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Paper:

Reservoir Flood Routing Simulation for Dam Safety Management in Thailand

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A reservoir flood routing simulation software with spillway operation rules that are readable and configurable by the spillway operator is developed in this study. The software is part of the Dam Safety Remote Monitoring System used by the Electricity Generating Authority of Thailand. The flood routing simulation is implemented using a storage-indication routing method, which is a hydrologic method. The spillway operation rules are exhibited in a tree-based structure, in which the spillway gate opening is derived from the current reservoir water level (RWL), spillway gate opening, and flood situation if the peak inflow has passed. The simulation results show that the simulated RWL is similar to the RWL data in the dam construction manual. This verifies the accuracy of the reservoir flood routing simulation, which is useful for planning the spillway operation.

Keywords: reservoir flood routing, simulation, disaster prevention, dam safety management

1. Introduction

In Thailand, the Electricity Generating Authority of Thailand (EGAT) [1] aims to provide affordable energy and services to the country to improve the quality of life and strengthen the country's competitiveness. EGAT generates, acquires, transmits, and sells bulk electric energy via its own transmission network, primarily to the Metropolitan Electricity Authority (MEA) and the Provincial Electricity Authority (PEA), which distribute electricity to resident consumers. The generating capacity of EGAT constitutes 37.12% or 15,757.13 MW of its total managed capacity as of 2018. Other sources of electricity include electricity procured from private power plants and neighboring countries. From the total generating capacity of EGAT, renewable energy is an important source accounted for 19.02%, which is mostly from hydropower plants. Along with the hydropower plants, EGAT operates 14 large and important dams across the country, as illustrated in **Fig. 1**. Dams can be categorized into three primary types: two concrete (gray circled), ten embankments (brown circled), and two impervious faced rockfill (blue circled) dams.

As described in the guidelines provided by the International Commission on Large Dams (ICOLD) [2], routine surveillance, periodic dam safety review, dam safety data management, safe water management, emergency preparedness, and dam safety maintenance should be performed to ensure the safe operation of dams. In 2013, EGAT initiated the Dam Safety Remote Monitoring System (DS-RMS), which is a collaborative project among EGAT, the National Electronics and Computer Technology Center (NECTEC), and Geotechnical Engineering Research and Development Center at Kasetsart University (GERD-KU). The main objective was to enhance the dam monitoring system to reassure the downstream public of the dam safety conditions. The most significant improvement over the conventional method is the automatic acquisition of safety-related measurements, which enabled comprehensive information to be remotely obtained in real time and dam safety conditions to be evaluated by an expert system within minutes. An important part of DS-RMS is the reservoir flood routing simulation software that simulates the reservoir water level (RWL) in the dam based on the effects of human-readable and configurable spillway operation rules, water inflow, and outflow. The simulation results allow the dam operator to operate the spillway based on the projected data, which are more informative than the data acquired for each instant. Hence, RWL can be maintained at an optimal level to prevent flood disasters during the flooding season and prevent drought during summer.

For a dam safety management system similar to DS-RMS, Kwater developed Kwater Dam Safety Management System (KDSMS) [3] as an enterprise management system that manages all information pertaining to safety management activities. KDSMS serves three groups of users: field managers, headquarters, and research centers. Instruments such as those to measure

Fig. 1. Large electricity generating dams maintained by EGAT.

seepage, pore pressure, internal deformation, surface displacement, and stress/temperature of concrete were installed at the dams for automated data acquisition based on dam type. KDSMS has been proven to yield rapid and systematic decisions for evaluating dam safety. However, in KDSMS, reservoir flood routing simulation is a separate procedure that is not embedded in the system.

Several software packages for flood routing simulation exist, such as MIKE [4] from Denmark, HEC-Ressim [5] from the United States, and SOBEK [6] from the Netherlands. These software packages are well established in the field and water research activities. However, the reservoir flood routing simulation developed in this study has a customized feature that allows the spillway operator to quickly change the spillway operation rules. Furthermore, the spillway operation rules are preserved in a tree-based structure that is understandable by the user.

As presented in [7], a flow routing model was developed to simulate the 2011 devastating flood in Thailand. The model includes the inundation effect to improve the accuracy of the simulated hydrograph. The results of the study suggest that the flow routing process in the channel alone is insufficient to reproduce realistic river flows during a flood. A flood routing model developed to account for the high leakage rate of a river in China to determine the effect of unsaturated leakage on the total leakage discharge was presented in [8]. Automatic data access was implemented using the MIKE 11 hydrodynamic module for transparent information exchange. In [9], the effect of an entire population of reservoirs in the northeast regions of the United States with different scenarios of climate change was investigated based on a simulated topological river network. The availability of water resources is estimated to decrease despite increased precipitation owing to an increase in evapotranspiration. Consequences of broad-scale dam removal and dam building have been reported. Finally, in [10], the Pasak MIKE model is presented to simulate reservoir flood routing based on spillway operation optimized through a genetic algorithm (GA) with inflow calculated from telemetry and a numerical weather prediction (NWP) model or artificial neural network (ANN). The model provides an optimal spillway operation scenario to mitigate floods and droughts for downstream residents.

All of these studies were based on flood simulations. However, human-readable and configurable spillway operation rules or different scenarios of the operation were not emphasized to mitigate flood and drought disasters. Herein, a method to realize reservoir flood routing simulation with spillway operation rules that are human readable and configurable based on tree-based structures is presented.

2. Spillway Operation

Most of the dams maintained by EGAT are large dams with a height from the foundation of 15 m or more or a height between 5 and 15 m with a capacity exceeding 3 million m^3, as defined by ICOLD. These dams have large capacities to store water from catchment areas upstream during the rainy season and discharge water for consumption and agriculture during summer.

The spillway operation, which balances water storage and discharge, is vital to the safety of residents downstream and upstream. Some downstream residential areas can be flooded if the amount of water discharged is significant, whereas some agricultural areas can experience insufficient water if the discharge amount is extremely small. Meanwhile, the upstream residential area can be flooded if the water level in the reservoir is extremely high. The spillway operation task is difficult because of weather uncertainties and the effects of El Niño and La Niña. Hence, new technologies such as DS-RMS have been developed and employed to facilitate the management of reservoir operation, particularly the spillway operation, by enabling rapid and accurate decisions for addressing uncertain situations with more confidence.

2.1. Limitations of Spillway Operation

The operation of a spillway that balances the necessity for water and the safety of a dam affected by excessive water is limited by several factors, as follows:

- The precipitation amount can be difficult to predict over a long period. Hence, the annual inflow data for the reservoir are uncertain.
- The storage capacity of downstream rivers is limited. Excessive water discharge can cause flooding in residential areas near rivers.
- If the water storage capacities of the downstream rivers are full or nearly full, then the duration of the spillway discharge must be prolonged, which causes a higher RWL and dam safety risks.
- For the case where the RWL exceeds the normal high water level, a significant amount of water discharge is necessary to limit the water level below the maximum high water level, thereby causing flooding in residential areas near the downstream rivers.

2.2. Rule Curves for Spillway Operation

The general guidelines for the spillway operation aim to maintain the RWL between two rule curves, i.e., the upper rule curve (URC) and the lower rule curve (LRC), to maximize the availability and usability of the water reserve and maintain dam safety. Typically, water is discharged through generators to generate electricity. Only special cases, such as generator maintenance or flash floods, require discharging through spillway gates. Separately considering each case, if the RWL surpasses the URC, then water should be discharged through the generators to maintain the RWL below the URC. If the RWL is between the URC and LRC, then water can be discharged as required through the generators. If the RWL is below the LRC, then water can be discharged only when necessary, such as draining water to limit saltwater intrusion. If the RWL is below the minimum water level, then water discharge should be halted to ensure the sufficient amount of water to maintain the dam structure.

Another type of rule curve is the flood control rule curve (FCRC), which is used during the flooding season. The RWL is maintained under the FCRC such that the reservoir can provide sufficient storage for the inflow from the flood and storm. Maintaining the RWL under the FCRC is necessary to prevent dam overtopping failure.

2.3. Spillway Operation Manual

To finely manage the spillway operation, EGAT developed a spillway operation manual based on simulation results for various situations. This manual is used as a guideline to control the spillway operation during the flooding season such that the RWL does not increase above the maximum high water level or the dam crest. An example of a spillway operation manual is described in Section 4.4 which contains operation rules in a tree-based structure. To use the spillway operation manual in a real situation, other factors should be considered, such as the weather forecast, current inflow, and river capacity downstream. A meeting with other stakeholders in the National Water Resource Committee (NWRC) of Thailand will be held to devise a plan to operate the spillway during the flooding season.

3. Flood Routing Algorithms

Flood routing refers to flood routing in reservoirs, streams, rivers, and breaching dams. For streams and rivers, flood routing is a procedure that determines or predicts the timing and magnitude of a flood wave as a function of time at a point on a stream from known or assumed data at one or more points upstream. Additionally, it can refer to a procedure that calculates the outflow from a stream channel once the inflow, lateral contributions, and channel characteristics are known. For reservoirs, flood routing refers to a procedure that determines the outflow hydrograph and RWL from the inflow hydrograph with information regarding the elevation, storage, and discharge characteristics of the reservoir and spillways. For the breaching dam, the hydrographs at downstream locations are derived from the hydrograph generated by the breach or failure of the dam. Generally, two classes of flood routing methods exist: *hydraulic* and *hydrologic* methods.

3.1. Hydraulic Method

The hydraulic method is based on the conservation of mass and momentum. This method depends on the theory of unsteady flow hydraulics and the solutions of differential equations. To solve this problem, input data such as topographic data of channel geometry, reach lengths, roughness, downstream boundary conditions, and inflow hydrographs are required.

The conservation of momentum in the hydraulic method represents the translation effects on the flood wave, whereas the conversation of mass represents the storage effects on the flood wave. The translation effects

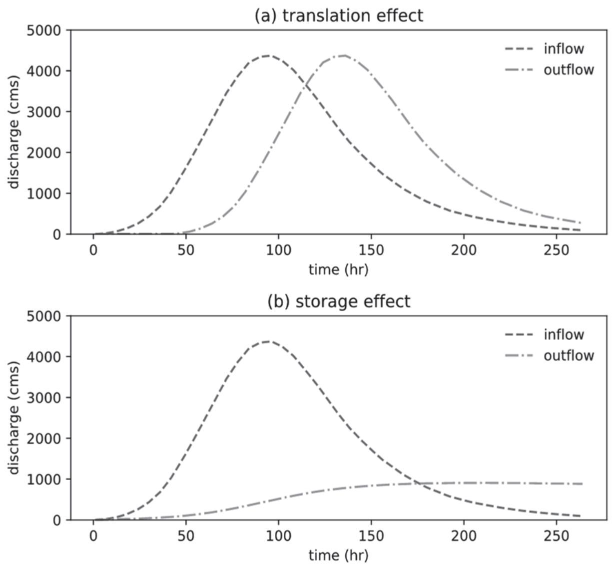

Fig. 2. Translation and storage effect of the channel on flood wave.

describe the flood wave that maintains the hydrograph shape as it moves downstream, as shown in **Fig. 2(a)**. The storage effects describe the flood wave, in which the discharge is attenuated by the storage to reduce the peak flow and change the shape of the hydrograph, as shown in **Fig. 2(b)**. Therefore, the hydraulic method can represent both translation and storage effects and is appropriate for cases involving extremely small or steep stream gradients, where the acceleration terms are important, such as in the case of sluggishly moving water and dam breach.

3.2. Hydrologic Method

The hydrologic method is based on the conservation of mass, whereas the conservation of momentum is simplified based on the storage discharge relation. The main assumption in this method is that the acceleration terms are negligible compared with the other terms in the equation. This assumption is reasonable for many cases of flood routing simulation for streams with a moderate gradient, where the water surface is level or nearly level. The hydrologic method was used in the reservoir flood routing simulation implemented in this study to determine the RWL and outflow of the dams for upcoming hours.

4. Reservoir Flood Routing Simulation Implementation with Configurable Operation Manual

The implementation of the reservoir flood routing simulation software in DS-RMS are discussed below.

4.1. Required Features

The reservoir flood routing simulation software developed for the dams maintained by EGAT as part of DS-RMS should exhibit the following features:

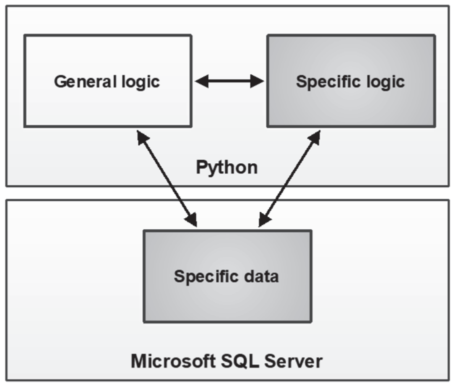

Fig. 3. Design of reservoir flood routing simulation software.

- Simulated reservoir flood routing should estimate the RWL for three types of dams, i.e., concrete dam, embankment dam, and impervious faced rockfill dam, totaling 12 dams.
- Spillway operation rules should be easily reconfigurable. Different scenarios of spillway operations can be simulated and tested such that the operating rules can be adjusted based on the current situation.
- The software can be accessed online from any computer through a web browser by implementing a web application.

4.2. Design

EGAT closely monitors 14 important power-generating dams through DS-RMS. In 12 of these dams, spillway gates must be operated and reservoir flood routing simulation software is required to predict the future RWL to maintain the safety of the dams, particularly during the flooding season or during storms. To implement the reservoir flood routing simulation software for all 12 dams, the differences in the characteristics of these dams must be considered. For example, each dam exhibits a different relationship between the reservoir capacity and RWL. In addition, the spillway operation rules to specify the spillway gate opening height of the dams are different. In addition, some of the dams have fuse plug dikes that hinder artificial channels to operate as an auxiliary or emergency spillway. Therefore, the architecture of the reservoir flood routing simulation software should be able to represent all the characteristics of the 12 dams.

Based on the required features and the specifications mentioned above, the design of the reservoir flood routing simulation software can be represented by a block diagram, as shown in **Fig. 3**, where

- the general logic is a shared part of the algorithm or logic that is the same for a number of dams, such as the implementation of the storage-indication routing method, the interpolation of parameters to be used as the inputs of the simulation, or the logic that fetches and interprets the spillway operation rules.

This common logic was implemented using Python programming language;

- the specific logic is the logic of the software that is specific to only one or a few dams, such as the effect of fuse plug dikes on the simulation for Ratchaprapha and Huai Kum dams or the use of specific spillway operation rules for storm conditions of the Srinakarin Dam. This specific logic was also implemented using Python programming language;
- the specific data are data that are specific to each dam, such as elevation-storage data, elevation-discharge data based on gate opening, or spillway operation rules. These data are stored in a relational database management system (RDBMS), which is a Microsoft SQL Server (MS SQL), using a table format. Therefore, complex information such as spillway operation rules must be transformed into a database table, as described in Section 4.4.

4.3. Storage-Indication Routing Method

As described in [11], for a reservoir with the assumption of a level water surface or a channel with a slow-rising flood wave where the acceleration terms of the flood are relatively small, the storage-indication routing method can be used. This method is a hydrologic method that uses a continuity equation based on mass conservation, as shown in Eq. (1), where I_t and I_{t+1} are the inflows (in cubic meters per second, cms) for time t and $t+1$, respectively. O_t and O_{t+1} are the outflows (cms). S_t and S_{t+1} are the storage volumes (in million cubic meters, MCM), and Δt is the difference between $t+1$ and t, which is configurable (e.g., 1 h, 2 h, etc.).

$$\frac{(I_t+I_{t+1})}{2}-\frac{(O_t+O_{t+1})}{2}=\frac{(S_{t+1}-S_t)}{\Delta t}, \quad (1)$$

$$\frac{(S_{t+1}-S_t)}{\Delta t}+\frac{O_{t+1}}{2}=\frac{(I_t+I_{t+1})}{2}-\frac{O_t}{2}. \quad (2)$$

The information required for the calculation of this method includes the elevation-storage relation, elevation-discharge relation, and inflow data. An example of the elevation-storage relation for the Sirikit dam is shown in **Table 1** which describes the relation between the water level in the reservoir and the volume of the water stored. An example of the elevation-discharge relation is shown in **Table 2** which describes the relationship between the spillway gate opening (m) and the outflow (MCM/h) for each specific RWL. An example of a probable maximum flood (PMF) is presented in Section 5.1.

For the simulation, the RWL for the next hour was calculated based on the information of the current hour. Eq. (1) can be rearranged as Eq. (2) such that the terms on the left contain all the information of the next hour, i.e., S_{t+1} and O_{t+1}. It is noteworthy that I_{t+1} is already known in the current hour because every time step of the inflow is known in advance as the input of the simulation. From a value of the spillway gate opening and the data shown in **Table 2**, the terms on the left-hand side of Eq. (2) can be calculated as B for each value of the RWL, as shown in Eq. (4), to generate a data table. Subsequently, the terms on the right-hand side of Eq. (2) are used to calculate the lookup value A, as shown in Eq. (3). Finally, the RWL for the next hour is determined from the RWL, where $B(\text{RWL})=A$.

Table 1. Example of elevation-storage relation for Sirikit dam.

RWL (m MSL)	Storage (MCM)
70.00	0
80.00	50
90.00	150
100.00	400
110.00	1050
120.00	1990
130.00	3300
140.00	4700
150.00	6700
160.00	9000
170.00	11600

Table 2. Example of elevation-discharge relation for Sirikit dam showing outflow in cubic meter per second (cms).

GATE OPENING (m)	RWL (m MSL)				
	157.5	159.5	161.5	163.5	165.5
0	0	0	0	0	0
1.6	171	199.5	225.5	248.5	266
3.2	306.5	362	415	467	518
4.8	428	510	590	668	739.5
6.4	507.5	642.5	749.5	852.5	948.5
8	507.5	785.5	910	1030	1142.5
9.6	507.5	785.5	1090.5	1428	1778.5

$$A=\frac{(I_t+I_{t+1})}{2}-\frac{O_t}{2}, \quad (3)$$

$$B(\text{RWL})=\frac{(S_{t+1}(\text{RWL})-S_t)}{\Delta t}+\frac{O_{t+1}(\text{RWL})}{2}. \quad (4)$$

It is noteworthy that the data table of the RWL and B typically does not contain the value of B, which exactly matches the value of A. An interpolation is required to identify the RWL whose B value is between two existing values in the data table. As shown in Eq. (5), B_1, B_2 and RWL_1, RWL_2 are presented in two consecutive rows in the table, and B is between B_1 and B_2, whereas the RWL is derived through interpolation.

$$\frac{B-B_1}{B_2-B_1}=\frac{\text{RWL}-\text{RWL}_1}{\text{RWL}_2-\text{RWL}_1}. \quad (5)$$

4.4. Configurable Spillway Operation Rules

Rules for the spillway operation developed by EGAT have been developed and are included in the dam operation manual. These rules are presented in a tree-based structure and includes *conditions* and *actions*, as shown in **Fig. 4**. The conditions are at the branches of the tree, whereas the actions are at the leaves. To step through each

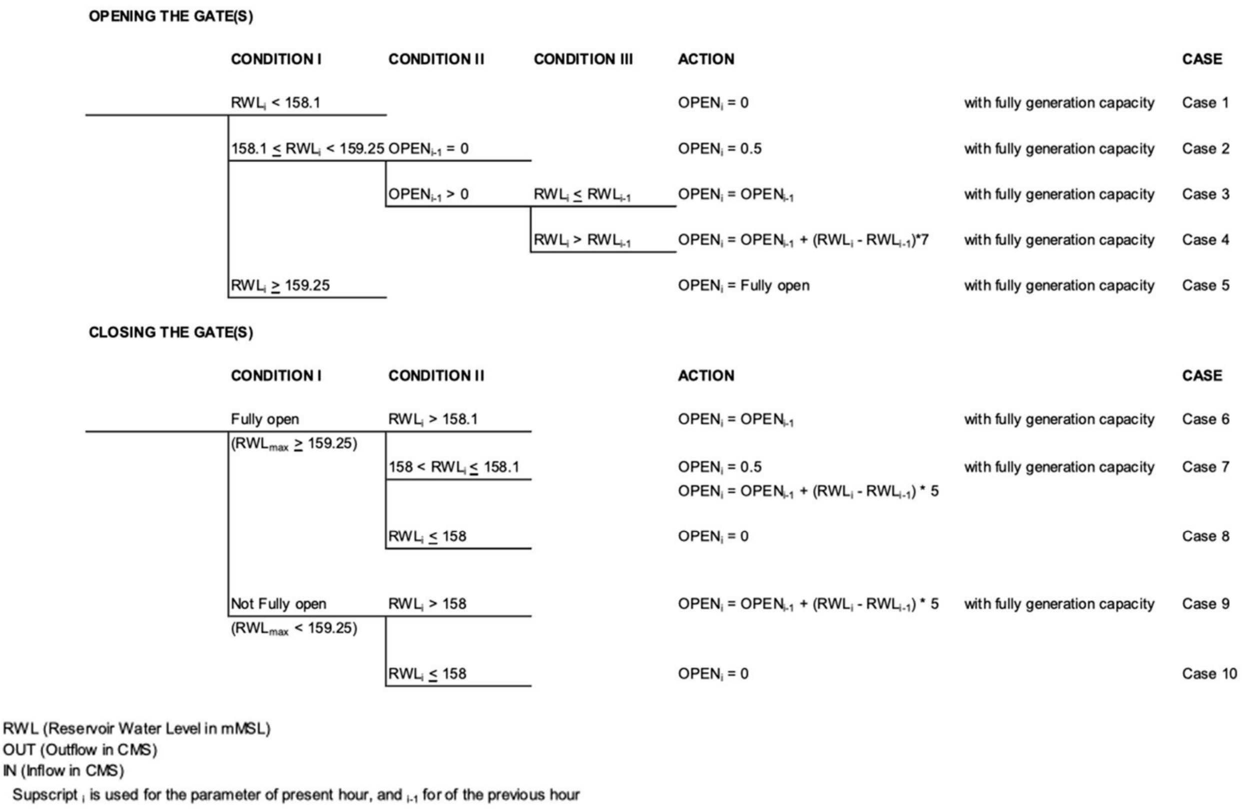

Fig. 4. Spillway operation rules for the Sirikit Dam as described in manual.

branch, conditions such as the RWL or gate opening value being in specific ranges must be satisfied. After stepping through the branches to a leaf, an action is selected to update the gate opening or the outflow value such that it will be used in the next time step. These rules, which contain information regarding the spillway operation, must be included in the simulation to incorporate the effect of real spillway discharge.

To implement a reservoir flood routing simulation that is applicable to 12 dams with different spillway operation rules, the rules must be stored in the database for each dam. Because other parts of DS-RMS and the simulation use the MS SQL relational database as data storage, the system will be easier to maintain if the tree-based structure of the rules can be stored in MS SQL. Therefore, the branches and leaves of the tree are designed to be represented by each row of a data table, as shown in **Fig. 5**.

The root of the tree-based structure starts at rows with field level = 0. Two starting points exist in this table for the simulation steps before (opening gates, *operation type* = 1) and after (closing gates, *operation type* = 0) the peak of the inflow. The *condition* field of each row was evaluated to traverse the tree. If the condition is *true*, then the next row to be evaluated is identified by the *child* field. If the condition is *false*, the next row to be evaluated is identified by the *friend* field. These logics represent moving further through each level of the branch whose condition is satisfied. Finally, when the leaf of the tree is reached (*item type* = 1), the *condition* field is repurposed as an action that updates the value of the gate opening or outflow. The information within these fields is automatically updated as the user inputs the spillway operation rules from **Fig. 4** through the graphical user interface (GUI) shown in **Fig. 6**.

4.5. Overall Implementation

To implement the reservoir flood routing simulation software for DS-RMS, elevation-storage data, elevation-discharge data, and inflow data for several recurrent periods must be obtained and input into the database for all 12 dams. Subsequently, the simulation results are calculated for each time step whose period is configurable, such as 1 h, 2 h, etc. The details of the simulation are shown in the flowchart in **Fig. 7**.

To start the simulation, the initial values of the RWL, inflow, and outflow or gate opening were initialized once at the beginning of the simulation in step 1, as shown in **Fig. 7**. Because the inflow data are known in advance, in step 2, the inflow data for the current and next hours can be obtained to calculate an intermediate value A to determine the RWL, as described in Eq. (3). Another required value is the outflow or spillway discharge from the elevation-discharge data through the spillway gate opening height. The outflow can be incremented with outflows from the generators and other outlets of the dam. Subsequently, in step 3, the RWL for the next hour is determined by interpolation from a data table generated using Eq. (4). Next, the spillway gate opening height for the next hour

	Id	Friend	Child	ItemType	Level	Condition	Case	OperationType
1	1	NULL	37	NULL	0	NULL	NULL	0
2	2	NULL	34	NULL	0	NULL	NULL	1
3	34	35	39	0	1	RWL[i] < 158.1	NULL	1
4	35	36	42	0	1	158.1 <= RWL[i] < 159.25	NULL	1
5	36	NULL	55	0	1	RWL[i] >= 159.25	NULL	1
6	37	38	58	0	1	RWL[i] >= 159.25	NULL	0
7	38	NULL	61	0	1	RWL[i] < 159.25	NULL	0
8	39	40	NULL	1	2	OPEN[1][i] = 0	1	1
9	40	NULL	NULL	1	2	OPEN[2][i] = 0	1	1
10	42	43	47	0	2	OPEN_last_open[1]==0	NULL	1
11	43	NULL	44	0	2	OPEN_last_open[1] > 0	NULL	1
12	44	45	51	0	3	RWL[i] <= RWL_last_open	NULL	1
13	45	NULL	53	0	3	RWL[i] > RWL_last_open	NULL	1
14	47	48	NULL	1	3	OPEN[1][i] = 0.5	2	1
15	48	NULL	NULL	1	3	OPEN[2][i] = 0.5	2	1
16	51	52	NULL	1	4	OPEN[1][i] = OPEN_last_open[1]	3	1
17	52	NULL	NULL	1	4	OPEN[2][i] = OPEN_last_open[2]	3	1
18	53	54	NULL	1	4	OPEN[1][i] = OPEN_last_open[1] + (RWL[i] - RWL_last_open) * 7	4	1
19	54	NULL	NULL	1	4	OPEN[2][i] = OPEN_last_open[2] + (RWL[i] - RWL_last_open) * 7	4	1

Fig. 5. Spillway operation manual represented by database table.

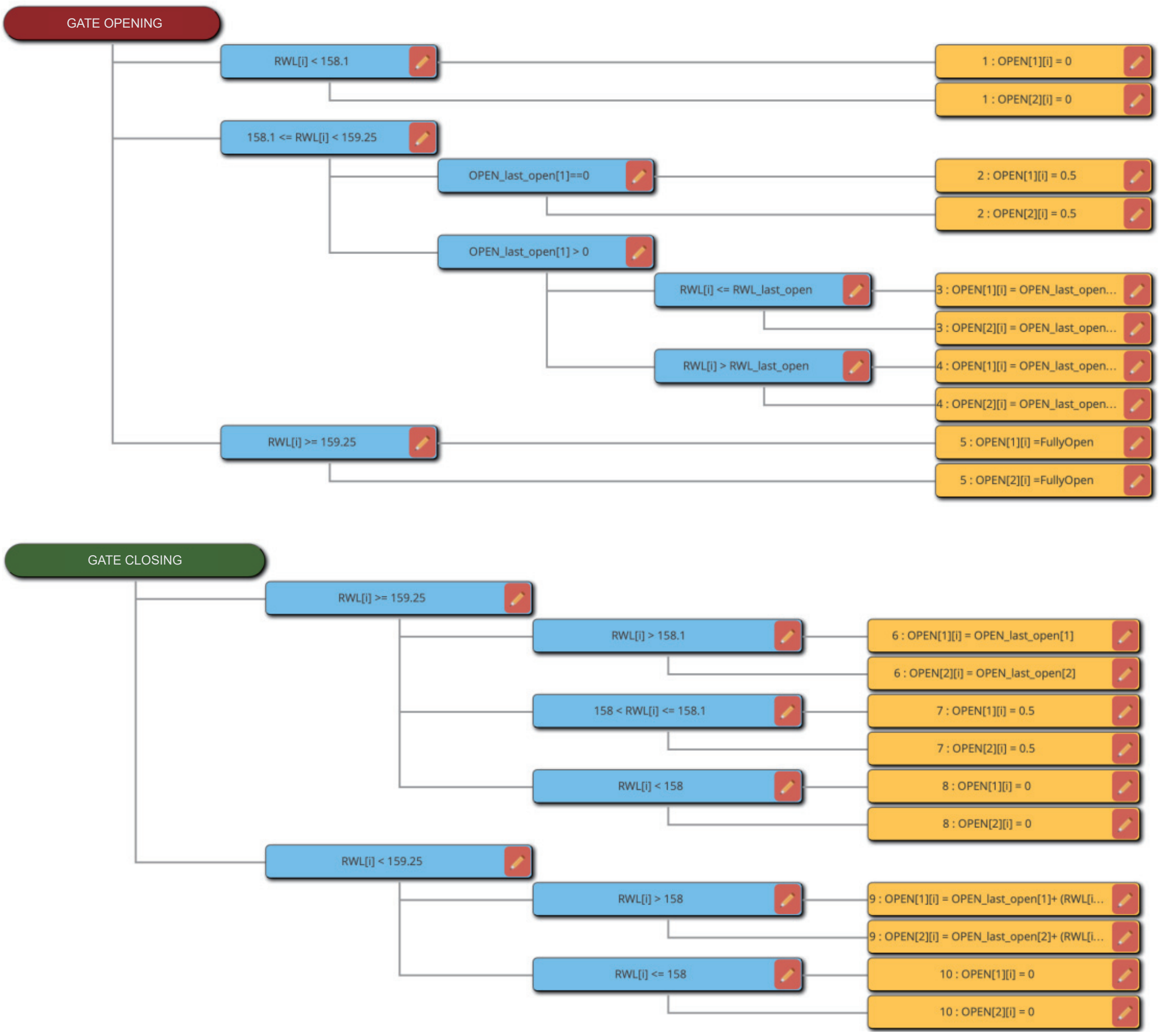

Fig. 6. Spillway operation rules as input by user for simulation.

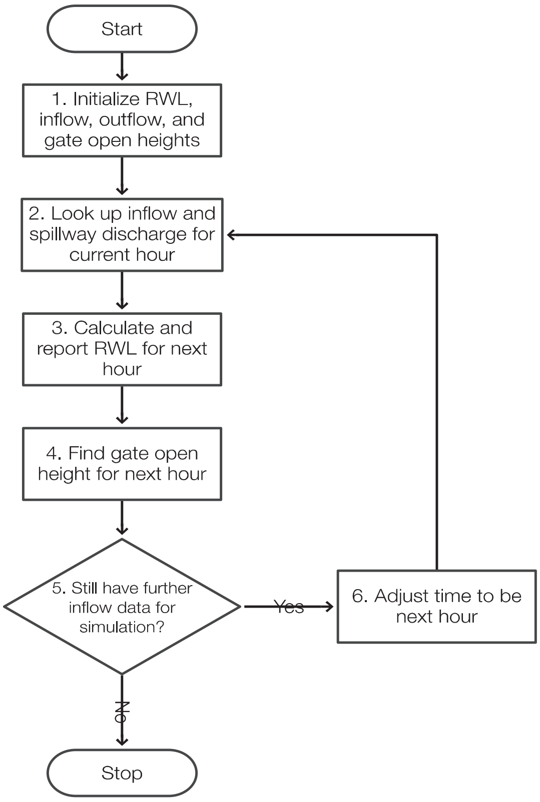

Fig. 7. Flowchart for simulation.

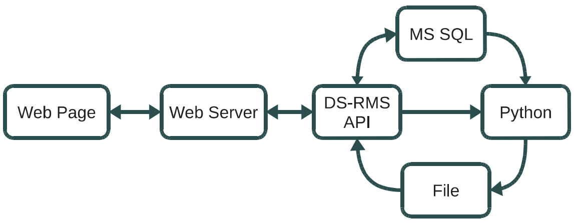

Fig. 8. Overall components of reservoir flood routing simulation software.

is determined in step 4 from the spillway operation rules and the dam status, such as the current RWL and current gate opening. Finally, the remaining inflow data are verified. If more data are available, then the simulation will continue for the next hour.

The overall components of the reservoir flood routing simulation software are shown in **Fig. 8**. The simulation begins with the user selecting the input parameters provided on the web page, such as the initial RWL, inflow hydrograph, and outflows from the generators and outlets. The web page uses Asynchronous JavaScript and XML (AJAX) technology to send the parameters to the web server, which is implemented through Internet Information Services (IIS). The web server calls the DS-RMS API, implemented using C# programming language, to obtain the simulation results. The DS-RMS API prepares the parameters that are sent from the web page, such as the initial RWL, outflows from outlets, and selected inflow hydrographs, and sends the parameters to the Python script to execute the simulation. The Python script acquires more data from the MS SQL database, such as the elevation-storage data, elevation-discharge data, and spillway operation rules, to generate the simulation results. The Python script returns the simulation results in a comma-separated value (CSV) file to the DS-RMS API. Subsequently, the DS-RMS API returns the simulation results through the web server to the web page. Eventually, the web page shows the results on the screen, such as the RWL, spillway gate opening data, outflow, etc., for the user to analyze the situation.

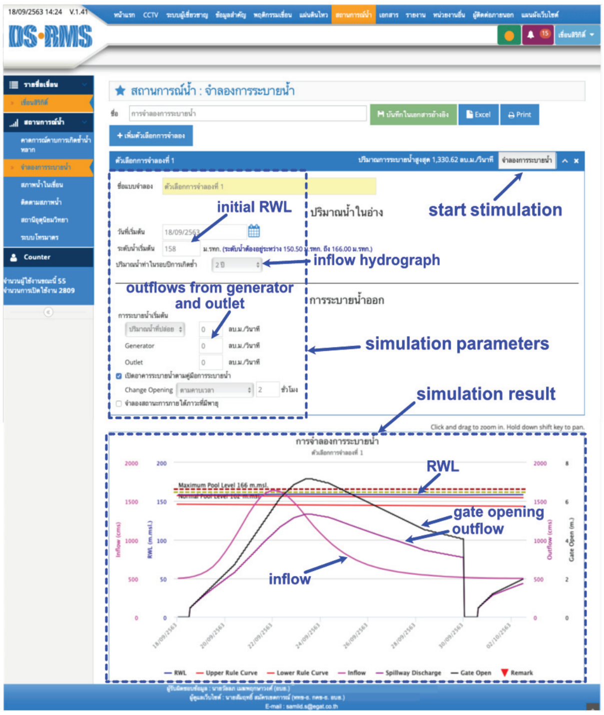

Fig. 9. Reservoir flood routing simulation software in DS-RMS screen.

The GUI of the web-based reservoir flood routing simulation software as part of DS-RMS is shown in **Fig. 9**. Simulation parameters, such as the initial RWL, inflow hydrograph, and outflows, were filled and selected before the simulation was started. The simulation was executed by pressing a button, and the simulation results were displayed with the values of the RWL, inflow, outflow, and gate opening on the graph. The user can observe the RWL and compare it with the critical levels, such as the maximum high water level, normal high water level, or rule curves to decide whether to operate the actual spillway gates promptly.

5. Simulation Results

5.1. Simulation Accuracy

The accuracy of the reservoir flood routing simulation mentioned in Section 4 was validated by comparing it

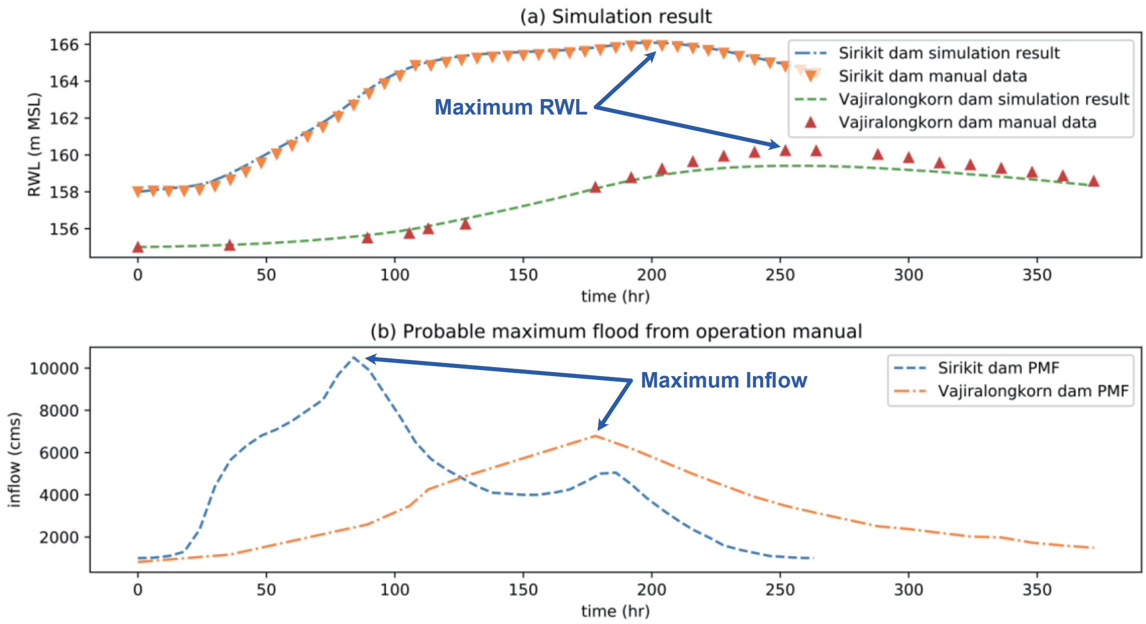

Fig. 10. Simulation results and probable maximum flood (PMF) for Sirikit and Vajiralongkorn dam.

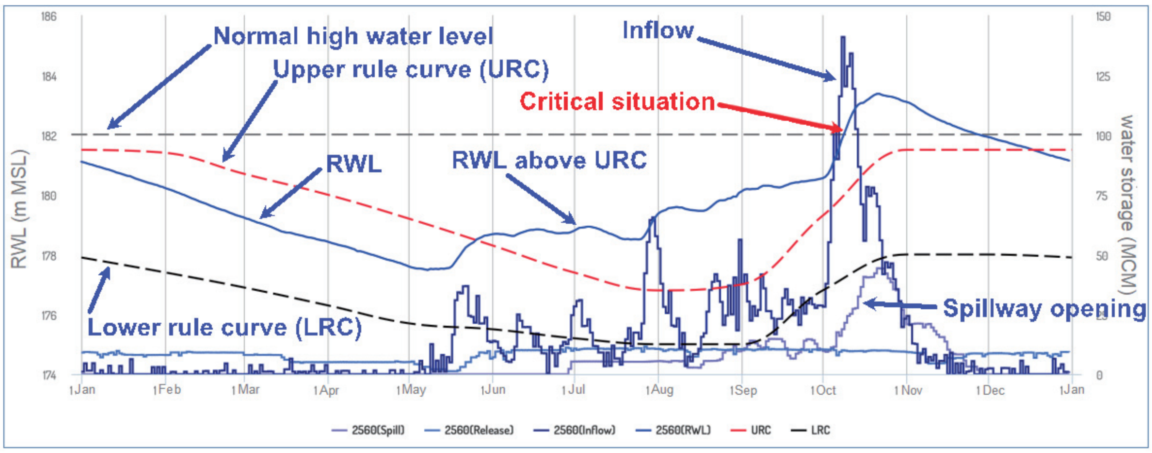

Fig. 11. Water situation at Ubol Ratana dam in 2017.

with the data prepared during the construction of the dam described in the dam construction manual. Given the PMF as the inflow to the simulation, the simulation results of the Sirikit and Vajiralongkorn dams were generated and compared with the RWL during the PMF from the dam construction manual data, as shown in **Fig. 10**. The reservoir behaves as a buffer for water storage. As the inflow increases, the RWL increases because the outflow is limited by the spillway opening and is lower than the inflow. When the inflow decreases and is lower than the outflow, the RWL starts to decrease. The occurrence of the maximum RWL was delayed and did not occur at the same time as that of the maximum inflow. Accurate values of the magnitude and time of the RWL from the simulation were indispensable during planning to mitigate dam safety risk and the downstream flood of residential areas. From the comparison, the average relative errors were calculated to be 0.1159% and 0.2507% for the Sirikit and Vajiralongkorn dams, respectively, whereas the maximum relative errors were 0.2253% and 0.5180%, respectively. The results show that the simulation reflects the actual behavior of the spillway operation and discharge on the RWL of the dams, and it can be used to plan for well-informed actions of the spillway operation during the flooding season.

5.2. Use Case Scenario

Simulations are performed when a difficult decision is required. For example, at the Ubol Ratana Dam in 2017, several storms arrived in the northeast region of Thailand. As shown in **Fig. 11**, the spillway operation could not adhere to the rule curves because of the flood downstream. The RWL was above the URC. The situation continued until a normal high water level was reached.

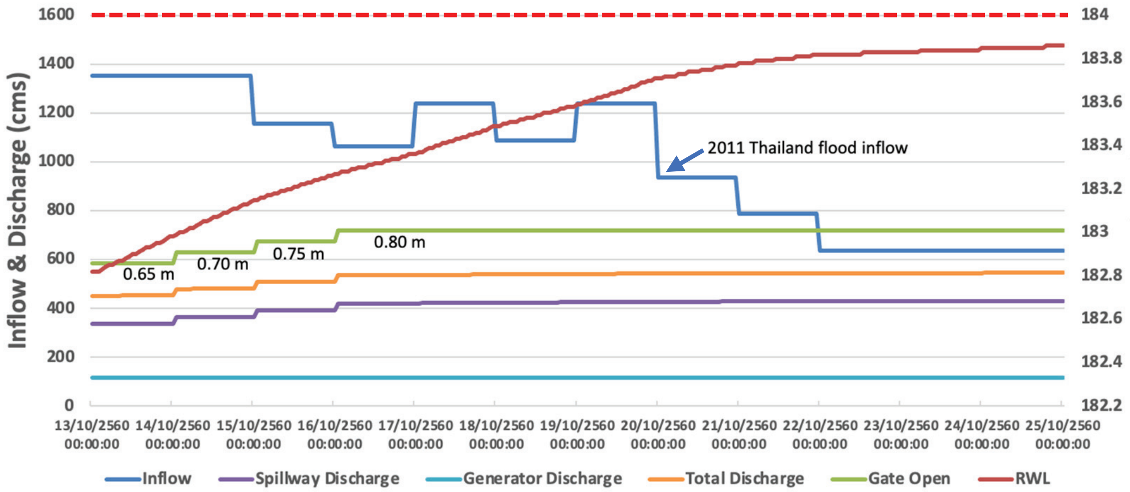

Fig. 12. Simulation result of Ubol Ratana dam in October 2017.

Subsequently, a decision had to be made at that critical situation to balance the flood in the downstream and upstream areas and ensure the safety of the dam. If a higher discharge cannot be realized, then more flooding will occur in the upstream residential areas and the dam safety is jeopardized. If a higher discharge is realized, then more flooding will occur in the downstream residential areas. At this point, the simulation was executed with the modified spillway operation rules to limit the total discharge at specific values. The inflow hydrograph from the 2011 Thailand flood was used to assess the situation. As shown in **Fig. 12**, the results indicated that the RWL can be maintained below the crest of the Nonsang district dike (184.0 m), which protects a residential area upstream from the flood. Hence, the discharge was limited, as simulated, and prevented excessive flooding in the residential areas downstream.

6. Conclusion

A reservoir flood routing simulation software with spillway operation rules that are human readable and configurable for the spillway operator was realized in this study. The flood routing simulation was implemented using the storage-indication routing method, which is a hydrologic method. The spillway operation rules were presented in a tree-based structure implemented based on a table in a relational database. The spillway gate opening was derived from the current RWL, spillway gate opening, and flood situation when the peak inflow has passed. The GUI was designed on a web-based application such that the simulation can be executed on any web browser. The simulation results showed that the simulated RWL data were similar to the RWL data in the dam construction manual. This verified the accuracy of the reservoir flood routing simulation, which is useful for planning the spillway operation.

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