Real time control of nature-based solutions

Towards Smart Solutions and digital twins in Rangsit Area, Thailand

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Research article

Real time control of nature-based solutions: Towards Smart Solutions and Digital Twins in Rangsit Area, Thailand

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ARTICLE INFO

ABSTRACT

The intensity and frequency of hydro-meteorological hazards have increased due to fast-growing urbanisation activities and climate change. Hybrid approaches that combine grey infrastructure and Nature-Based Solutions (NBSs) have been applied as an adaptive and resilient strategy to cope with climate change uncertainties and incorporate other co-benefits. This research aims to investigate the feasibility of Real Time Control (RTC) for NBS operation in order to reduce flooding and improve their effectiveness. The study area is the irrigation and drainage system of the Rangsit Area in Thailand. The results show that during the normal flood events, the RTC system effectively reduces water level at the Western Raphiphat Canal Station compared to the system without RTC or with additional storage. Moreover, the RTC system facilitates achieving the required minimum volume and increasing the volume in the retentions. These findings highlight the potential of using RTC to improve the irrigation and drainage system operation as well as NBS implementation to reduce flooding. The RTC system can also assists in equitable water distribution between Klongs and retention areas, while also increasing the water storage in the retention areas. This additional water storage can be utilized for agricultural purposes, providing further benefits. These results represent an essential starting point for the development of Smart Solutions and Digital Twins in utilizing Real-Time Control for flood reduction and water allocation in the Rangsit Area in Thailand.

1. Introduction

Floods affect more people than any other natural hazards, with 1.65 billion people affected between 2000 and 2019 (UNDRR, 2020). Furthermore, floods are also the most frequent natural hazard, constituting 44% of the natural hazard events that occurred during the same period.

Grey infrastructure such as dams, dikes, canals, sewers, and tunnels have been the traditional approach for flood protection and mitigation. In most cases, this approach is considered as a single objective, high-cost solution. Several studies indicate that such an approach only reduce the impact in the considered areas, and may not be flexible enough to provide adequate protection against the increased intensity and

frequency of extreme flood events (Brink et al., 2016). Nature-based Solutions (NBSs) often provide a resilient and sustainable approach that incorporates co-benefits (e.g., recreation, habitat creation, carbon sequestration, air pollution reduction) to flood risk reduction, but still might not be enough to completely mitigate extreme hydro-meteorological events (Kabisch et al., 2016). Therefore, NBSs are often connected to grey infrastructure in so-called 'hybrid measures'. This can provide an adaptive and resilient strategy to cope with climate change uncertainties, incorporate co-benefits that enhance environmental sustainability and biodiversity, and improve socio-economic activities and water security (Alves et al., 2020; Dorst et al., 2019; Vojinovic et al., 2021; Watkin et al., 2019). Their functioning can be further improved by the use of online modelling, monitoring and system

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control technologies which together deliver a 'Smart Solution' with efficient performance, reduced maintenance costs, and faster decision making. Furthermore, when placed within the wider context of data and model integration, i.e. *Digital Twins*, such solutions offer improved opportunities in the management and operation of water systems (Fig. 1). Nowadays, digital twins are increasingly becoming valuable to water professionals (Karmous-Edwards et al., 2019). Digital twins combine models with heterogeneous data sources to interpret and predict the behaviour of a real system, and technologies such as Telemetry, Supervisory Control And Data Acquisition (SCADA) systems and Internet of Things (IoT) are invaluable for this purpose. In the case of NBS, the application of such technologies can deliver ecosystem services more efficiently and help respond to climate change effects (Arts et al., 2015; Goddard et al., 2021; Gulsrud et al., 2018; Li and Nassauer, 2021; Nigro et al., 2014; Nitoslawski et al., 2019).

The so-called Smart technologies have been widely studied and applied in water systems. For example, Li and Nassauer (2021) studied technology in support of nature-based solutions for urban nature; Vanrolleghem et al. (2005) and Zacharof et al. (2004) studied modelling real-time control (RTC) for urban wastewater systems; Riaño-Briceño et al. (2016) developed an open-source toolbox for designing RTC of urban drainage systems; Löwe et al. (2016) evaluated how the consideration of runoff forecast uncertainty influences the efficiency of the RTC scheme, Li (2020) proposed a data-driven improved real-time control optimisation-simulation tool to optimize fuzzy control efficiency and to reduce downstream flooding volume at a real-world urban drainage systems and Sadler et al. (2020) explored RTC of stormwater systems for mitigating flood risk due to sea level rise.

Although there are many studies on smart technologies for water systems, none of the above studies focus on the potential benefit of implementing RTC for improving the capacity of NBS or hybrid measures to reduce flooding. Therefore, Smart NBSs in this research will focus on the effectiveness of RTC in reducing flooding and increasing the capacity of NBSs.

RTC techniques can be used to automatically control structures in real-time according to pre-established rules and/or weather and hydraulic conditions (Bilodeau et al., 2018). Some of the advantages that RTC can provide include improvements to water storage management, flood prevention, system operation, operational costs, optimisation of the retention time, and system capacity (Marsalek, 2000; Wahlin, 2002). By using RTC for NBS, grey infrastructure such as pumping stations, weirs, sluices, inlets, and outlets are needed to regulate water system issues.

This research investigates the feasibility of upgrading an existing passively-controlled NBS system to a Smart NBS by introducing (active) RTC and eventually developing a Digital Twin for the Rangsit case. To do so, the control is performed through the simplest and most common controllers called the proportional-integral-derivative (PID controllers) (Malaterre, 1995) in a supervisory feedback control scheme. The application is carried out in the irrigation and drainage system of the Rangsit Area in Thailand, in order to reduce flood risk and achieve equitability in water distribution between retention areas. The currently implemented NBS in the area is furrows, which connect the irrigation and drainage systems.

This article is organised as follows. Section 2 introduces the theoretical background for developing RTC. Section 3 provides general information about the case study along with available modelling and data. Section 4 explains the methodology proposed and used in this research to develop RTC and evaluate its performance. Section 5 presents the results of the application, which demonstrate the utility of RTC in terms of flood reduction and equitability in water distribution between retention areas. Section 6 discusses the impact of using RTC. Finally, in section 6, some conclusions are drawn, and suggestions for further research are made.

2. Theoretical background

2.1. Feedback control scheme

A feedback control scheme is a closed loop scheme, which means that any deviation of the system output from the set point in the current control step will be used in the subsequent control step to generate a corrective control action which aims to return the system output back to its desired value.

The advantage of a feedback control scheme is that all kinds of perturbations are indirectly considered, as their effect is included in the determined system output. A feedback control scheme is reactive, which means the control action is only taken when a deviation from the set point happens (Malaterre et al., 1998; Van Overloop, 2006). Fig. 2A shows a general schematisation of a feedback control scheme. The scheme consists of the measuring element (sensor), the comparator, the controller, and the actuator. The comparator is where the desired output (i.e., setpoint or target value for a variable) and the actual output of the controlled process are compared. The resulting output from this component represents the current control system error, indicating the deviation between the actual output and the desired output. Typically, the desired output is entered into the system by a user, while the sensor measures the actual output of the system. The controller is responsible for executing control commands, with the objective of reducing its input (i.e., the system signal) to zero. The actuator is used to physically influence the process to receive the controller's control signal. Through mechanisms such as adjusting valves or gates, the actuator acts upon the
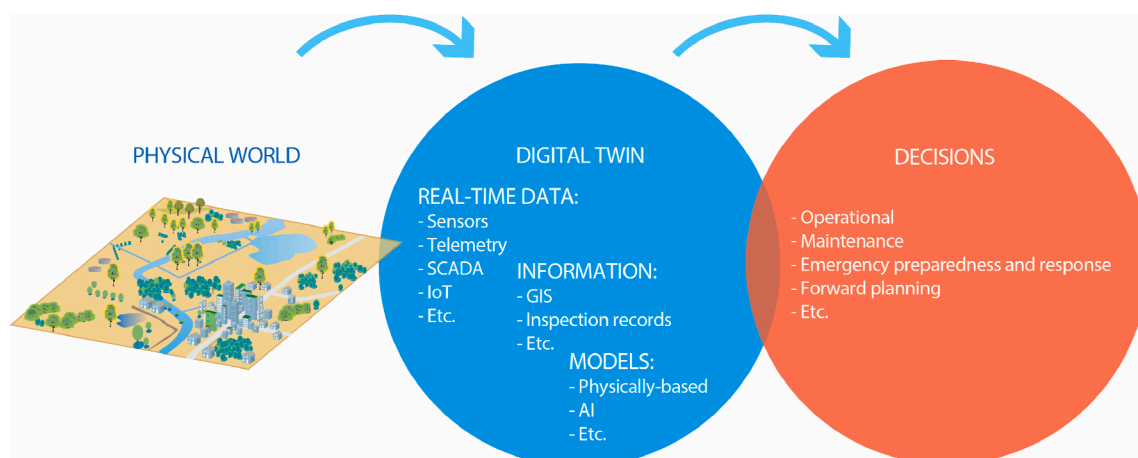

Fig. 1. Smart technologies and Digital Twins in the management and operation of water systems.
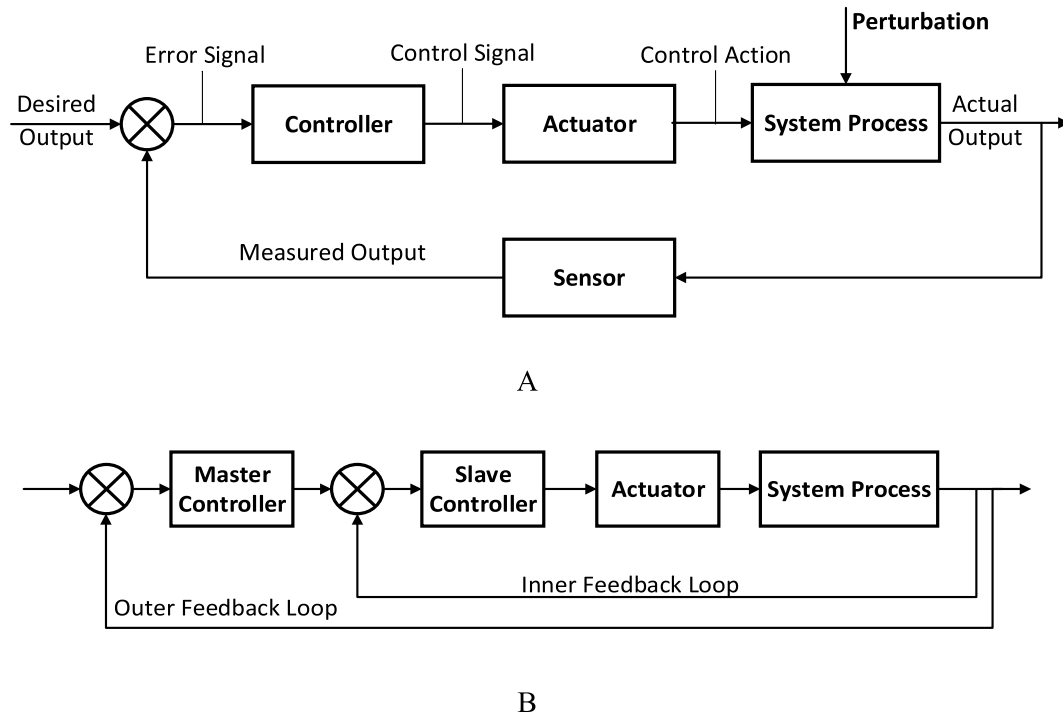
Fig. 2. Schematisation of Feedback Control Scheme (A) and Feedback Control with master and slave controller (B).

system to bring the actual output closer to the desired output. The system's response is continuously monitored through the sensor, and the feedback loop enables iterative control adjustments. The actuator's role is crucial in effectively implementing the control signals and driving the system towards producing the desired output.

However, in addition to the controllers of the gates, Schuurmans et al. (1999) suggested that a master controller and a slave controller can be effectively applied to the control of water levels in irrigation and drainage canals. A master controller is used to determine the additional discharge that should be directed to the canals during flood situations. The role of a master controller is to determine the setpoint of the slave controller. So, the master controller is not directly connected to the actuator. Fig. 2B shows the concept of a Schematisation feedback control with master and slave controllers.

2.2. Proportional-integral-differential controller (PID controller)

The role of the PID controller is to preserve desired values of the controlled variables using three tuning parameters, which are P: proportional, I: integral, and D: derivative. The proportional gain (P) is used to determine the value of the control action in proportion to the difference between the measured control variable and its desired setpoint. Using the proportional gain (P) alone would lead to steady-state offset errors, so the integral (I) parameter is used to eliminate this error. The derivative (D) parameter is used to reduce overshooting and oscillations (Wahlin, 2002). The PID controller was developed in 1936 and is the controller that is most often applied in control engineering. Equation (1) shows the mathematical formulation of the PID controller action.

$$u(t) = K_p e(t) + K_i \int_0^t e(T)dT + K_d \frac{de(t)}{dt} \tag{1}$$

where, $u(t)$: the control action, $e(t)$: the deviation from the setpoint ($e(t) = y_{ref} - y(t)$). K_p, K_i, K_d: the proportional, integral, and derivative gain parameters, respectively.

The behaviour and response of the PID controller can be adjusted by tuning the K_p, K_i, and K_d parameters in order to stabilise the control system. The control system sensitivity mainly depends on the

proportional gain, so increasing K_p will make the system more oscillatory and less stable. On the other hand, increasing the K_i parameter will increase the amplitude of the oscillations. For the Derivative term, increasing the K_d parameter will reduce the time of dampening out and make the response faster, but it can also amplify the noise (Romero et al., 2012).

2.3. Controlled variables and control actions

There are two types of open channel controls that are based on the position of the control gate in relation to the controlled variable: upstream control and downstream control. In upstream control, the control structure is located in the downstream end of the canal reach and is used to control the flow upstream of it. Here, the control variable is usually the upstream water level. For the downstream control, the control structure is located at the upstream end of the canal reach and is used to control the flow downstream of it. Here, the control variable can be the water level downstream the gate or the discharge passing through the gate. In both control types, the control action taken to bring the controlled variables to their setpoints can be changing the gate level or the gate width, but usually, the gate level is adjusted. Fig. 3 shows a sketch of an underflow gate with its possible controlled variables.

3. Description of the case study and available data

The case study area is the irrigation and drainage system of Rangsit Area, which is located in Pathum Thani Province, the eastern part of the Chao Phraya valley, central Thailand. The system consists of Raphiphat canal (i.e., main Raphiphat canal, Western Raphiphat canal, Southern Raphiphat, Hokwa-sai-bon canals), Rangsit canal, 12 main irrigation canals or so-called "Klongs" in Thai (K1 to K12), Klong control structures, and farms and furrows as shown in Fig. 4.

Klongs are used for both irrigation and drainage. Klongs are fed by water from the Western Raphiphat Canal and drained into the Rangsit Canal. At the beginning of each Klong a gate is used to control the discharge, and at the end of each Klong another gate is used to control the water level. Klongs also supply water to the farms, where water is
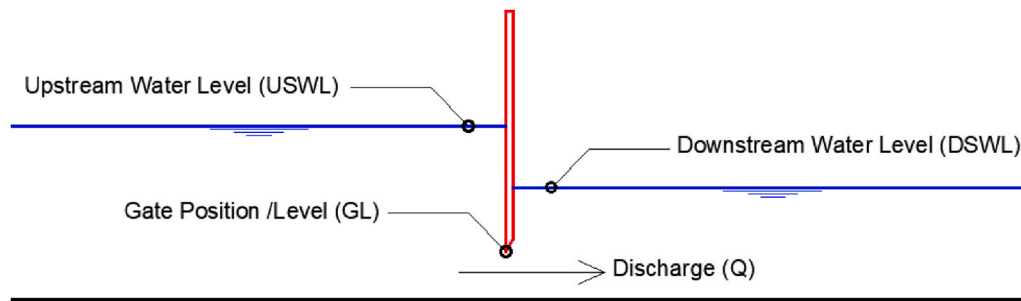
Fig. 3. Sketch of an underflow gate.

stored in furrows.

Furrows are used as a NBS to store part of the diverted excess flood water and prevent overtopping of the irrigation and drainage system canals in Rangsit Area (Ditthabumrung and Weesakul, 2019; Mashiyi, 2021; Watkin et al., 2019). Although these furrows occupy 20–25% of the palm oil farms area, the water availability they provide throughout the year means that production has doubled (Watkin et al., 2019). According to the Hydro Informatics Institute (HII) in Thailand, a field with furrows can store up to 1.875 m^3 of water per m^2 of the farm area during floods. Under normal conditions, 0.4375 m^3 per m^2 of the farm area should be preserved in the furrows in order to have enough water for farm production.

Previous studies show the potential of the furrows in the Rangsit area in reducing flood risk (Ditthabumrung and Weesakul, 2019; Mashiyi, 2021), in addition to providing environmental and social co-benefits (Watkin et al., 2019). As Klong 7 and 8 have the most extensive storage areas (2.58 km^2 and 8.41 km^2), this research focuses on applying RTC to these canals (See Fig. 4).

Currently, this system is operated manually by the Royal Irrigation Department (RID) to divert the excess flood water of the Pasak River to the Gulf of Thailand and to supply and distribute water for agriculture in the area. For example, in October 2016, flood water was diverted into the Raphiphat Canal as part of the pre-established flood emergency procedure by the RID. This emergency operation was to prevent the flood peak wave from the Pasak River coinciding with the flood peak wave from the Chao Phraya River and causing flood downstream at Ayutthaya (a UNESCO World Heritage site) and the Bangkok Metropolitan Region.

A MIKE 11 hydrodynamic model is available from the study of Ditthabumrung and Weesakul (2019). This model was built for modelling the irrigation and drainage system of Rangsit Area and it has been calibrated and validated. The model includes the irrigation network layout, the Klongs' cross sections, information on the Klongs' gates, as well as boundary condition discharges and water levels of the main regulators. The MIKE 11 model layout of the Rangsit Irrigation and Drainage System is shown in Fig. 4.

4. Methods

4.1. Hydro-dynamic model

The MIKE 11 model developed and calibrated by Ditthabumrung and Weesakul (2019) was converted to MIKE Hydro River as it provides more options for simulating control rules of hydraulic structures.

To simulate the NBS furrows, the same approach that had been used by Ditthabumrung and Weesakul (2019), Watkin et al. (2019), and Mashiyi (2021) was followed. Since multiple furrows are connected to one Klong, the approach is to sum up the spatially distributed NBS furrows into schematised retention areas with the equivalent total capacity for each Klong (Fig. 5). The RTC system in this research is applied up to the level of Klongs, not to the level of fields. Therefore, the approximation of NBS furrows into one retention area of each Klong is

also applicable. The simplification of modelling each furrow connected to the klongs as one retention area is considered acceptable because in the proposed control system, the gates connecting furrows to a Klong would only have two states: all open or all closed.

To simulate the NBS furrows of Klong 7 and Klong 8, the farms containing furrows related to these Klongs were calculated. However, all the furrows cannot be included directly in the MIKE Hydro River model as it will be too complex and cause instabilities. Therefore, schematised retentions are used as NBS furrows to store water. Two schematised retention areas (A7, A8) are calculated from the digitised farms. The areas of A7 and A8 are 2.58 km^2 and 8.41 km^{2,} respectively. A7 and A8 retention areas were connected to Klong 7 and Klong 8 using aggregated canals (Fig. 5). These aggregated canals are used to add an underflow gate to regulate the flow from Klong 7 and Klong 8 to the retention areas.

To add retention areas (A7 and A8) to the MIKE Hydro River Model, there are three options available, namely: a side structure with storage, an elevation-area relationship, and adding a storage area to the downstream cross-section. However, with the first option no observation points can be used in the model to monitor water storage or water level in the retention area. The last option is to add the storage area to the downstream cross-section of each aggregated canal by setting a closed boundary at the end of these canals. This, as well as the elevation-area relationship, are the two best are the best retention area methods, as suggested by Ditthabumrung and Weesakul (2019). Adding a storage area to the downstream cross-section method is selected for this research as it is the most suitable method to simulate retention areas based on the analysis in Appendix 1.

4.2. Feedback control strategy

4.2.1. Proposed control structures and monitoring network

The proposed control strategy would necessitate implementation of telemetry and SCADA technologies, which could then be coupled with the model and used for the RTC operation of NBS. The structures that will be controlled are the intake gates of Klong 7 and Klong 8 (G12 and G14), the irrigation gates of the aggregated retention areas A7 and A8 (G22 and G23), and the downstream gates of Klong 7 and Klong 8 (G13, and G15). A direct feedback control scheme (Fig. 2A) is used with an "Open/Close" controllers for G22 and G23, and PID controllers for G13 and G15. While for G12 and G14 a supervisory feedback control scheme (Fig. 2B) is used with a master controller to determine the discharge setpoint for both gates, and a slave PID controller for each gate to achieve its setpoint. In addition to the existing water level gauging station on Western Raphiphat Canal, the proposed monitoring network would require discharge measurement sensors for G12 and G14, water level sensors upstream and downstream G13 and G15, and water level sensors upstream and Downstream G22 and G23 (Fig. 5).

The operational rules for G12 and G14 are based on discharge control and distribution between Klong 7 and Klong 8 depending on the water level data at the Western Raphiphat station and in the retention areas (A7 and A8). So, the controlled variables of G12 and G14 are the discharges passing through them. For G13 and G15, the objective is to
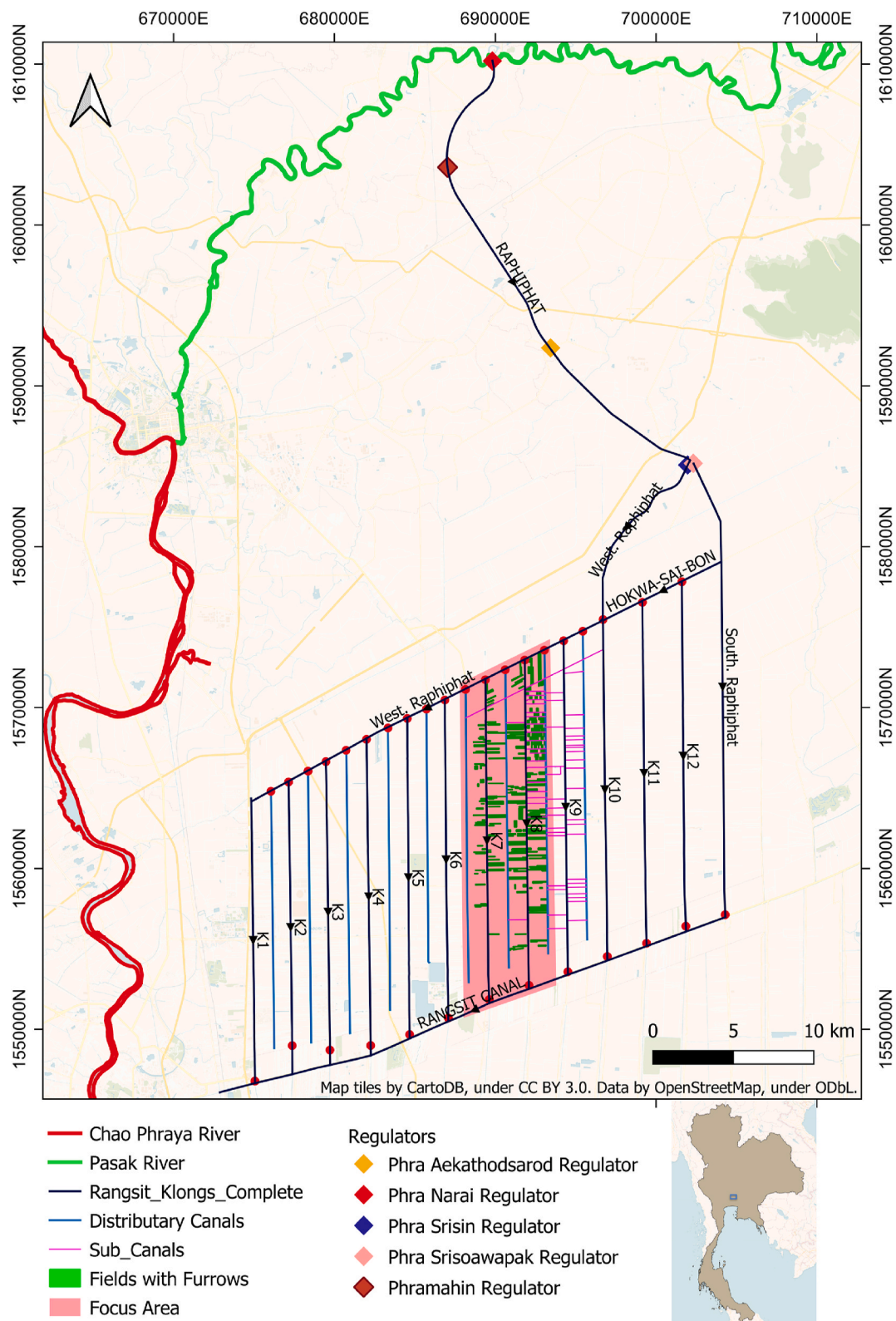
Fig. 4. Rangsit irrigation and drainage system components and layout.

stabilise the water level in Klong 7 and Klong 8, as well as to prevent overtopping, so their controlled variables are the water levels upstream of each of them. For G22 and G23, the objective is to (as fast as possible) achieve the minimum water demand during normal conditions, and to drain excess water to the retention areas in case of floods. Therefore, these gates have only two states: fully open or fully closed.

4.2.2. Feedback control strategy development

A feedback control strategy is developed to investigate the feasibility of applying an RTC system to improve the operation and fulfil its irrigation and drainage goals, considering the capacity limitations of the NBS furrows. The flowchart of the developed feedback strategy is presented in Fig. 6. The objective of the developed strategy can be

Fig. 5. Layout of Klongs 7 and 8 with the digitised farms including furrows (A) and Layout of Klongs 7 and 8 with the aggregated retention areas simulated in the model (B).

Fig. 6. Flowchart of the Proposed Control Strategy with the Triggers and Setpoints of the Control Structures, WL_{WRC} is the water level at Western Raphiphat Canal station; $USWL_{G13}$ and $USWL_{G15}$ are the water levels upstream G13 and G15; Q_{G12} and Q_{G14} are the discharges passing through G12 and G14; WD_{A7} and WD_{A8} are the water depths in the retention areas A7 and A8; Q_f is the total discharge to be distributed between Klong 7 and Klong 8 during flood; Q_s is the scheduled discharge to be distributed between Klong 7 and Klong 8 during normal situation; Q_m is the discharge that should be diverted from the Western Raphiphat Canal during flood to reduce water level and is calculated by the master controller; Δt_c is the control time step; P is the percentage used for the gradual change of the setpoints within the transition zone.

summarised as follows: 1) reduce flooding by reducing the water level in the Western Raphiphat Canal below a threshold (2.3 m + MSL); 2) achieve equitability in water distribution between the retention areas; 3) maintain minimum water storage in the furrows; 4) prevent overtopping

in Klong 7 and Klong 8.

The first feedback control strategy is to reduce flooding. The maximum water level threshold at the Western Raphiphat Canal station is 2.3 +MSL, based on the observed level during the 2016 flood. So, in

this study, the flood situation is defined when the water level at the Western Raphiphat Station exceeds 2.3 +MSL. During flood situations, the proposed action in the developed strategy is to increase the discharge passing through G12 and G14 and distribute it with equity according to the available capacity of the retention areas related to each Klong.

The second objective of the strategy is in relation to water distribution. The discharge distribution factors are related to the deficit volumes of the retention areas and need to be calculated. The factors are developed for two situations; no flooding and flooding. For the no flooding situation, the total discharge supply (Q_s) for both Klongs is assumed to be the same as total discharge as without control, while the way it is distributed depends on the water volumes in the retention areas (A7 and A8). The distribution factors for the discharge between Klong 7 and Klong 8 (R7$_{nf}$ and R8$_{nf}$) in the no flood situation are calculated as per Equation (2) and Equation (3). In the case of flooding situation, a master controller is used to determine the additional discharge that should be abstracted from the Western Raphiphat Canal and directed to Klong 7 and 8, in order to keep the water level below the flood threshold. The distribution factor used to distribute discharge between Klong 7, and Klong 8 are R7$_f$ and R8$_f$ (Equation (4) and Equation (5))

$$\mathbf{R7_{nf}} = \frac{(\mathbf{WD_{min} - WD_{A7}}) \times \mathbf{A7_{area}}}{[((\mathbf{WD_{min} - WD_{A7}}) \times \mathbf{A7_{area}}) + ((\mathbf{WD_{min} - WD_{A8}}) \times \mathbf{A8_{area}})]} \quad (2)$$

$$\mathbf{R8_{nf}} = \frac{(\mathbf{WD_{min} - WD_{A8}}) \times \mathbf{A8_{area}}}{[((\mathbf{WD_{min} - WD_{A7}}) \times \mathbf{A7_{area}}) + ((\mathbf{WD_{min} - WD_{A8}}) \times \mathbf{A8_{area}})]} \quad (3)$$

$$\mathbf{R7_f} = \frac{(\mathbf{WD_{max} - WD_{A7}}) \times \mathbf{A7_{area}}}{[((\mathbf{WD_{max} - WD_{A7}}) \times \mathbf{A7_{area}}) + ((\mathbf{WD_{max} - WD_{A8}}) \times \mathbf{A8_{area}})]} \quad (4)$$

$$\mathbf{R8_f} = \frac{(\mathbf{WD_{max} - WD_{A8}}) \times \mathbf{A8_{area}}}{[((\mathbf{WD_{max} - WD_{A7}}) \times \mathbf{A7_{area}}) + ((\mathbf{WD_{max} - WD_{A8}}) \times \mathbf{A8_{area}})]} \quad (5)$$

where R7$_{nf}$ and R8$_{nf}$ are the distribution factors of the total discharge in Klong 7 and Klong 8 in case of no flood situation; R7$_f$ and R8$_f$ are the distribution factors of the total discharge in Klong 7 and Klong 8 during the flood situation; WD$_{min}$ is the minimum water depth (0.45 m) that should be kept in the retention areas (A7 and A8); WD$_{max}$ is the max water depth (1.88 m) in the retention areas; WD$_{A7}$ and WD$_{A8}$ are the water depths in the retention areas (A7 and A8); A7$_{area}$ and A8$_{area}$ are the areas of the retention areas A7 and A8.

Another objective is to maintain minimum water storage in the furrows. The minimum water storage needed in the furrows is 0.45 m^3 per m^2 of the furrow fields, and its maximum capacity is 1.88 m^3 per m^2. Thus, the minimum water depth to be achieved is 0.45 m, and the maximum water depth that can be utilized (but not exceeded) during floods is 1.88 m for both retention areas.

The final objective of the strategy is to prevent overtopping in Klong 7 and Klong 8. Two water levels setpoint are defined for each downstream gate on Klong 7 and Klong 8. The first one is used during the flood situation to utilise the whole capacity of the Klongs to store water and make the process of draining water to the retention areas faster, but without overtopping the banks of the two klongs. The second setpoint is less than the first one and is used during the normal situation. For the downstream gates of Klong 7 (G13) and Klong 8, (G15), there are two different setpoints for each gate, which are used during the no flood situation and the flood situation. These setpoints are 1.7, and 2.0 +MSL for G13; and 1.5 and 1.8 m + MSL for G15. These thresholds were selected according to the bank's levels of Klong 7 and Klong 8.

The developed strategy is based on local controllers that regulate variables close to the control structures of Klong 7 and Klong 8 (i.e., G12 and G14 for controlling discharge at the upstream; and G13 and G15 for controlling water levels at the downstream). However, the setpoints of the controlled variables are dependent on the information coming from remote locations (water level at the Western Raphiphat Station, and the

water levels in the NBS retention areas). To avoid the sudden changes of the setpoints when switching between the flood situation and the normal situation, a transition zone is used in the control strategy. The transition zone is the situation when the water level at the Western Raphiphat Canal station is between 2.0 and 2.3 +MSL. For this zone, the setpoints are not constants but are gradually varied based on the measured water level at the Western Raphiphat Canal station.

4.3. Tuning of PID controllers parameters

The tuning process is to determine the best values of the PID controllers' parameters in order to have a stable control response while achieving the required setpoints with minimum deviations. In this study, we have investigated four different methods by using the data of the October 2016 event with constant setpoints. The most suitable method is used in this research. The results of the best performing method are given below, while the results of other methods can be seen in Supplementary 1.

Based on the analysis of tuning PID controllers' parameters, two different methods were employed for this research. A combined simulation was conducted to examine the disturbance effect between gates in the same canal reach. The first method uses the MIKE Hydro River default values for Gate 13 and 15 as the controller achieved the upstream water levels setpoints. The second method is the individual tuning method for G12 and G14. The set points used in the tuning process are shown in Table 1.

Individual tuning for G12 and G14 is used to find the optimal values of the PID parameters for each gate individually using the Autocal (Auto Calibration) optimisation tool (see Table 2). AutoCal tool from DHI is a general-purpose tool that is included in MIKE ZERO package. The Shuffled Complex Evolution (SCE) optimisation algorithm was used for the optimisation process using the preferable values of its parameters (DHI, 2017).

4.4. Operational scenarios and RTC performance evaluation

The developed strategy was evaluated based on the control objectives defined in Section 4.2.2. The criteria used to evaluate the performance of RTC are: 1) reduce flooding by reducing the water level in the Western Raphiphat Canal; 2) increasing water that will be stored and achieving the minimum water storage in the retention areas; 3) achieving equitability in water distribution between the retention areas; and 4) preventing overtopping in Klong 7 and Klong 8.

The evaluation is based on comparing two scenarios: baseline system (without RTC system) and with RTC system. The baseline system is based on the current operating rule in the study area, which is without an RTC system. The 'With RTC system' scenario assumes the feedback control rules and PID controllers from the developed strategy are implemented. For evaluating flood reduction, an extra storage with the area of 27.2 ha is also included in the evaluation as the stakeholders in the area are planning to implement this retention area.

The strategy is evaluated for two events. The normal flood event is based on the flood event of 2016. The extreme flood event is based on the flood event of 2011.

Table 1
Setpoints used in the tuning process.

Gate	Controlled Variable	Setpoint
G12	Discharge Passing Through the Gate	3.0 (m^3/sec)
G13	Upstream Water Level	1.7 m (+MSL)
G14	Discharge Passing Through the Gate	5.0 (m^3/sec)
G15	Upstream Water Level	1.5 m (+MSL)

Table 2
MIKE Hydro River PID parameters values (used for G13 and G15), and the PID parameters values resulted from the individual tuning (used for G12 and G14).

Gate	T_i (hrs)	T_d (hrs)	K_p (Unitless)	α_1	α_2	α_3
G12 and G14	0.1	0.1	0.01	1.0	1.0	1.0
G13 and G15	0.083333	0.000222	−1.0	1.0	1.0	1.0

5. Results

5.1. PID parameters tuning

The tuning of PID parameters for controllers G12, G13, G14, and G15 was performed. The controlled discharges of G12 and G14 using the PID parameters values resulted from the individual tuning method, and the controlled upstream water levels of G13 and G15 using the MIKE Hydro River default values of the PID parameters are presented in Fig. 7.

With the PID parameters from the individual tuning method, the controller was able to achieve the discharge setpoints for G12 and G14, as shown in Fig. 7A. Similarly, the upstream water level setpoints of G13 and G15 were achieved by the controller for the default values of the PID parameters as shown in Fig. 7B. However, for G13, the upstream water level could not be brought to the setpoint within periods from 2nd to 5th October. This is not because of the controller performance, as the gate was totally closed (Fig. 7D), but because of the incoming zero discharge from G12 (Fig. 7A).

Using suitable values of the PID parameters for each gate did not only improve the stability of the gate itself and its controlled variable, but also the stability of the other gate in the same canal. Fig. 7A and 7B show the stability of the controllers of the upstream gates G12 and G14. This also eliminated the oscillations and improved the stability of the controlled water levels of the downstream gates G13 and G15 (Fig. 7B and D) compared to other methods, which can be seen in Supplementary 1.

Therefore, the stability of the controller of each gate is not only dependent on the PID parameters for the controllers, but also the stability of the other gates located in the same reach, especially in a canal network with a flat topography like in the Rangsit Area.

5.2. Evaluating RTC performance

5.2.1. Flood reduction in the Western Raphiphat Canal

This section shows the flood reduction results in the Western Raphiphat Canal with and without RTC and with extra storage scenarios for a normal flood event (Fig. 8A) and an extreme flood event (Fig. 8B). For the normal flood event, the RTC system was able to reduce the water level at the Western Raphiphat Canal Station by about 0.25 m compared to the system without RTC and with extra storage (Fig. 8A). However, it is still about 0.05 m water level above the flood threshold.

From Fig. 8B, it can be seen that the proposed control system was not able to keep the water level at the Western Raphiphat Canal Station around the flood threshold during the extreme flood event. However, compared to the options without RTC and extra storage, the water level was reduced by about 0.5 m. Thus, RTC may be able to help to reduce
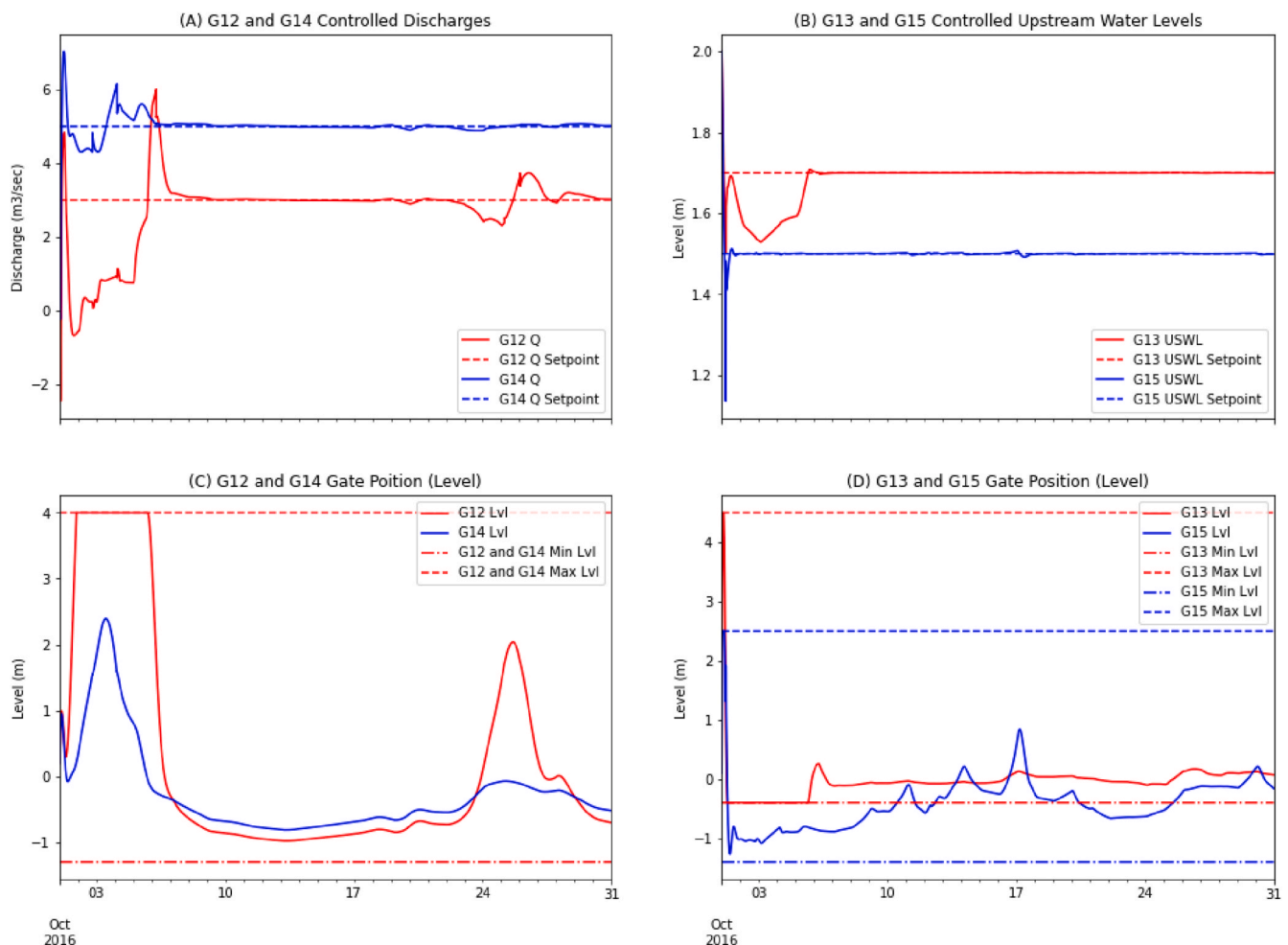

Fig. 7. Results of the controlled discharges of G12 and G14 (A) with their gate levels (C) using PID parameters from the individual tuning method; and the controlled upstream water levels of G13, and G15 (B) with their gate levels (D) using PID parameters from the MIKE Hydro River default.
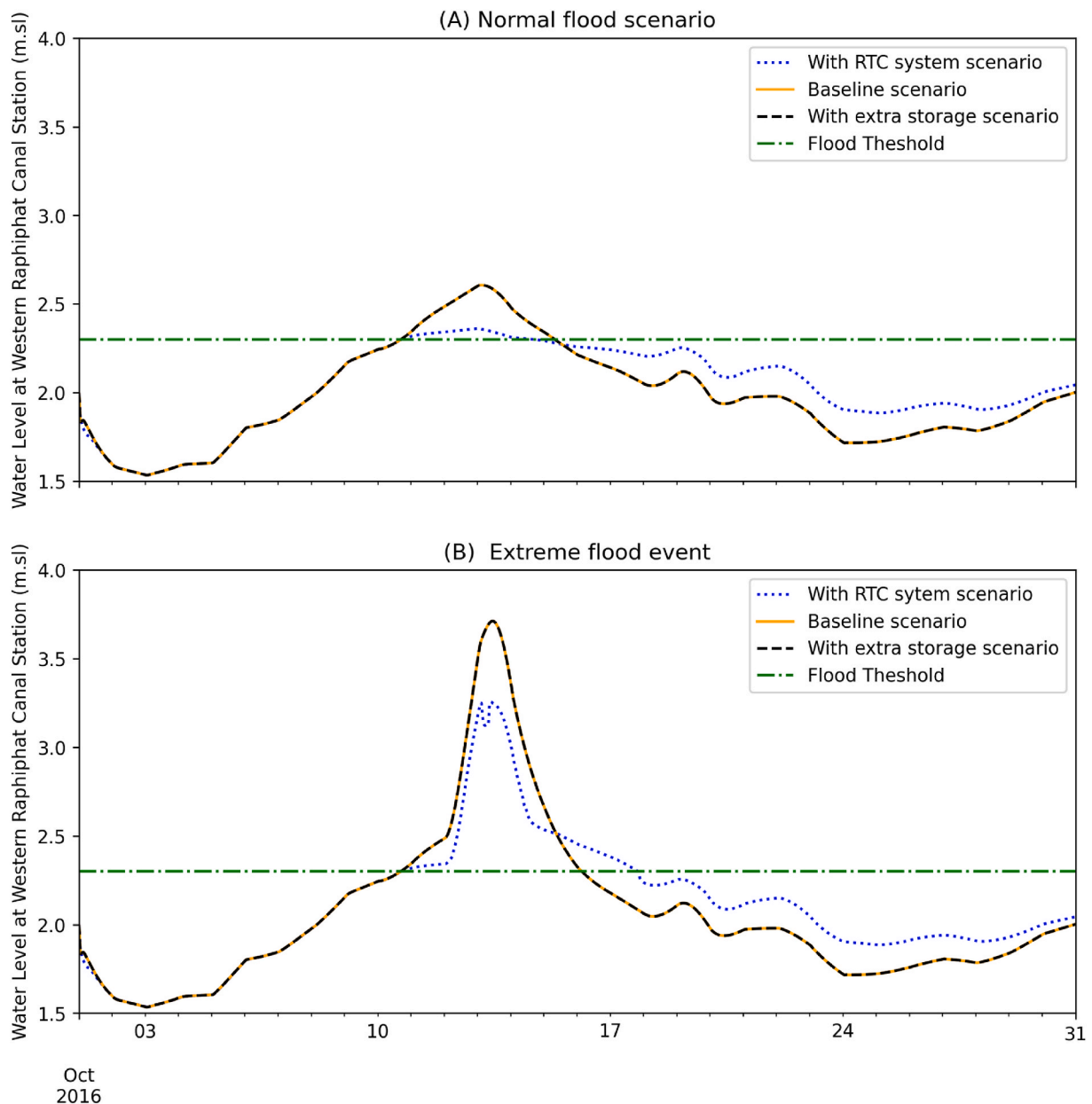
Fig. 8. Water level in the Western Raphiphat Canal of baseline, with RTC system and with extra storage scenarios for normal flood event (A) and extreme flood event (B).

the impact of flooding at the downstream.

We can also see that the water level increased after the flood peak in the case with RTC for both scenarios. This is due to closing the upstream gates G12 and G14 in the normal situation as soon as the required minimum water volumes had been achieved, as per the proposed strategy.

From both events, the results for the baseline scenario and the extra storage scenario have the same water level. The reason for that is the extra storage that stakeholders would like to implement is very small compared the amount of water from flooding.

5.2.2. Water storage in the retention areas

The results of water volume in retention areas with and without the RTC system for flood and extreme flood scenarios in Klong 7 and Klong 8 are shown in Fig. 9A and B, respectively. From the results, it can be seen that the minimum water volumes were achieved for both retention areas during the normal flood scenario and the extreme flood scenario. For the

system without RTC, the retention areas were only opened by the local framers starting from the 13th October (close to the flood peak), while in the system with RTC, the water begins to fill in the retention at the beginning of the events. As a result, the RTC scenario (green dash-dotted and blue dotted line) can store more water in the retentions during the events compared to without the RTC strategy (orange and red lines).

5.2.3. Equitability in water distribution

Regarding water distribution, the main criteria applied in this research was to achieve equitability. The water discharge is distributed to Klong 7 and Klong 8 in no flood situation (water level at Western Raphiphat Canal <2.3 m) according to the relative water volumes required to achieve the required minimum water depth in the retention areas A7 and A8. While during flood situations (water level at Western Raphiphat Canal >2.3 m) the water is distributed according to the relative available volumes until the maximum capacity of A7 and A8. Applying the proposed strategy, equitability was achieved as shown in
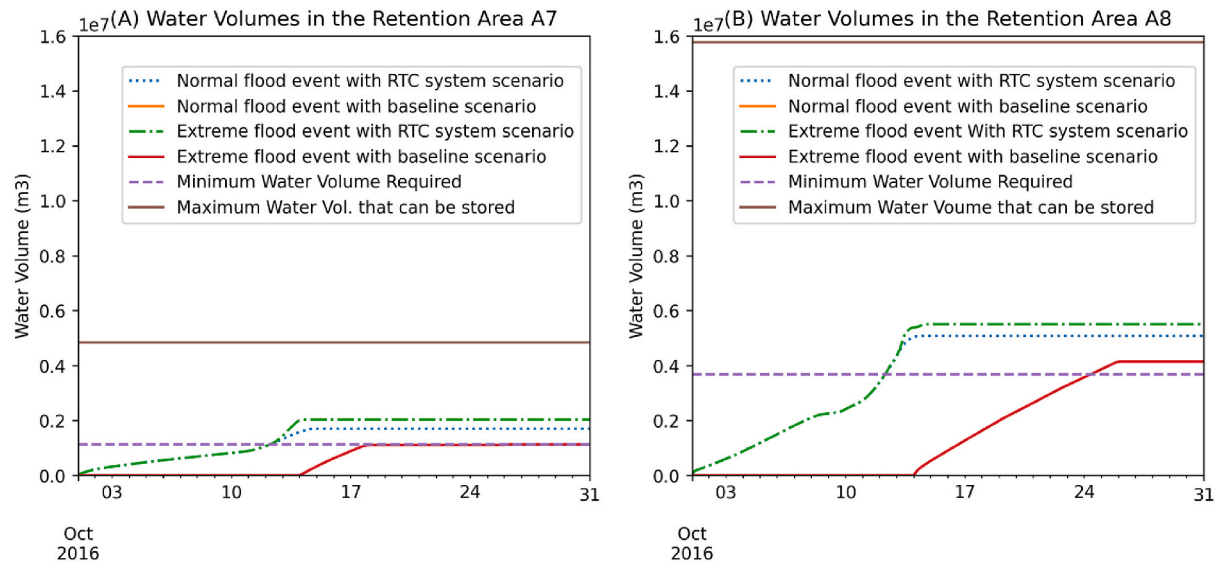
Fig. 9. Water volume of flood and extreme flood events with RTC system and baseline scenarios in the retention area A7 (A) and A8 (B).
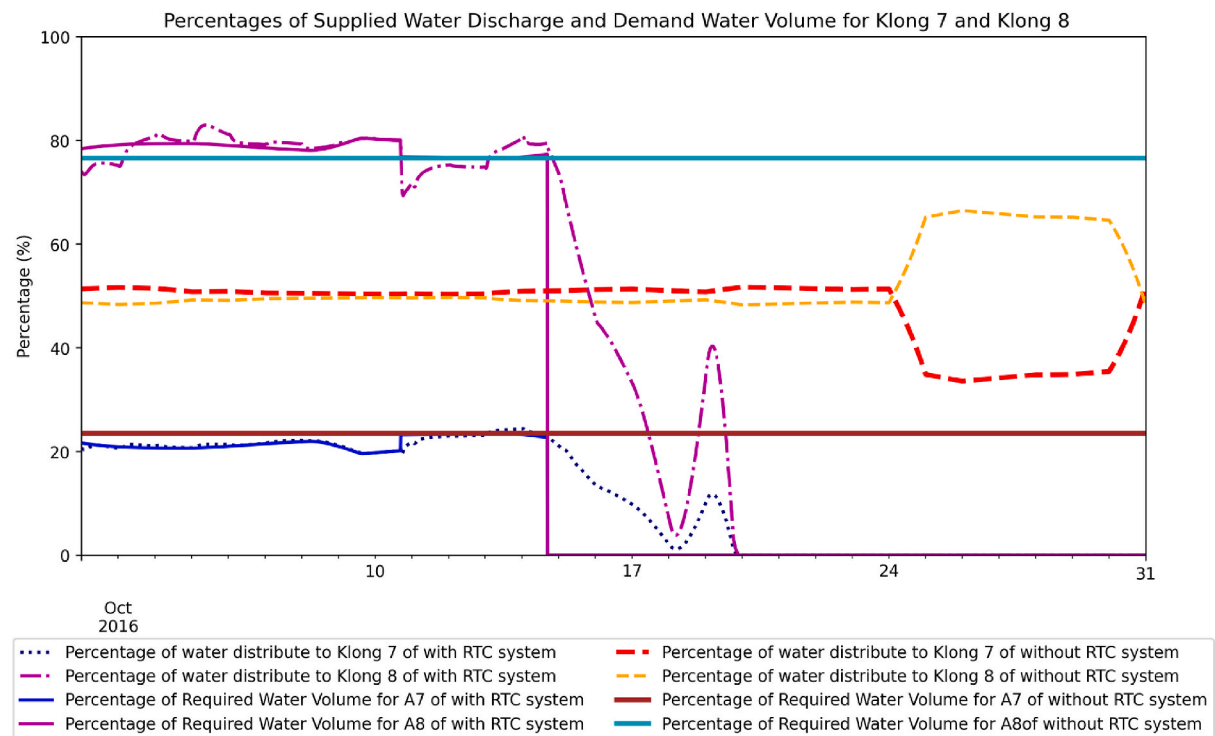

Fig. 10. Percentage of supplied water to Klong 7 and Klong 8 and the percentage of required water volumes in the retention areas A7 and A8 for the normal flood scenario.

Fig. 10. The percentages of the diverted water discharged to Klong 7 and Kong 8 are very similar to the percentages of the required water volumes for the retention area A7 and A8 based on the relative water needs. However, deviations between the applied water discharges percentage and the required water volumes percentage can be seen between the 14th and 19th October. This is due to the smooth transition rules that were used for the setpoints of the controlled gates, in order to improve the control system stability.

For the without RTC system, even though water distributes to Klong 7 and Klong8 equally by around 50 percent, it does not meet the required water volume for both Klongs as Klong 8 has an irrigation area three times larger than Klong 7.

5.2.4. Preventing overtopping

Fig. 11 shows the result of overtopping of the system for the scenarios with and without RTC for both normal flood and extreme flood scenarios in Klong 7 (A) and Klong 8 (B). From the results, it can be seen that there was no overtopping of either klong during both scenarios, except at the end of Klong 8 at the end of the extreme flood (Fig. 11B). This is because the maximum water level in the scenario with the RTC system is higher than without the RTC system, due to the increased discharges directed to both klongs during the flood.
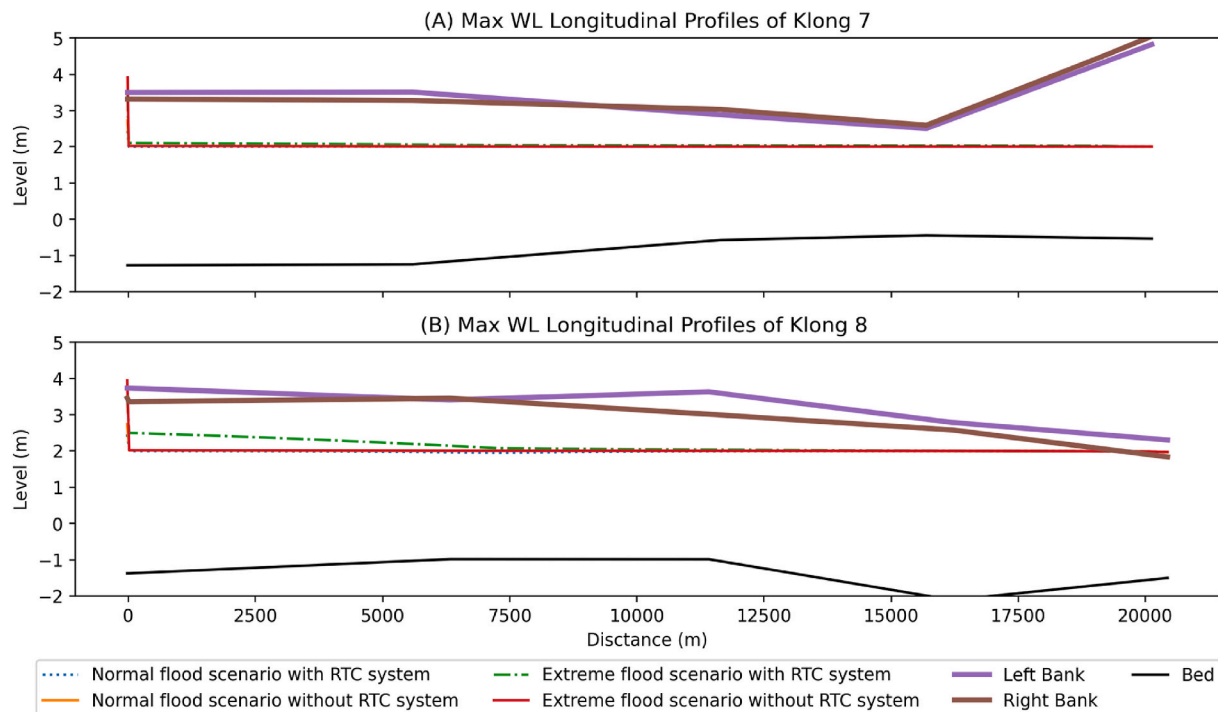
Fig. 11. Maximum water level of RTC system and without RTC for the normal food and extreme flood scenarios on longitudinal profiles in Klong 7 (A) and in Klong 8 on (B).

6. Discussion

This study focused on the implementation of Smart NBSs by using RTC to control and operate water in the irrigation and drainage system of the Rangsit Area, Thailand. A classical feedback control is used in this study. The developed strategy for the irrigation and drainage system of the Rangsit area shows the potential of PID feedback control for achieving the control objectives with stable performance without oscillations during flood events with discharge similar to the 2016 flood. There are also some general advantages of the feedback PID control, such as the simplicity and easy applicability. However, to apply the feedback control, it is important to tune PID control parameters to define the most suitable parameter for the case study. This is the main disadvantage, as it is difficult to tune PID parameters that are suitable for different flow regimes. Another disadvantage of a completely automated system is that instabilities in one gate can lead to undesirable control of another downstream.

In RTC evaluation scenarios, four control objectives were considered which are: 1) reduce flood risk by reducing the water level in the Western Raphiphat Canal below a threshold (2.3 m + MSL); 2) achieve equitability in water distribution between the retention areas; 3) maintain minimum water storage in the retention areas; and 4) prevent overtopping in Klong 7 and Klong 8. From the above results, it can be seen that the RTC system can help achieve the minimum required volume and increase the volume in the retentions. Moreover, The RTC system can also be used to automatically operate the system before the flood peak without any overtopping in the Klongs. This can help reduce the flood downstream as the water has been diverted and stored in the retention areas.

However, for extreme flood scenarios, it can be seen that even RTC cannot help to keep the water level at around the flood threshold. This could be because the developed feedback control strategy in this study included only two Klongs, which underestimate the potential of the control system for reducing the water level in the Western Raphiphat canal during the extreme flood scenario. Therefore, future studies may include all the furrows of the other Klongs to investigate the maximum

capacity of the RTC.

As mentioned above, one of the limitations in this study is that NBS furrows cannot be included individually into the hydrodynamic model as it is too complex and causes instabilities. Therefore, the furrow areas have to sum up all the NBS furrow area into schematised retention areas with the same total capacity as the total capacity of the furrows. This approach was also used in Ditthabumrung and Weesakul, (2019), , Watkin et al., (2019), Mashiyi (2021), and Mashiyi et al., (2023). Our future work will proceed in the direction of developing a full Digital Twin for the Rangsit area, in Thailand.

7. Conclusion

Effective water resources operation and control is a crucial task in reducing flood risks and providing water supply. This research has investigated the feasibility and the benefits of using SMART-NBS focusing on RTC to reduce floods and increase water storage of NBS measures for agriculture. The work presented here is part of a wider effort to develop a Digital Twin that combines various data and models to achieve better operational efficiency in the case study area. The case study area is an irrigation and drainage system in Rangsit area, Thailand. The NBS is comprised of furrows which are used to store part of the diverted excess flood water and prevent overtopping of the irrigation and drainage system canals. Currently, this system is operated manually by the Royal Irrigation Department (RID) to divert the excess flood water of the Pasak River to the Gulf of Thailand and to supply and distribute water for agriculture in the area. The control strategy was developed and tested with two operational scenarios; a baseline system (a passive system without RTC) and the system with RTC, for the 2016 and 2011 flood events. The feedback control strategy with PID parameters was used for the RTC scenario. The simulation for controlling rules of hydraulic structures was performed by using MIKE Hydro River.

The results indicate that (i) RTC has potential in improving the operation of the hybrid irrigation and drainage system during flood events; (ii) RTC can help to distribute the water between Klongs and retention equally; and (iii) RTC can help to increase the water storage in

the retention areas, which can be used for agriculture. The methods presented in this study thus represent an important starting point towards Smart-NBSs by means of Real Time Control for flood reduction and water allocation. In future research, we aim to investigate the potential of model predictive control with real-time data for operating the irrigation and drainage system.

Credit author statement

Laddaporn Ruangpan: Conceptualization, Methodology, Writing - Original Draft, Writing - Review & Editing, Visualization; **Mosaab Mahgoub:** Conceptualization, Methodology, Investigation, Visualization, Writing - Review & Editing; **Yared Abayneh Abebeb:** Conceptualization, Methodology, Visualization, Writing - Review & Editing; **Zoran Vojinovic:** Conceptualization, Methodology, Visualization, Writing - Review & Editing, Supervision; **Surajate Boonya-aroonnete:** Conceptualization, Methodology, Writing - Review & Editing, Supervision, Resources**; Arlex Sanchez Torresb:** Conceptualization, Methodology, Writing - Review & Editing, Supervision; **Sutat Weesakule:** Writing - Review & Editing, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118389.

Appendix B. Simulating retention area

The methods for simulating retention area were investigated by comparing the water level increase and inflow discharge in the retention area. The resulted water levels in the retention areas and their inflow discharges using both approaches are shown in Fig. A1.
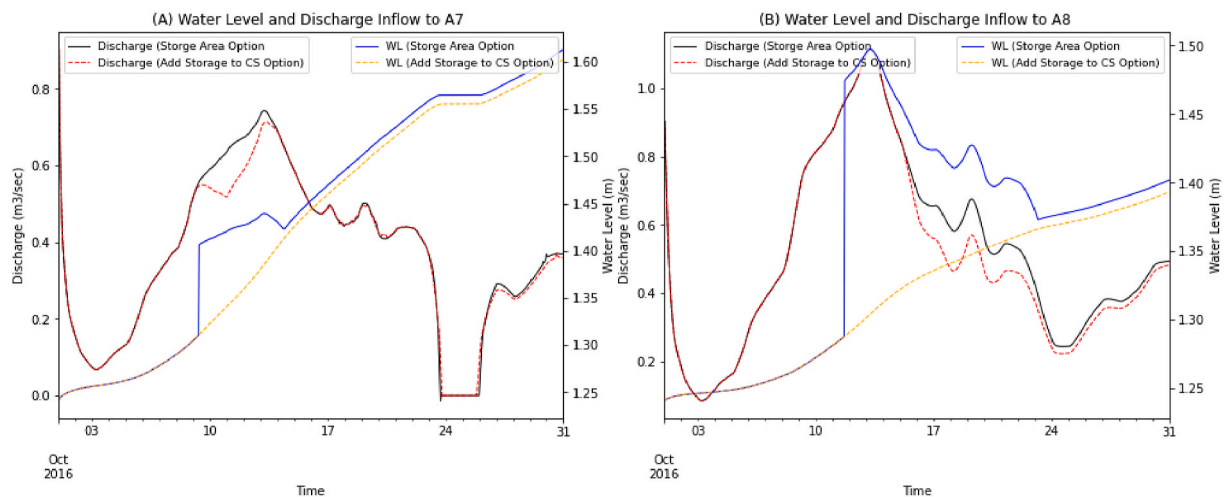

Figure A1 Water Level and Discharge Inflow to A7 (A) and A8 (B) using Storage Area option and the Adding the Area to Cross Section option

In the case of the Storage Area option, it can be observed that there is a sudden increase in the water level of A7 (Fig. A1A) and A8 (Fig. A1B) around the 10th October, even though there is no sudden increase in the inflow discharge to the two retention areas. Similarly, decreases in the water levels can also be noticed in both retention areas, despite no negative discharges causing these water level decreases. The reason could be a numerical error in the exchange between the canal and the storage area as the governing equation for both are different.

For the Add Storage Area to a Cross Section method, the relation between the water level and the discharge is the simple reservoir routing equation in which the rate of change of water stored in the reservoir is equal to the difference between the inflow and outflow discharges. From the results, it can be concluded that the Add the Storage Area to a Cross Section method is more suitable for this research to simulate retention areas.

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