Cyber to Real World Integrated Emulation Testbed for Dam Safety Management and Water Governance Systems

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[ASEAN IVO : ASEAN ICT Virtual Organization]

This work was produces as part of the ASEAN IVO project (http://www.nict.go.jp/en/asean_ivo/index.html) titled, [Cyber to Real World Integrated Testbed for Dam Safety Management and Water Governance System], and financially supported by NICT (http://www.nict.go.jp/en/index.html).

[NICT : National Institute of Information and Communications Technology]

Agenda

- CyReal Testbed
- Dam Safety Management and Water Governance System
  - Flood Routing Simulation
- Machine Learning Model for Inflow Forecasting
- Results
- Conclusion

CyReal Framework by NICT

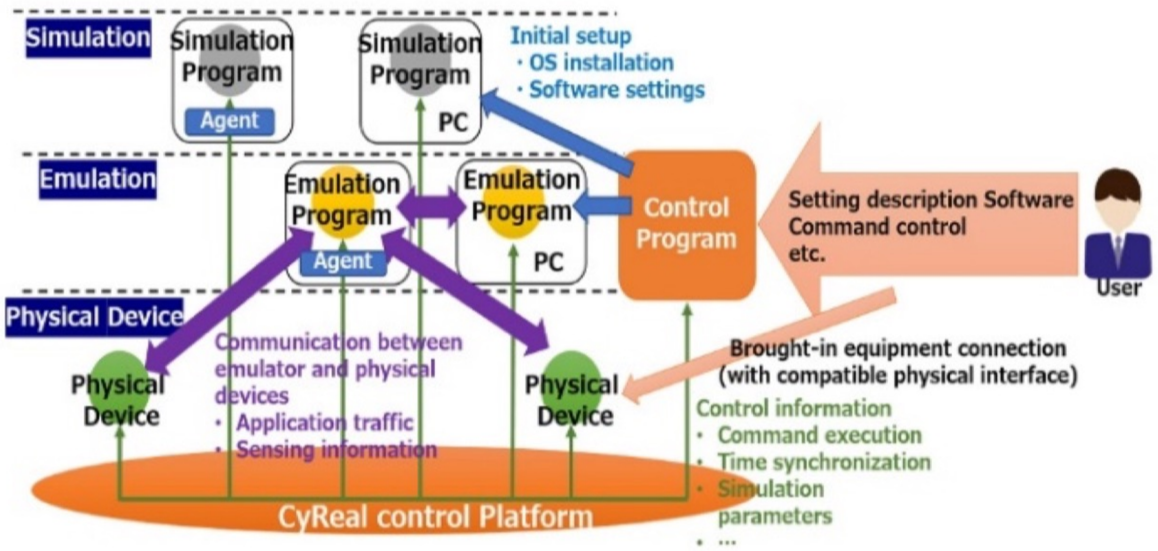


Fig. 1. A sample structure of CyReal environment.

- **Integrated Simulation and Emulation** – CyReal enables seamless integration of simulations, emulations, and real-world systems for testing ICT applications efficiently.

  Cost-Effective R&D – It **minimizes research and development costs** by providing a virtual testbed, reducing the need for real-world infrastructure setup.

  Disaster Prediction and Response – The platform supports applications like flood damage prediction and evacuation advisory systems, enhancing disaster preparedness.

Airport or Seaport?

Thailand's Worst Crisis in 70 Years…

Seven Major Industrial Parks are Flooded Billions of Dollars are Lost

Dam Operation

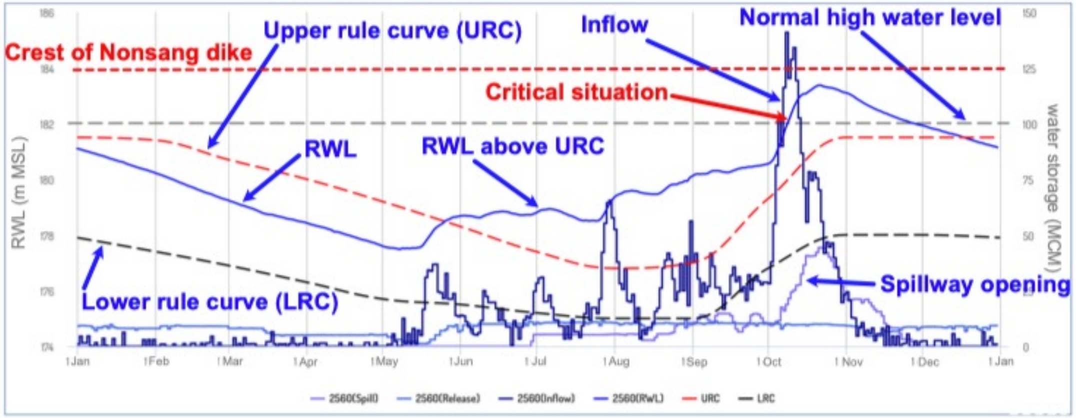


Fig. 2. Water situation at Ubol Ratana dam in 2017.

- In 2017, several storms arrived in the northeast region of Thailand.
- The spillway operation of Ubol Ratana Dam could not adhere to the rule curves because of the flood downstream

- **Ensuring dam safety** requires continuous monitoring, maintenance, and a comprehensive operation plan.
- **Managing upstream water storage** effectively helps avoid dam failures caused by excessive or insufficient reserves.
- Maintaining **the Reservoir Water Level (RWL)** between the Upper Rule Curve (URC) and Lower Rule Curve (LRC) is crucial for balancing dam safety and effective water resource management.
- Exceeding the URC can lead to **potential flood risks**, while dropping below the LRC may cause **drought-related issues**, necessitating precise monitoring and controlled water release strategies.

Flood Routing Simulation

OPENING THE GATE(S)

CONDITION I	CONDITION II	CONDITION III	ACTION		CASE
$RWL_i < 158.1$			$OPEN_i = 0$	with fully generation capacity	Case 1
$158.1 \leq RWL_i < 159.25$	$OPEN_{i-1} = 0$		$OPEN_i = 0.5$	with fully generation capacity	Case 2
	$OPEN_{i-1} > 0$	$RWL_i \leq RWL_{i-1}$	$OPEN_i = OPEN_{i-1}$	with fully generation capacity	Case 3
		$RWL_i > RWL_{i-1}$	$OPEN_i = OPEN_{i-1} + (RWL_i - RWL_{i-1})*7$	with fully generation capacity	Case 4
$RWL_i \geq 159.25$			$OPEN_i$ = Fully open	with fully generation capacity	Case 5

CLOSING THE GATE(S)

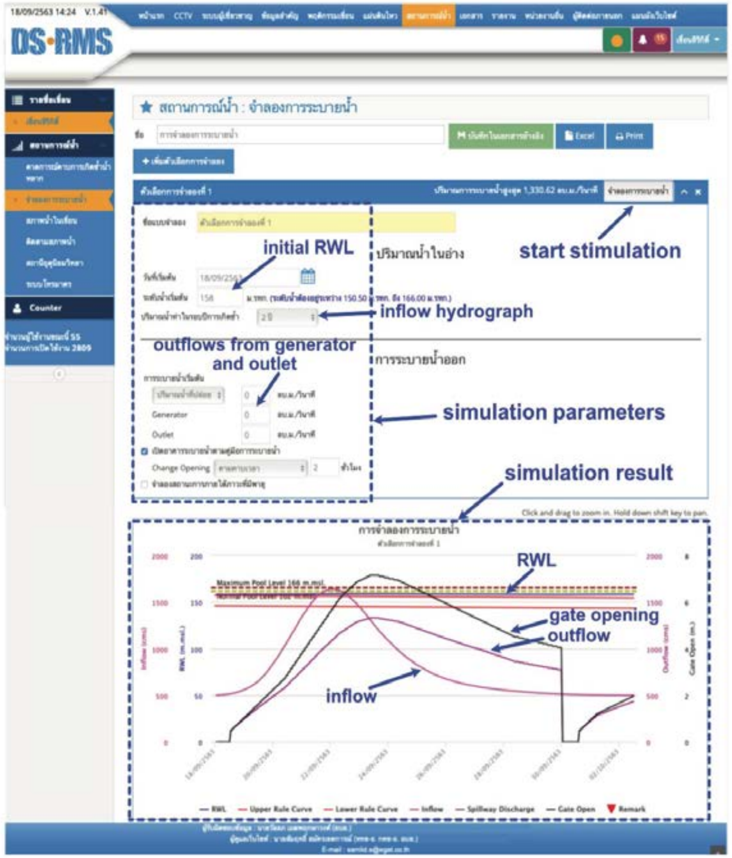
CONDITION I	CONDITION II	ACTION		CASE
Fully open ($RWL_{max} \geq 159.25$)	$RWL_i > 158.1$	$OPEN_i = OPEN_{i-1}$	with fully generation capacity	Case 6
	$158 < RWL_i \leq 158.1$	$OPEN_i = 0.5$ $OPEN_i = OPEN_{i-1} + (RWL_i - RWL_{i-1}) * 5$	with fully generation capacity	Case 7
	$RWL_i \leq 158$	$OPEN_i = 0$		Case 8
Not Fully open ($RWL_{max} < 159.25$)	$RWL_i > 158$	$OPEN_i = OPEN_{i-1} + (RWL_i - RWL_{i-1}) * 5$	with fully generation capacity	Case 9
	$RWL_i \leq 158$	$OPEN_i = 0$		Case 10

RWL (Reservoir Water Level in mMSL)
OUT (Outflow in CMS)
IN (Inflow in CMS)
Supscript $_i$ is used for the parameter of present hour, and $_{i-1}$ for of the previous hour

Spillway operation rules as described in manual.

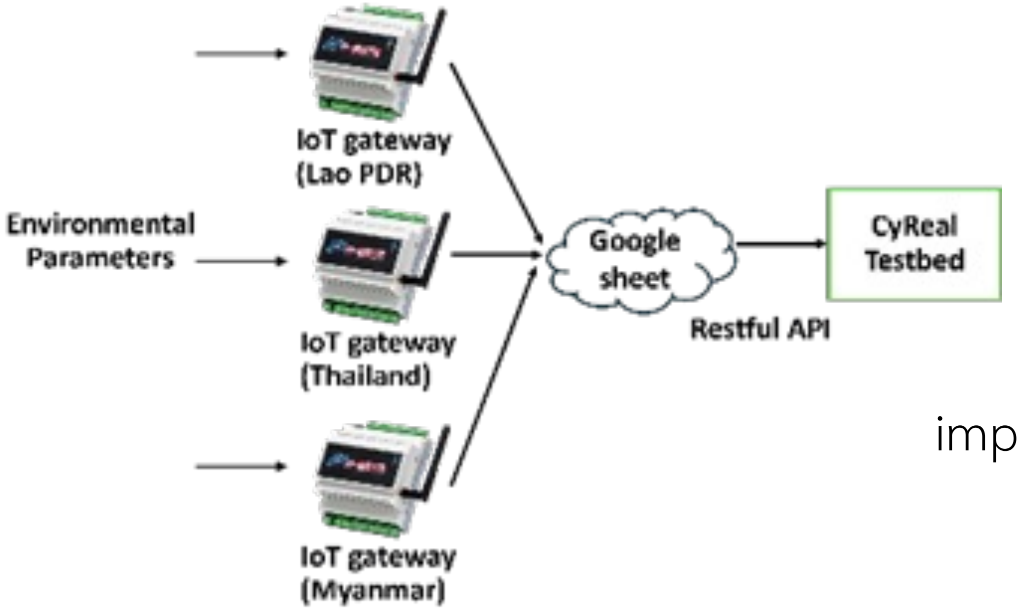
- To finely manage the spillway operation, a spillway operation manual based on several situations has been developed.
- The manual is used as a guideline to control the spillway operation.
- In a real situation, other factors should be considered, such as weather forecast, current inflow, river capacity.

Flood Routing Simulation

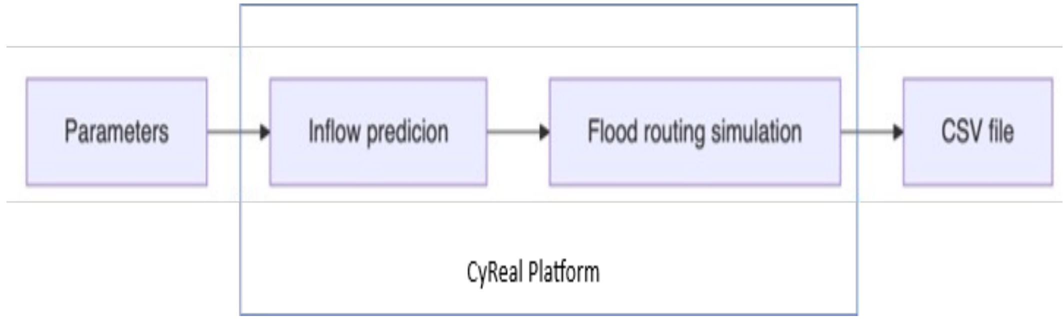


Reservoir flood routing simulation software in DS-RMS screen.

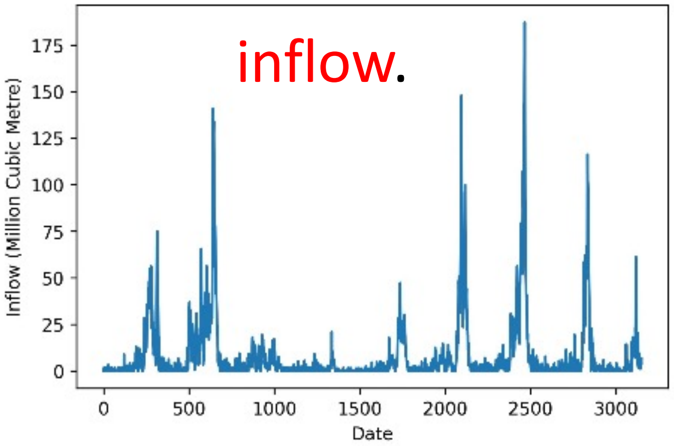
- Web-based reservoir flood simulation software uses simulation parameters to generate simulation result.
- Input simulation parameters include initial RWL, inflow hydrograph (static), outflows from generator and outlet.
- Simulation result includes RWL, outflow from spillway discharge, gate opening, and outflow.
- Simulated RWL is compared with the critical levels, such as maximum high water level, normal high water level to decide how to operate the actual spillway.

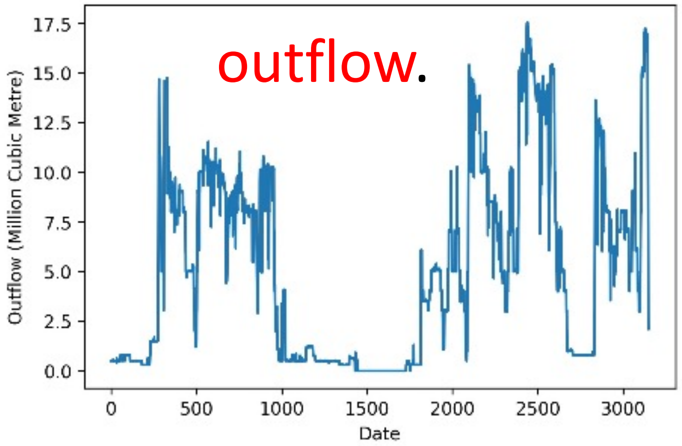


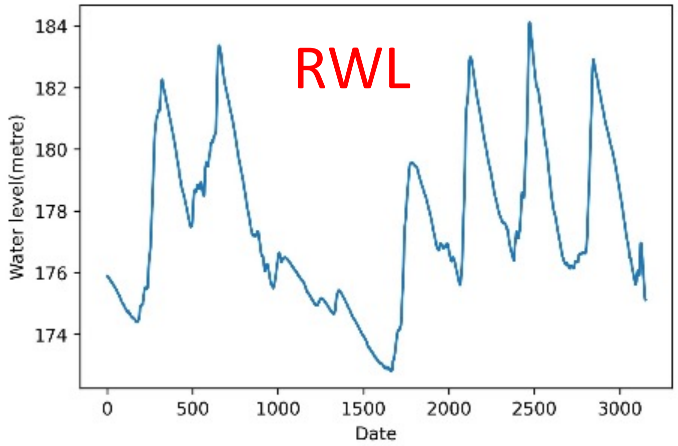
Overall diagram of proposed system



implementation of Flood routing integrated simulation







- 3,000 days of inflow, outflow, and RWL data at Ubol Ratana Dam from January, 2016, to August, 2024.
- The RWL was managed based on the incoming inflow to ensure that it did not exceed the dam crest level
- Peaks in inflow during the rainy season, and the magnitude and duration of the outflow were managed. The RWL nearly reached the dam crest level when inflow peaks were higher and prolonged longer.
- LSTM) model was used for inflow forecasting. It was trained and validated using monthly large-scale climate indices data, and the results showed that a correlation coefficient ranging from 0.5 to 0.6 was achieved.

Recurrent Neural Network based Inflow Forcasting

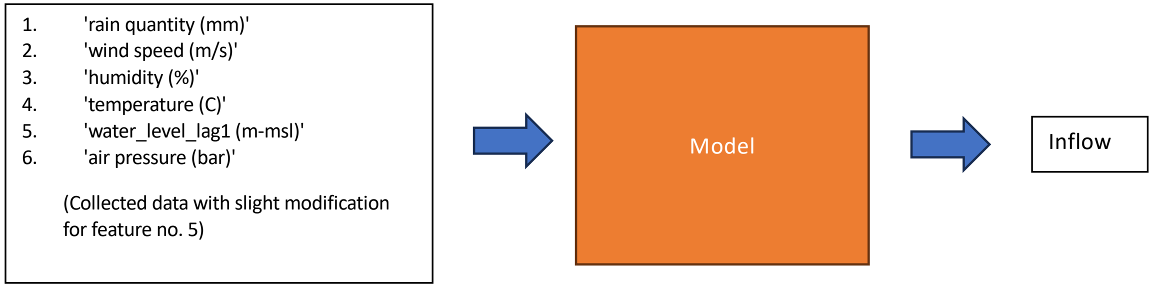
$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}, \qquad (1)$$

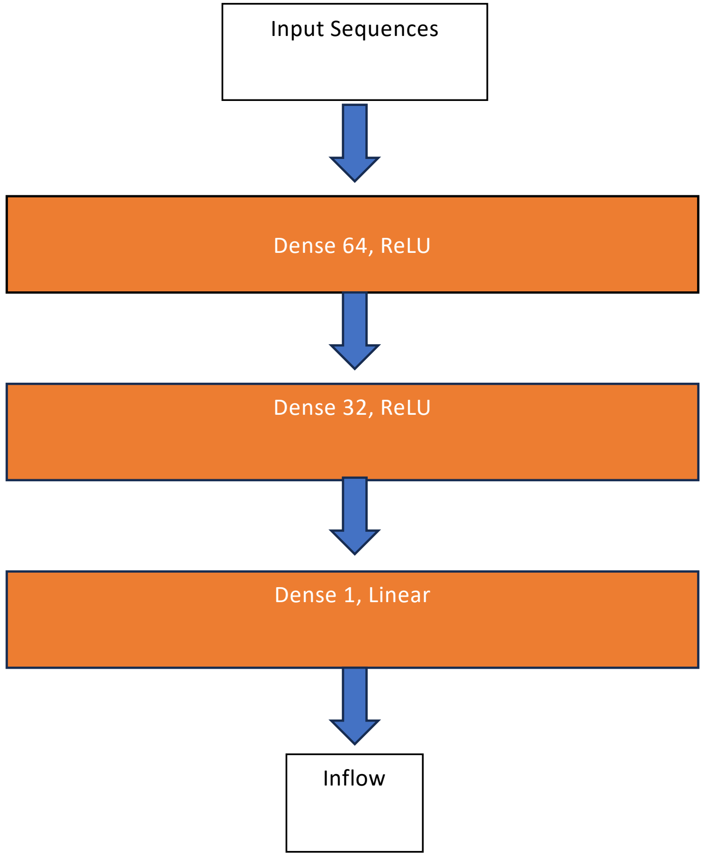
$$CC = \frac{\sum_{i=1}^{n}(y_i-\bar{y})(\hat{y}_i-\bar{\hat{y}})}{\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2 \sum_{i=1}^{n}(\hat{y}_i-\bar{\hat{y}})^2}} \qquad (2)$$

The performance of the regression models is evaluated using the Root Mean Square Error (RMSE) and Correlation Coefficient (CC), as expressed in Eqs. (1) and (2), respectively:

- RNNs are can capture long-term dependencies within the data—making them highly effective for sequence forecasting tasks.
- The RNN utilizes Backpropagation Through Time (BPTT), which helps mitigate the vanishing gradient problem.

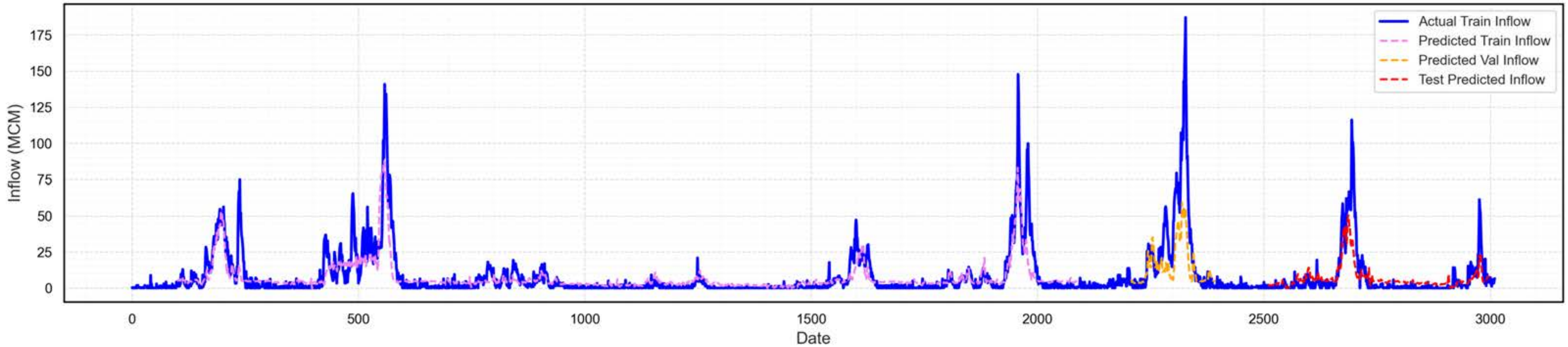
Machine Learning Model for Inflow Forecasting





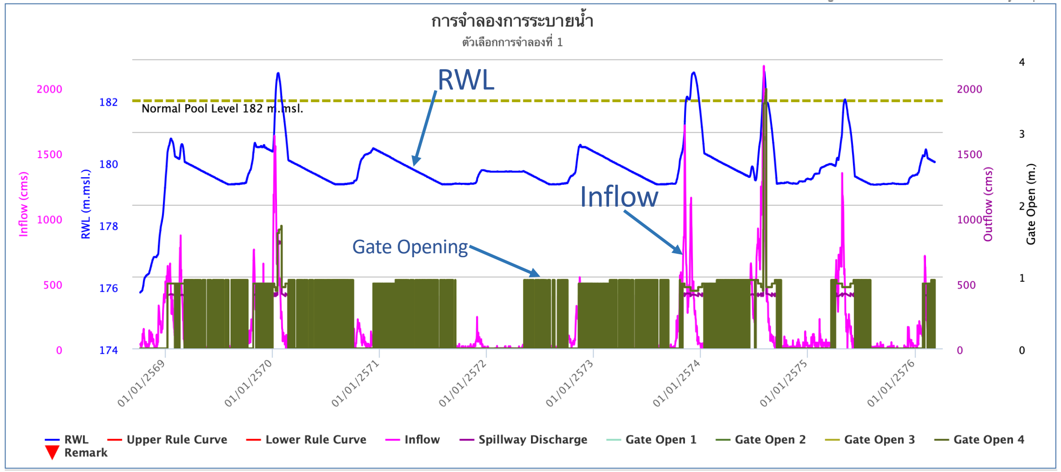
- **The model has three RNN layers consisting of 64 units with ReLU activation function, 32 units with ReLU activation function, and 15 unit with linear activation function.**
- **Six environmental parameters were collected by the developed Remote Terminal Unit and used as inputs to the model.**
- **The dataset was split into 70% training data, 20% validation data, and 10% testing data.**
- **Huber loss is used for loss evaluation during the training phase. Huber loss combines Mean Squared Error (MSE) and Mean Absolute Error (MAE), making it less sensitive to outliers.**

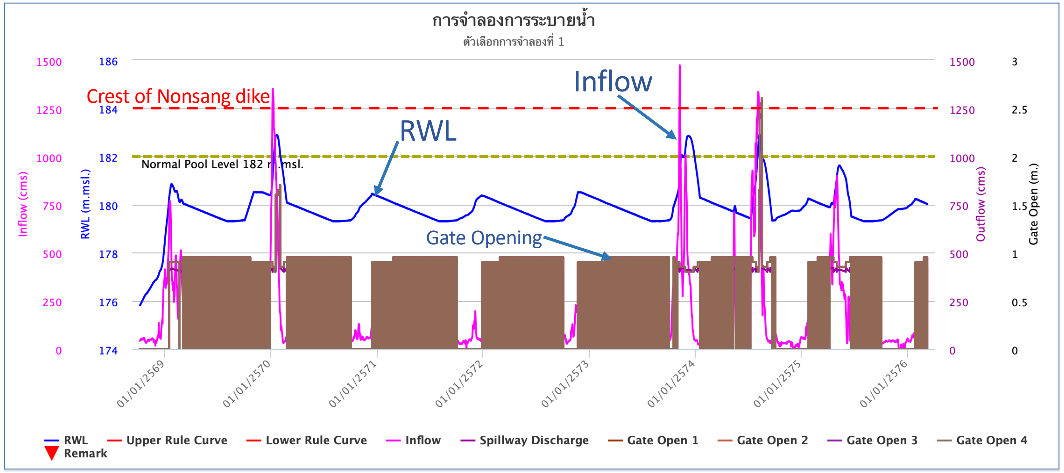
Simulation results



- Experiments were conducted to determine the settings and parameters that yielded the best model performance.
- The number of epochs, batch size, and lookback size were set to 100, 64, and 100, respectively, to predict 15 inflow outputs.
- The best performance—with a CC of 0.8231 and an RMSE of 11.72 MCM—was achieved

Simulation results





Integrated flood routing simulation

Flood simulation results from actual inflow.

- Multiple sharp peaks of inflow caused steep increases in RWL.
- RWL peaks lagged several hours behind the inflow peaks.
- the spillway gates were opened up to 3.5 m, resulting in outflows that closely mirrored the high inflow hydrograph.
- In the predicted inflow case, a similar inflow hydrograph , RWL, and gate opening patterns can be observed.

Flood simulation results from predicted inflow.

Conclusion

- A cyber-to-real-world integrated testbed named CyReal was designed and applied for dam safety management and water governance in emulation mode.
- An IoT gateway was developed to collect environmental data and to transmit these data to an RNN-based inflow forecasting model implemented on the CyReal testbed.
- Using daily environmental data from 2016 to 2024, the proposed model was able to forecast 15-day-ahead inflows with a correlation coefficient greater than 0.8, representing an improvement over previously reported models based on monthly large-scale indices.
- By combining 15-day-ahead inflow forecasts with the flood routing simulation, the forecasted inflow that most closely matched the actual inflow was directly input into the simulation. . This approach enabled the determination of optimal spillway operation rules that better reflect real-world conditions in advance.


Thank you for your attention
Q & A