For constant downstream depth and equal-volume operation modes, the thinking for implementing the aforesaid feedback control algorithms is basically the same, and the main difference lies in presetting of the upstream target water level of check gate. The upstream target water level of check gate in constant downstream depth operation mode is its design value and keeps unchanged all the time, while the upstream target water level of check gate in equal-volume operation mode changes with flow dynamically. In this research, the upstream target water level of check gate changes linearly with the whole transition process in a preset equal-volume operation mode. That is to say that the upstream target water level of check gate changes linearly from the initial value to the final value during the whole time interval from the occurrence of a sudden event to the completion of feedforward control and regulation.

3.3 Downstream section of accident pool

3.3.1 Demands for operation

During the emergency operations of downstream section of an accident pool, it is considered that the flows passing through upstream and downstream check gates of all channel pools reduce linearly to 0 from normal operation condition of the project (**Figure 14**).

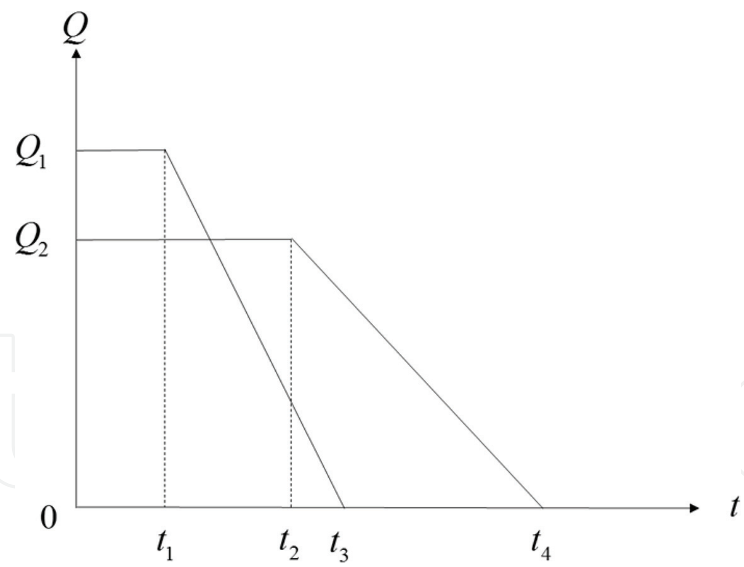

Figure 14.
Upstream and downstream flow change processes of any channel pool at downstream accident pool.

In the figure, Q_1 is the water discharge through check gate corresponding to upstream check gate under normal operation condition of the current channel pool; Q_2 is the water discharge through check gate corresponding to downstream check gate under normal operation condition of the current channel pool; t_1 is the time when the regulation of upstream check gate starts; t_2 is the time when the regulation of downstream check gate starts; t_3 is the time when the regulation of upstream check gate ends; and t_4 is the time when the regulation of downstream check gate ends.

All check gates of downstream accident pool take the downstream check gate as a boundary condition, and emergency operations is carried out. Therefore, during this process, the aforesaid t_1 and t_3 can be taken as known parameters, t_2 and t_4 as unknown parameters, and then they can be converted to the determination of the start time t_2 and end time t_4 of regulation of downstream check gate.

Therefore, the operation of downstream accident section generally is similar to volume control algorithm. The purpose of water level control is realized by regulating channel pool volume [6]. At present, we have obtained the operation strategy analysis of downstream check gate after an accident occurs upstream. The operation process is that the opening of check gate is performed according to conventional regulation opening at each step [7]. Actually, the operation of check gate under an emergency may not follow conventional opening change constraint, but be the maximum opening. Therefore, for the operation strategy of downstream accident section, an equation can be established according to water budget with a known change ΔV of water body volume in channel pool. With another condition added, t_2 and t_4 can be determined by combining the equation and the condition. This chapter puts forward three methods for reference.

3.3.2 Methods for operation

3.3.2.1 Equal proportion reduction of water discharge through check gate

The water discharge through all check gates at downstream accident pool reduces in an equal proportion, and the reduction of discharge is the same per unit time, as shown in **Figure 15**.

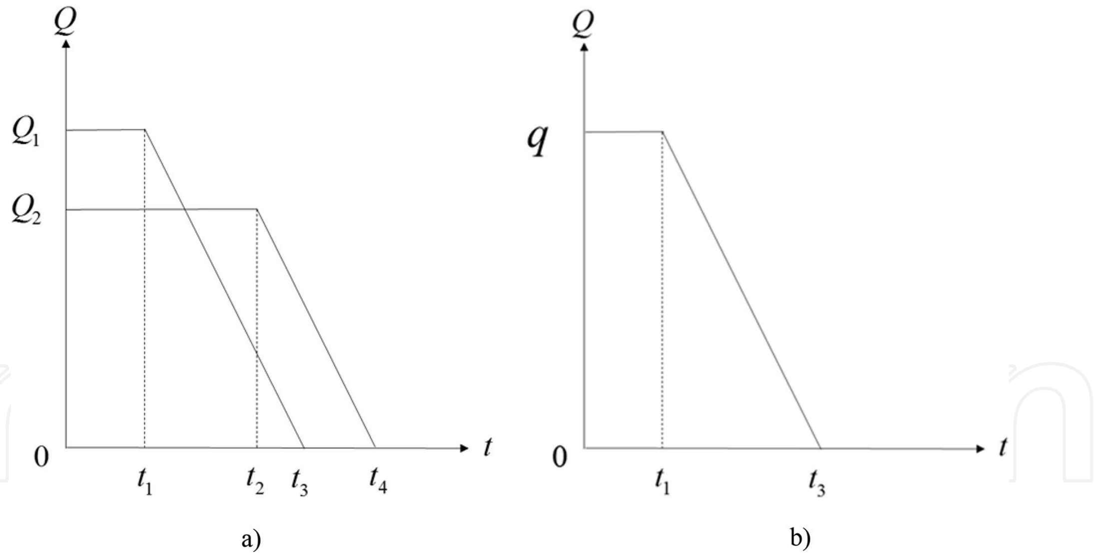

Figure 15.
Schematic diagram of equal proportion reduction of water discharge through check gate. (a) Upstream and downstream flow change processes of channel pool. (b) Flow change process at the turnout of such channel pool.

By using this method, we obtain

$$\frac{Q_2}{t_4 - t_2} = \frac{Q_1}{t_3 - t_1} \tag{6}$$

During emergency operations, the volume of water body flowing into such channel pool through upstream check gate is

$$\Delta V_u = Q_1 t_1 + \frac{1}{2}(t_3 - t_1)Q_1 \tag{7}$$

During such process, the volume of water body flowing out of such channel pool is

$$\Delta V_d = Q_2 t_2 + \frac{1}{2}(t_4 - t_2)Q_2 + q t_1 + \frac{1}{2}(t_3 - t_1)q \tag{8}$$

then, the volume change ΔV of water body in the channel pool is

$$\Delta V = \Delta V_d - \Delta V_u \tag{9}$$

Put Formulas (7) and (8) into Formulas (9), and then we obtain

$$2\Delta V = (t_2 + t_4)Q_2 + (t_1 + t_3)q - (t_1 + t_3)Q_1 \tag{10}$$

From water budget, we know that

$$Q_1 = Q_2 + q \tag{11}$$

Put Formula (11) into Formula (10), and then we obtain

$$\frac{2\Delta \mathrm{V}}{Q_2} = t_2 + t_4 - t_1 - t_3 \tag{12}$$

By combining Formulas (4)–(6) and (4)–(12), we can obtain

$$t_2 = \frac{\Delta}{VQ_2} + \frac{t_1 + t_3}{2} - \frac{Q_2}{2Q_1}(t_3 - t_1) \tag{13}$$

$$t_4 = \frac{Q_2}{2Q_1}(t_3 - t_1) + \frac{\Delta V}{Q_2} + \frac{t_1 + t_3}{2} \quad (14)$$

Because $Q_1 \geq Q_2$, we can obtain from Formula (15)

$$t_2 \geq \frac{\Delta V}{Q_2} + t_1 \quad (15)$$

Namely, the regulation start time of downstream check gate is later than that of upstream check gate.

3.3.2.2 Starting regulation of all check gates at the same time

The regulation of check gate of all channel pools of downstream accident pool and the check gate of downstream accident pool starts at the same time, but ends at different times, as shown in **Figure 16**.

By using this method, we know that the regulation start time of each check gate t_2 is the same, equaling to that of downstream check gate of accident pool. Then, there is only one unknown parameter t_4 under such condition.

During emergency operations, the volume of water body flowing into channel pool through upstream check gate is

$$\Delta V_u = \frac{1}{2} t_3 Q_1 \quad (16)$$

During such process, the volume of water body flowing out of such channel pool is

$$\Delta V_d = \frac{1}{2} t_4 Q_2 + \frac{1}{2} t_3 q \quad (17)$$

then, the volume change ΔV of water body in the channel pool is

$$\Delta V = \Delta V_d - \Delta V_u \quad (18)$$

Put Formulas (16) and (17) into (18), and then we obtain

$$2\Delta V = t_4 Q_2 + t_3 q - t_3 Q_1 \quad (19)$$

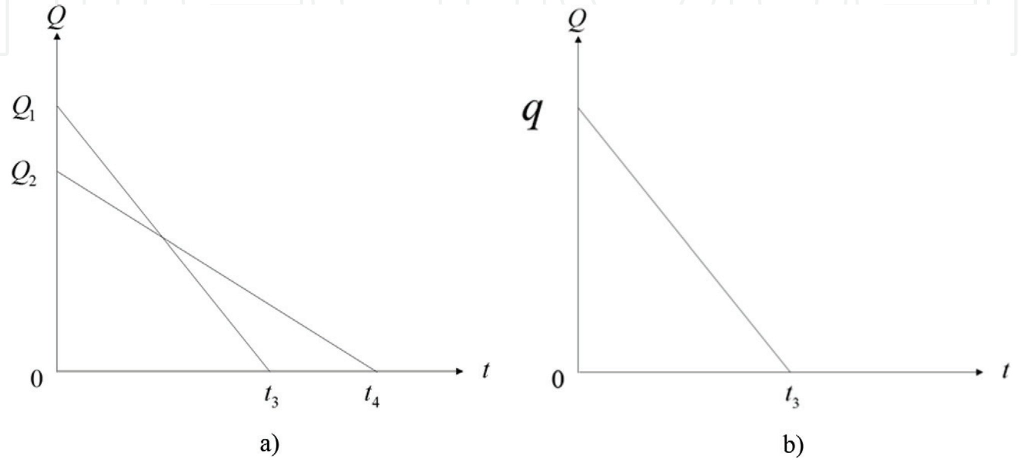

Figure 16.
Schematic diagram of equal proportion reduction of water discharge through check gate. (a) Upstream and downstream flow change processes of channel pool. (b) Flow change process at the dividing gate of such channel pool.

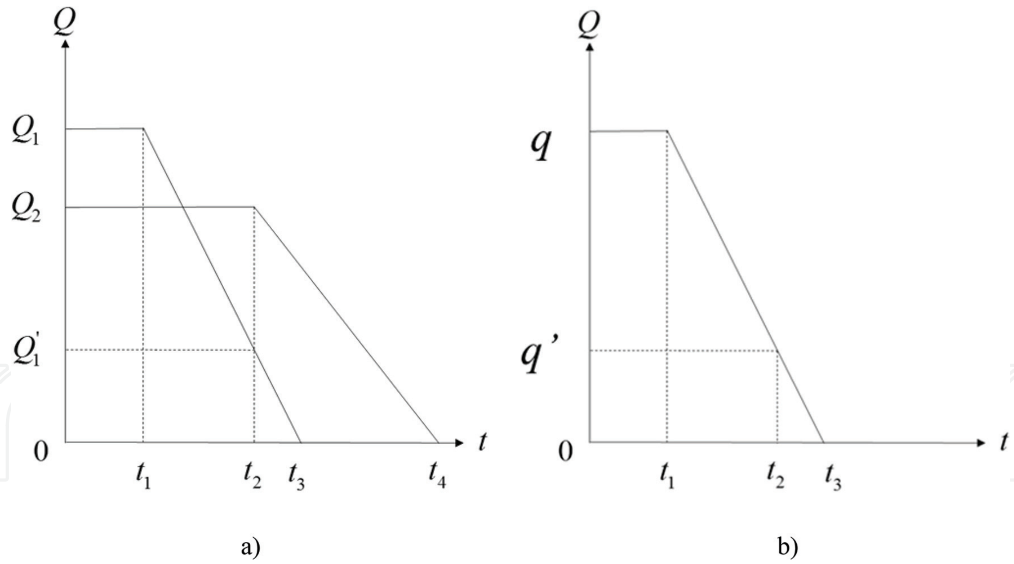

Figure 17.
Schematic diagram of equal proportion reduction of water discharge through check gate. (a) Upstream and downstream flow change processes of channel pool. (b) Flow change process at the dividing gate of such channel pool.

From water budget, we know that

$$Q_1 = Q_2 + q \tag{20}$$

Put Formula (20) into Formula (19), and then we obtain

$$t_4 = \frac{2\Delta V}{Q_2} + t_3 \tag{21}$$

From this Formula, we can see that the regulation end time of downstream check gate is always later than that of upstream check gate.

3.3.2.3 Performing control depending on change in water body volume in channel pool

The regulation start time of downstream check gate of the channel pool is controlled via the change of water body volume in the channel pool. In this chapter, assuming when the water body volume reduces $\frac{\Delta V}{n}$ (n is an integer), the regulation of downstream check gate starts. The operation process of this method is as shown in **Figure 17**.

In the figure, the water discharge through upstream check gate of channel pool corresponding to time t_2 is $Q_1^{'}$, and the water diversion at dividing gate is q, then we obtain

$$\frac{Q_1^{'}}{t_3 - t_2} = \frac{Q_1}{t_3 - t_1} \tag{22}$$

$$\frac{q^{'}}{t_3 - t_2} = \frac{q}{t_3 - t_1} \tag{23}$$

By time t_2, the volume of water entering the channel pool is

$$\Delta V_u = Q_1 t_1 + \frac{Q_1^{'} + Q_1}{2}(t_2 - t_1) \tag{24}$$

The volume of water body flowing out of channel pool is

$$\Delta V_d = Q_2 t_2 + q t_1 + \frac{q' + q}{2}(t_2 - t_1) \tag{25}$$

As described above, by time t_2, the change of water body volume in channel pool is

$$\frac{\Delta V}{n} = \Delta V_d - \Delta V_u \tag{26}$$

From water budget, we know that

$$Q_1 = Q_2 + q \tag{27}$$

Put Formulas (22)–(25), and (27) into (26), and then we obtain

$$\frac{2\Delta V}{nQ_2} = \frac{(t_2 - t_1)^2}{t_3 - t_1} \tag{28}$$

We obtain the following solution:

$$t_2 = t_1 + \sqrt{\frac{2\Delta V}{nQ_2}(t_3 - t_1)} \tag{29}$$

By time t_2, the volume of water entering the channel pool is

$$\Delta V_u^{'} = \frac{Q_1^{'}}{2}(t_3 - t_2) \tag{30}$$

The volume of water body flowing out of channel pool is

$$\Delta V_d' = \frac{Q_2}{2}(t_4 - t_2) + \frac{q'}{2}(t_3 - t_2) \tag{31}$$

As described above, after time t_2 and until completion of emergency operations, the change of water body volume in channel pool is

$$\frac{(n-1)\Delta V}{n} = \Delta V_d^{'} - \Delta V_u^{'} \tag{32}$$

Put Formulas (22), (23), (27), (30), and (31) into (32), and then we obtain

$$t_4 = \frac{2(n-1)\Delta V}{nQ_2} + \frac{(t_3 - t_2)^2}{t_3 - t_1} + t_2 \tag{33}$$

From Formula (29), we know that the regulation start time of downstream check gate t_2 is certainly later than that of upstream check gate t_1. Since the above derivation processes is obtained under the condition of $t_2 \leq t_3$, then by combining Formula (29), we obtain

$$t_3 - t_1 - \sqrt{\frac{2\Delta V}{nQ_2}(t_3 - t_1)} \geq 0 \tag{34}$$

We obtain the following via solution

$$\frac{\Delta V}{nQ_2} \leq \frac{t_3 - t_1}{2} \tag{35}$$

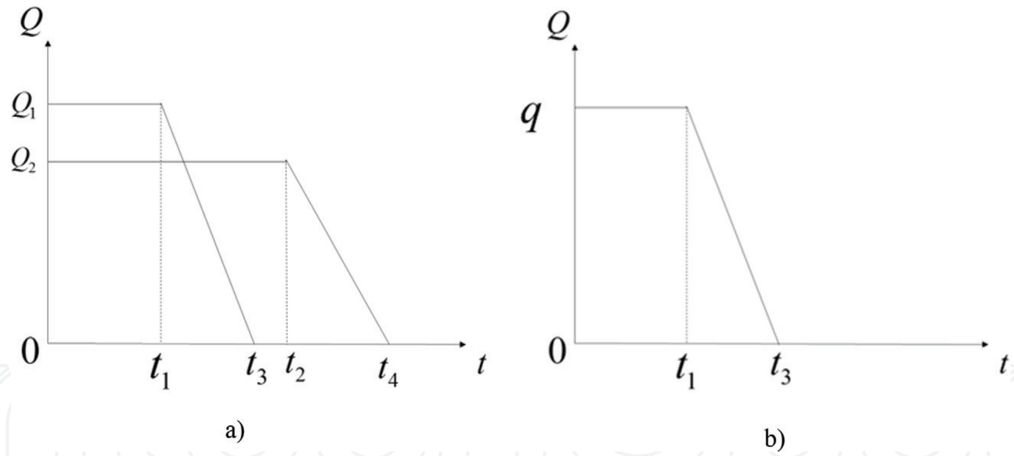

Figure 18.
Schematic diagram of equal proportion reduction of water discharge through check gate. (a) Upstream and downstream flow change processes of channel pool. (b) Flow change process at the dividing gate of such channel pool.

However, at $t_2 \geq t_3$, the operation method is shown in **Figure 18**.

Then by time t_2, the volume of water entering the channel pool is

$$\Delta V_u = \frac{Q_1}{2}(t_1 + t_3) \tag{36}$$

The volume of water body flowing out of channel pool is

$$\Delta V_d = Q_2 t_2 + q\frac{t_1 + t_3}{2} \tag{37}$$

By time t_2, the change of water body volume in channel pool is

$$\frac{\Delta V}{n} = \Delta V_d - \Delta V_u \tag{38}$$

From water budget, we know that

$$Q_1 = Q_2 + q \tag{39}$$

Put Formulas (36), (37), and (39) into (38), and then we obtain

$$t_2 = \frac{\Delta V}{nQ_2} + \frac{t_1 + t_3}{2} \tag{40}$$

After time t_2, no water flows into the channel, and then the volume of water flowing out of channel is

$$\Delta V_d' = Q_2 \frac{t_4 - t_2}{2} \tag{41}$$

Then we obtain

$$\frac{(n-1)\Delta V}{n} = \Delta V_d' \tag{42}$$

Put Formulas (40) and (41) into (42), and then we obtain

$$t_4 = \frac{(2n-1)\Delta V}{nQ_2} + \frac{t_1 + t_3}{2} \tag{43}$$

For this method, because the regulation start time of downstream check gate t_2 is later than the regulation end time of upstream check gate t_3, namely $t_2 \geq t_3$, then by combining Formula (40), we obtain

$$\frac{\Delta V}{nQ_2} + \frac{t_1 + t_3}{2} - t_3 \geq 0 \tag{44}$$

We obtain the following by solution

$$\frac{\Delta V}{nQ_2} \geq \frac{t_3 - t_1}{2} \tag{45}$$

From Formulas (44) and (45), we can see that for this method, the specific form of the operation method which takes volume as a control condition should be determined by comparing the magnitude relation between $\frac{\Delta V}{nQ_2}$ and $\frac{t_3 - t_1}{2}$.

4. Case study

Take the MRP for example. Assuming that 6th channel pool (from check gate for Shierli River to the check gate at the outlet of the inverted siphon for Baihe River) undergoes a sudden water pollution event, the control rules and algorithms proposed herein should be used immediately to control the check gates at accident section, and upstream and downstream sections of accident pool, to make emergency operations process realize rapidly and to ensure that water level thereafter reaches the target water level. In case of an accident under a simulated operating condition, the water diversion flow at the accident section is 126 m^3/s.

Firstly, in order to test the effectiveness of the algorithm herein, assuming that current control is constant downstream depth operation mode, analyze whether the steady water level after control completion satisfies requirements by using emergency control algorithm adopted herein. Secondly, in order to compare the operation results of constant downstream depth and constant downstream depth + equal-volume operation modes, further assuming that the constant downstream depth operation mode is used for downstream sections of accident pool, and that equal-volume control mode is used for some pools of the upstream section of polluted channel section, here the upstream 2-5 pools were assumed to be under equal-volume control mode while upstream 1 pool was assumed to be under constant water level control mode (the farther away the pool is from the accident section, the larger the pool is numbered), then compare the results of upstream some sections of accident pool obtained by using constant downstream depth and constant downstream depth + equal-volume operation modes respectively.

In constant downstream depth operation mode, see **Figures 19–25** for the operation process of accident pool, and upstream and downstream sections of accident pool.

4.1 Accident pool

Two check gates in accident pool were closed rapidly within 60 min (**Figure 19**), leading to violent water oscillation therein. Below we take the fluctuation process and initial water level deviation of upstream water level of check gate for example for display (**Figure 20**).

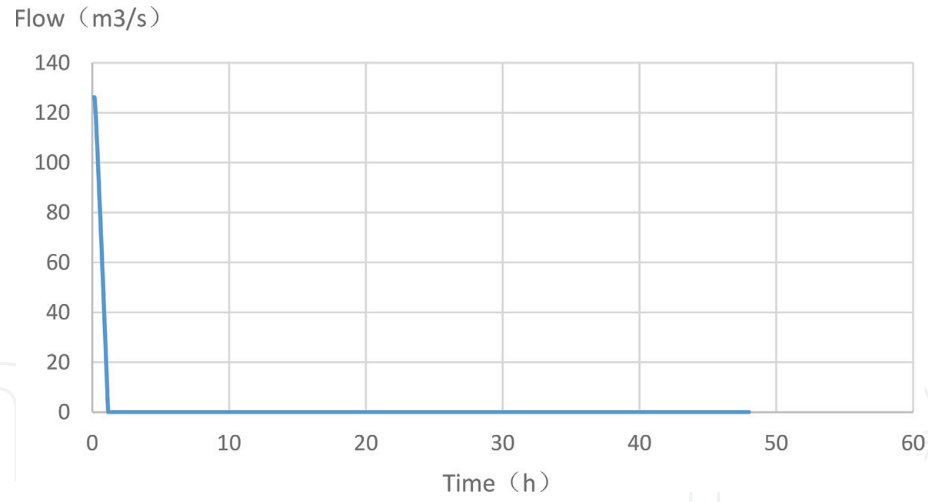

Figure 19.
Change process diagram of water discharge through check gate in accident pool.

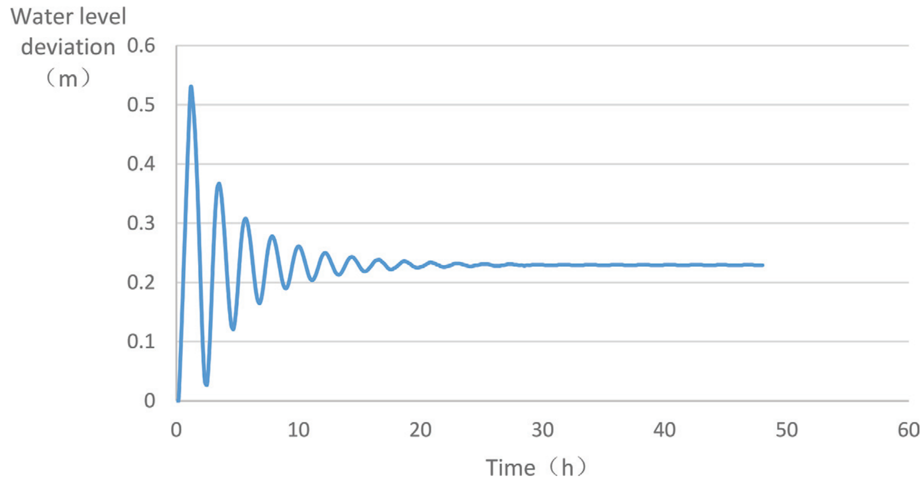

Figure 20.
Deviation change process diagram of upstream water level of downstream check gate in accident pool.

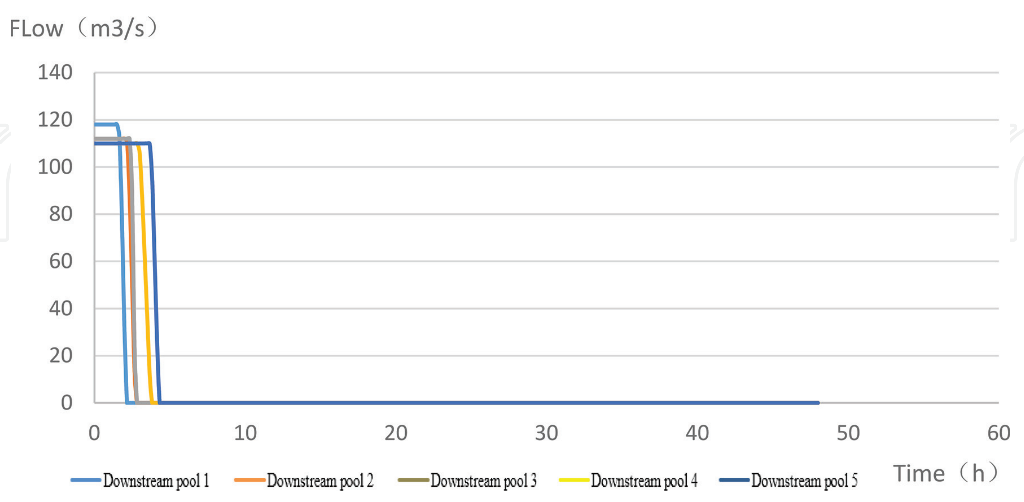

Figure 21.
Change process diagram of water discharge through check gate at downstream section of accident pool.

4.2 Downstream section of accident pool

For downstream section of accident pool, select the operation process of water discharge through five downstream check gates near to polluted channel section

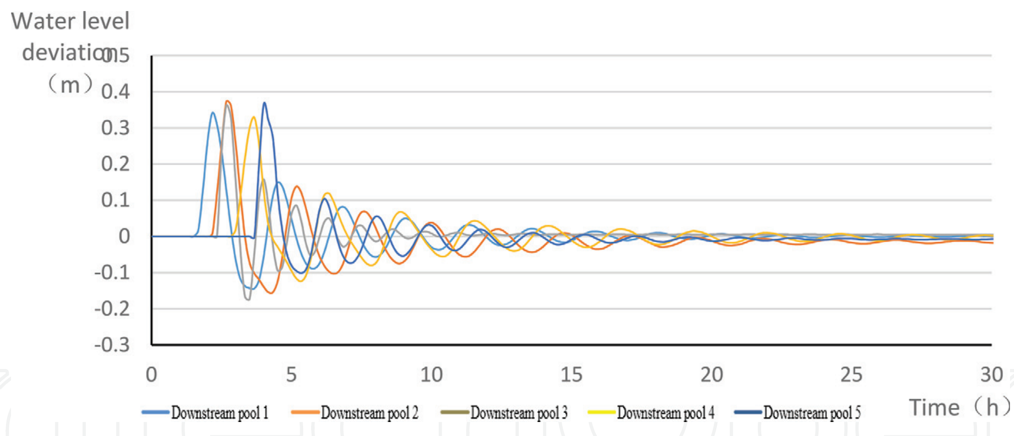

Figure 22.
Deviation change process diagram of upstream water level of check gate at downstream section in accident pool.

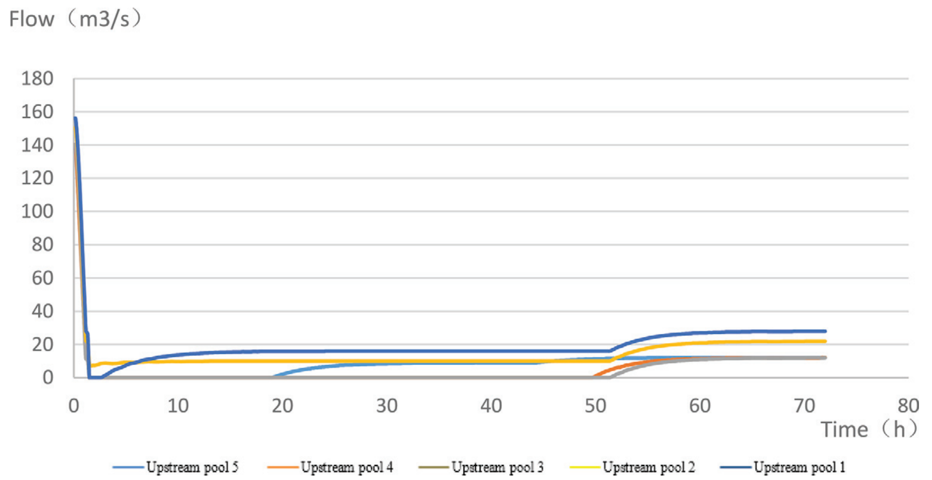

Figure 23.
Change process diagram of water discharge through check gate at upstream section of accident pool.

and the change process of upstream water level of check gate, as shown in **Figures 21** and **22**.

From **Figure 22**, we can see that the water level in accident pool meets constant downstream depth after stability. This is because that the water diversion flow change process at the downstream section was artificially determined and that the most upstream check gate at the downstream section was closed first. The feedforward analysis can be calculated by using the principle of volume compensation algorithm. And also, we can see that the fluctuation of the upstream water level of check gate is small, not more than 0.4 m. This is because that asynchronous closing operation was adopted at downstream section. This is reflected by the time when the change of water discharge starts in **Figure 21**.

4.3 Upstream section of accident pool

4.3.1 Constant downstream depth

For upstream section of accident pool, select the operation process of water discharge through five downstream check gates near to accident pool and the change process of the upstream water level of check gate, as shown in **Figures 23** and **24**.

From **Figure 24**, we can see that the water level at upstream section in accident pool meets constant downstream depth after stability. This is because feedback

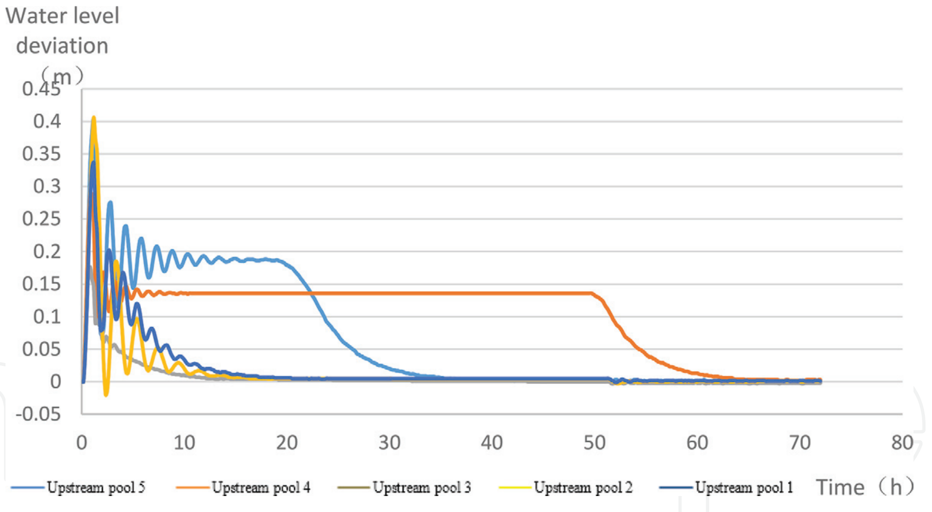

Figure 24.
Deviation change process diagram of upstream water level of check gate at upstream section in accident pool.

algorithm was used for the upstream section. Gradually regulate the flow of check gate to make channel pool volume come near to the target volume, making the upstream water level of check gate come near to the target water level. And from **Figure 23**, we can see that the synchronous closing method was used for check gate at upstream section. After check gate was closed completely for a period of time and then opened, the opening time was different. After stability, keep a certain flow unchanged to meet normal water supply at the upstream section. Because of nonuniform water discharge through check gate, discharge difference was used to regulate channel pool volume and to realize the control of the upstream water level of check gate.

4.3.2 Constant downstream depth + equal-volume

In constant downstream depth and equal-volume check gate adding constant downstream depth operation modes, the operation result of channel section is shown in **Figures 25–34**.

Figures 25 and **26** are the results of upstream check gate 1. From these figures, we can see that the results under two operating conditions are the same. This is because that the channel section corresponding to upstream check gate 1 was near

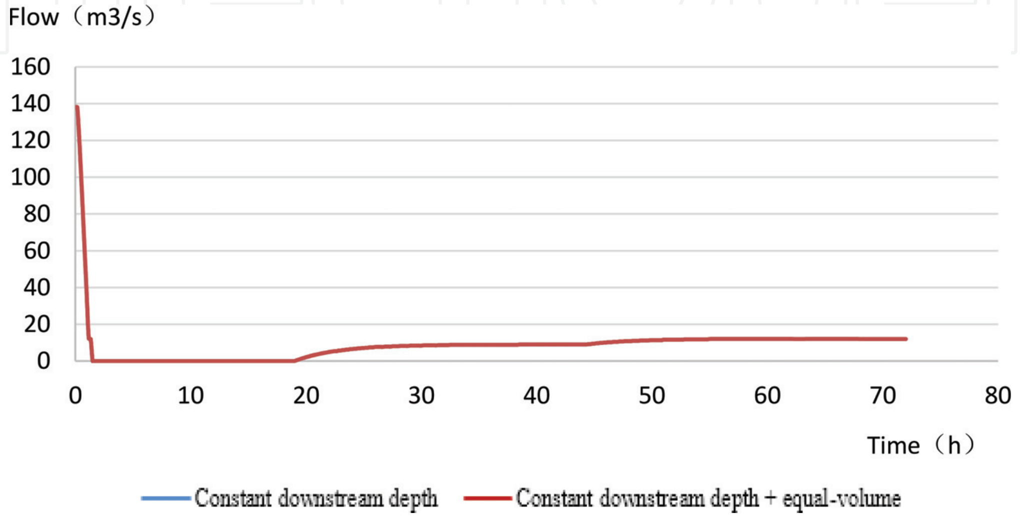

Figure 25.
Flow change of upstream check gate 1 under different operation conditions.

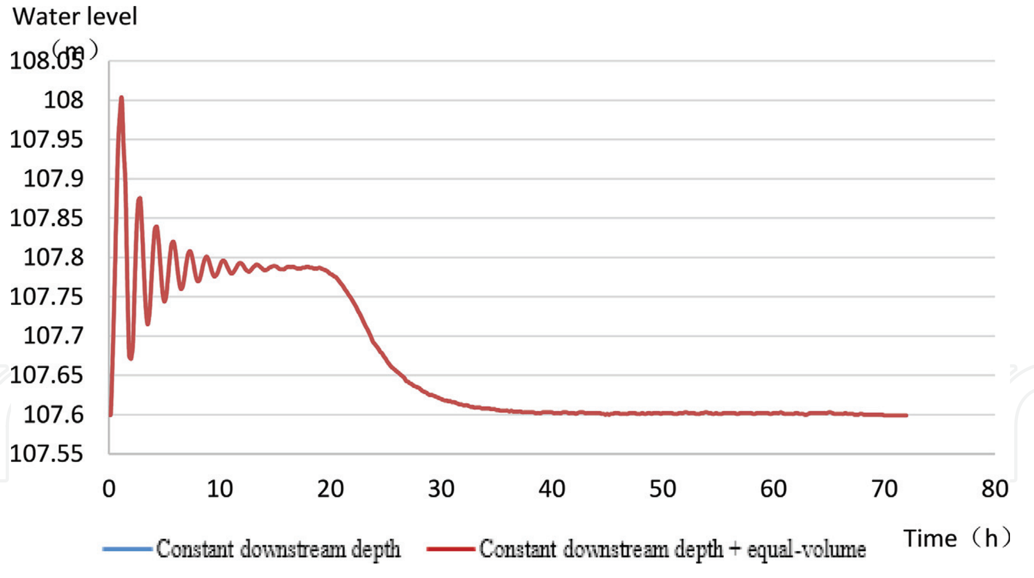

Figure 26.
Flow change of upstream water level of upstream check gate 1 under different operation conditions.

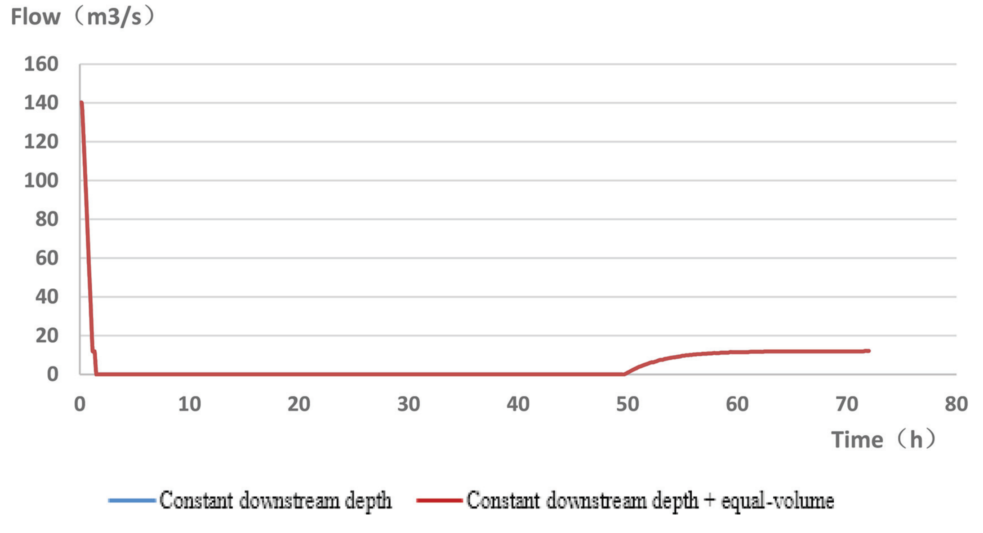

Figure 27.
Flow change of upstream check gate 2 under different operation conditions.

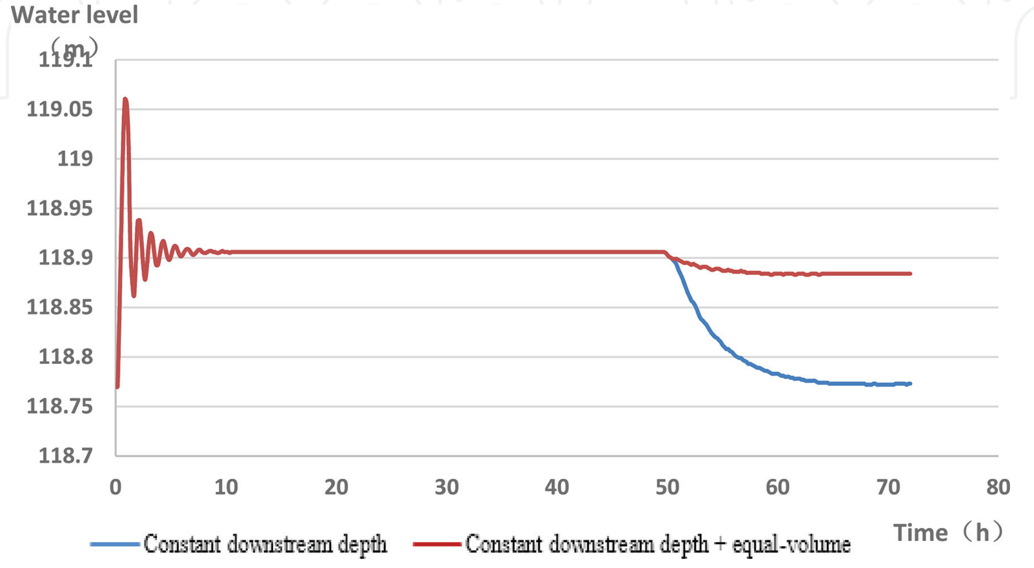

Figure 28.
Flow change of upstream water level of upstream check gate 2 under different operation conditions.

to downstream and constant downstream depth was adopted under such two operating conditions.

Figures 27 and **28** are the results of upstream check gate 2. From **Figure 28**, we can see the difference in the upstream water level of check gate under two operating conditions: steady upstream water level of check gate under equal-volume control is higher than the upstream water level in constant downstream depth operation mode. But from **Figure 27**, we cannot see the difference in opening and flow of check gate. Therefore, the reason that leads to nonuniform water level lies in nonuniform opening change of upstream check gate which is not reflected therein.

Figures 29–34 are the results of upstream check gates 3, 4, and 5 under two operating conditions. After comparing the upstream water level, water discharge and opening of check gate, respectively, we can find out the difference between the two operating conditions. In equal-volume operation mode, all upstream water levels of check gate after stability are higher than that in constant downstream depth operation mode. Under such condition, the water level drop rate of check gate will be smaller, and it is more favorable to the safety of the project. In equal-volume operation mode, check gate is opened at an earlier time, so the emergency regulation time corresponding thereto becomes shorter. Moreover, this situation is

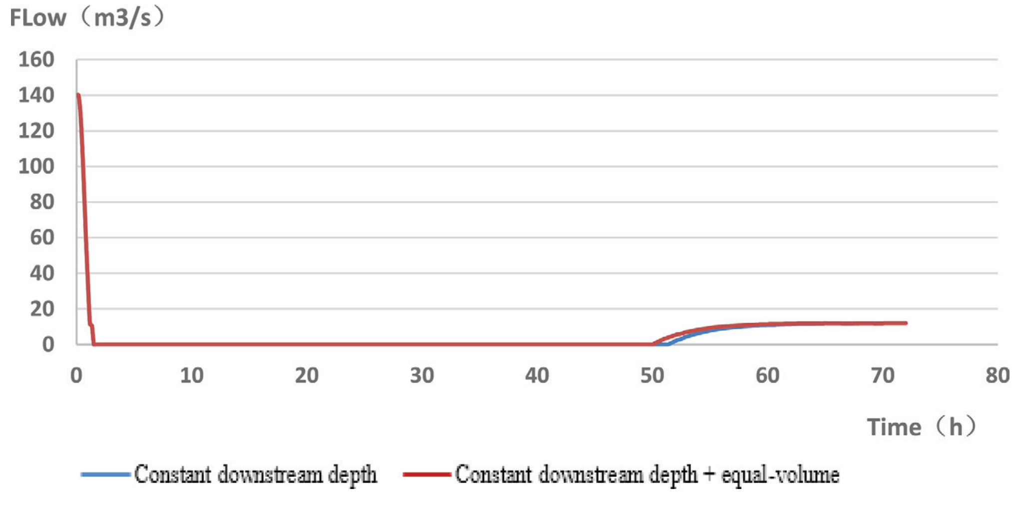

Figure 29.
Flow change of upstream check gate 3 under different operation conditions.

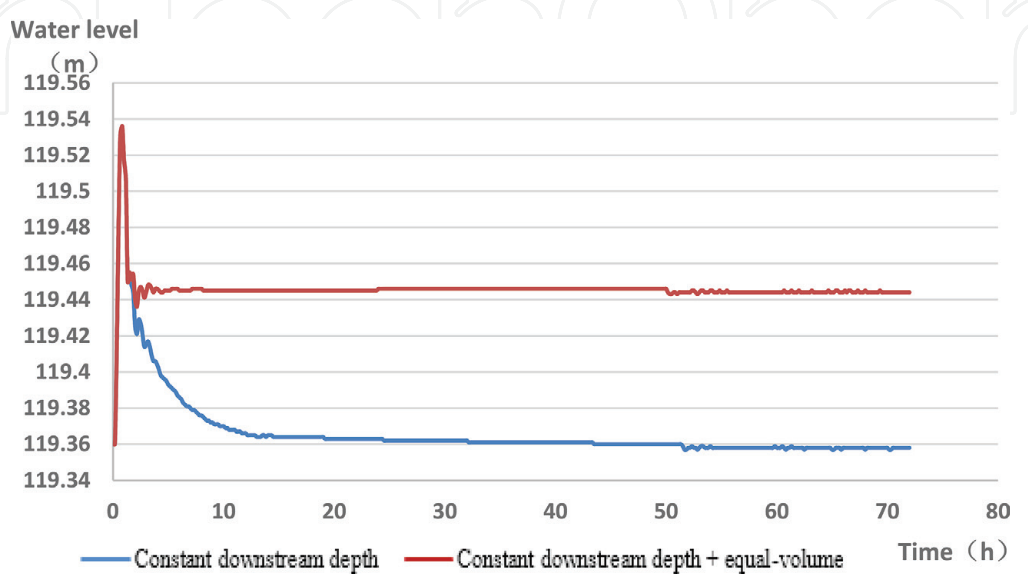

Figure 30.
Flow change of upstream water level of upstream check gate 3 under different operation conditions.

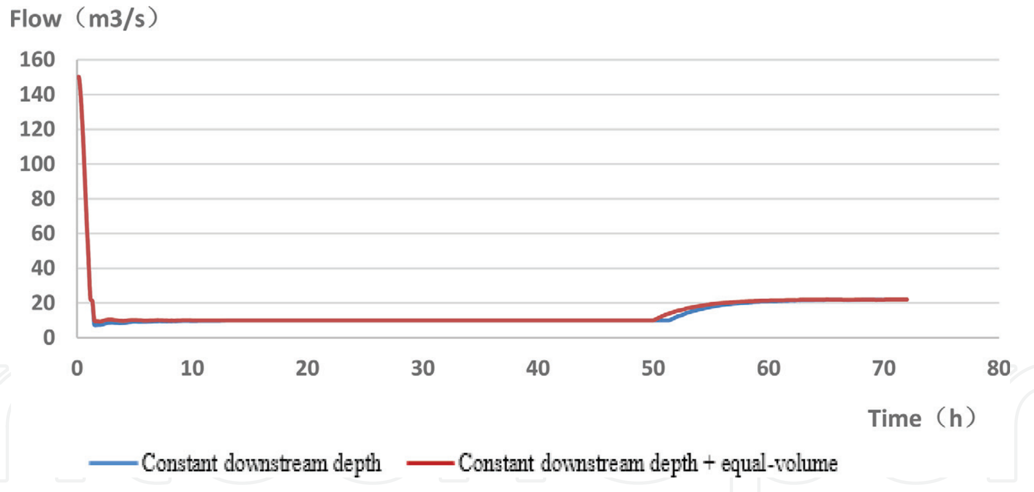

Figure 31.
Flow change of upstream check gate 4 under different operation conditions.

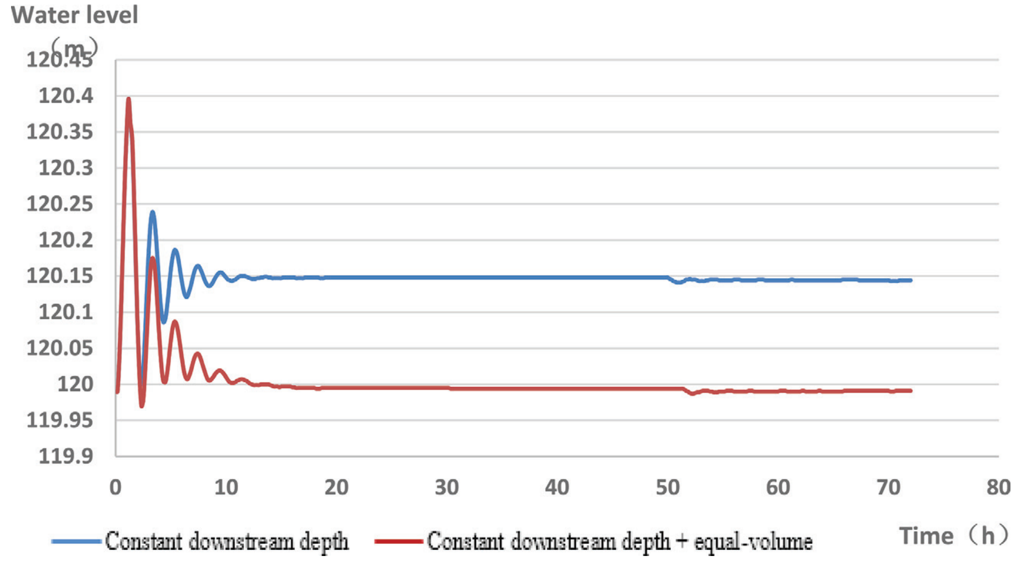

Figure 32.
Flow change of upstream water level of upstream check gate 4 under different operation conditions.

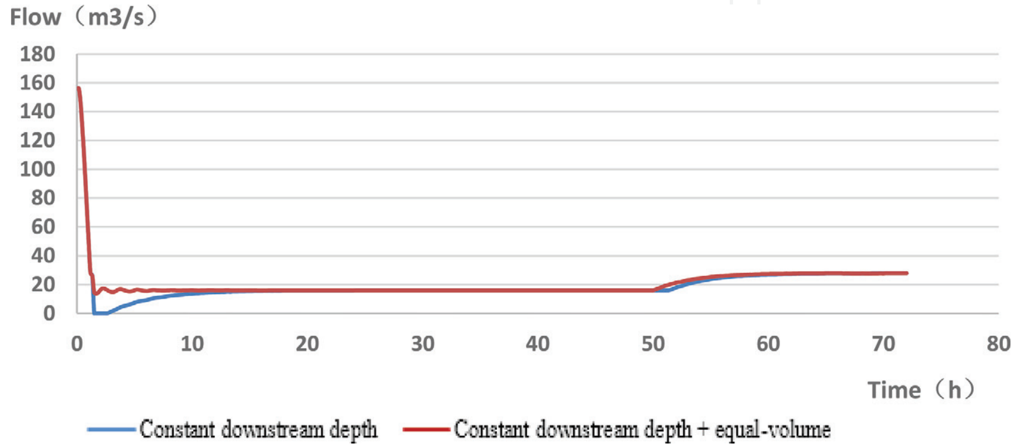

Figure 33.
Flow change of upstream check gate 5 under different operation conditions.

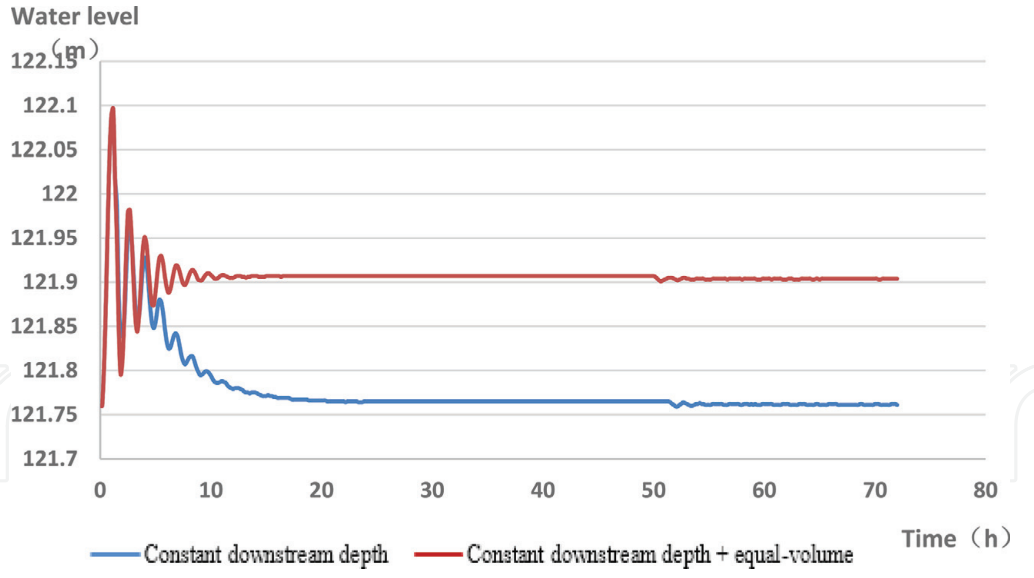

Figure 34.
Flow change of upstream water level of upstream check gate 5 under different operation conditions.

more obvious when nearer to upstream. This is because that the nearer it is to upstream, the greater the cumulative difference between equal-volume operation and constant downstream depth operation modes becomes, and the greater the check gate operating difference becomes.

5. Conclusions

This chapter develops a complete set of check gate operation rules and automatic control algorithm for sudden water pollution events in the MRP. For great change in channel pool operating conditions due to emergency operating conditions, a set of operational thoughts different from conventional ones is put forward. Emergency operations are divided into operation rules development and automatic control algorithm research. Sudden water pollution accidents under emergency operations' operating conditions of the main canal are divided into accident pool, joint emergency operations of upstream, and downstream sections of the accident pool. Different automatic control algorithms come up with different channel sections. The results of their applications indicate that the methods proposed can be used to guide safe, steady emergency operations of channel section, ensure steady water level in the final channel section, and keep it to the target water level.

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References

[1] Haddad OB, Beygi S, Mariño MA. Reservoir water allocation under abrupt pollution condition. Journal of Irrigation and Drainage Engineering. 2014;**140**(3): 04013017

[2] Wahlin BT, Clemmens AJ. Performance of historic downstream canal control algorithms on ASCE Test Canal 1. Journal of Irrigation and Drainage Engineering. 2002;**128**(6): 365-375

[3] Schuurmans J, Bosgra OH, Brouwer R. Open-channel flow model approximation for controller design. Applied Mathematical Modelling. 1995; **19**(9):525-530

[4] Clemmens AJ, Strand RJ. Downstream-water-level control test results on the WM lateral canal. Journal of Irrigation and Drainage Engineering. 2009;**136**(7):460-469

[5] Hof A, Schuurmans J. Simple water level controller for irrigation and drainage canals. Journal of Irrigation and Drainage Engineering. 1999;**125**(4): 189-195

[6] Clemmens AJ, Bautista E. Volume compensation method for routing irrigation canal demand changes. Journal of Irrigation and Drainage Engineering. 2005;**131**(6):494-503

[7] Soler J, Gómez M, Rodellar J, et al. Application of the GoRoSo feedforward algorithm to compute the gate trajectories for a quick canal closing in the case of an emergency. Journal of Irrigation and Drainage Engineering. 2013;**139**(12):1028-1036