REAL-TIME ADAPTIVE CONTROL (RTAC) FOR STORMWATER MANAGEMENT: A COMPREHENSIVE STUDY ON IMPLEMENTATION AND CASE STUDIES IN BRISBANE AND SYDNEY

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INTRODUCTION

Real-Time Adaptive Control offers a dynamic solution to these issues by employing real-time monitoring, predictive algorithms, and automated control mechanisms. Unlike fixed-threshold systems, RTAC can modify its behavior continuously in response to current and forecasted conditions. It uses a network of sensors, cloud computing platforms, and artificial intelligence to anticipate changes in rainfall and runoff, adjusting water release and storage strategies accordingly. By examining its implementation in Brisbane and Sydney, this paper evaluates RTAC's potential to modernize urban stormwater systems, enhance water security, and reduce the risk of flooding. At the core of RTAC is a flexible system design that includes water level sensors, computer-controlled valves, and predictive modeling software that all communicate through a centralized control platform. These components allow operators to manage urban water resources with greater precision and efficiency, enabling the storage of stormwater for future use while mitigating the risk of overflow and infrastructure failure.

YEAR CASE STUDY WAS IMPLEMENTED

2019 to 2023

CASE STUDY SUMMARY

This study examined the implementation of Real-Time Adaptive Control (RTAC) systems in urban stormwater management through pilot projects conducted in Brisbane (2019) and Sydney (2020-2023). The research aimed to evaluate RTAC's effectiveness in mitigating flood risks, optimizing stormwater storage, and enhancing operational responsiveness through advanced monitoring and control technologies.

In Brisbane, the pilot project tested a 500L water tank system equipped with ultrasonic water level sensors and a WiFi-controlled valve. The system utilized 12-hour rainfall forecasts to dynamically adjust water release strategies, demonstrating successful prevention of tank overflow during heavy rainfall events in March 2019. The Sydney implementation expanded on this foundation, deploying RTAC across multiple interconnected water tanks while incorporating more sophisticated LSTM-based rainfall prediction models and sensor fusion techniques to improve decision-making accuracy.

Key technological components included edge computing for low-latency local processing, cloud-based analytics for system-wide optimization, and low-power IoT networks (LoRaWAN and NB-IoT) for reliable device communication. The results showed significant improvements in flood prevention through proactive water release strategies and enhanced stormwater harvesting potential for non-potable uses. However, the studies also identified challenges in sensor calibration consistency and the need for more robust coordination between edge devices and central cloud systems, particularly when scaling to larger urban deployments.

METHODOLOGY

Key to this process is the integration of data streams from ultrasonic sensors, weather information from Bureau of Meteorology (BOM), and local infrastructure. The system processes this information in real time, using it to inform decisions on when to release or retain water. For example, if a significant storm is forecasted, the system will initiate an early release from water tanks to create additional capacity. This proactive strategy reduces the risk of downstream flooding and improves the overall efficiency of water management.

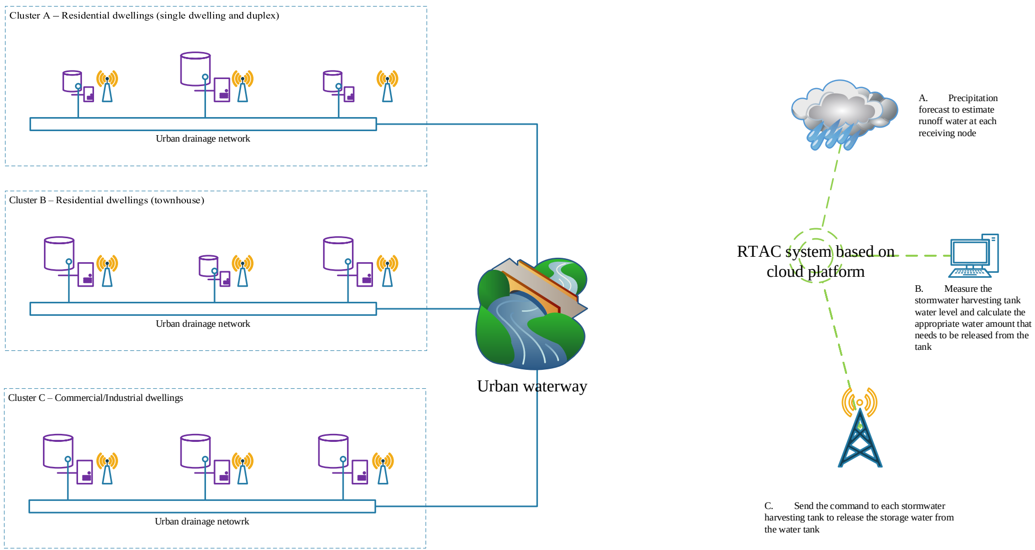

Figure 1 The control logic of the RTAC model (Meng, 2019)

Control panels serve as the operational hub, coordinating the flow of data between sensors and actuators while also linking to cloud platforms for higher-level analysis (Meng, 2019). Water levels are measured using ultrasonic sensors, which provide accurate, real-time feedback on tank conditions. Based on this data, computer-controlled valves adjust water flows automatically. The decisions behind these actions are driven by cloud-based software, which processes sensor inputs and weather forecasts through predictive algorithms to determine the most effective course of action. This dynamic interplay between physical and digital components allows RTAC systems to shift from static infrastructure toward intelligent, responsive stormwater networks.

SYSTEM ARCHITECTURE AND TECHNICAL IMPLEMENTATION

RTAC's control logic operates on a finite state machine model, shifting between three modes-monitoring, pre-release, and emergency response-based on real-time environmental inputs (Meng, 2019). These operational modes are triggered by water level data and weather forecasts. Unlike traditional systems that respond to pre-defined triggers, RTAC uses predictive algorithms to forecast potential flooding and adapt accordingly. This forward-looking logic enhances responsiveness and improves resource management.

The system's algorithm is written in Python and structured using multi-threaded programming. This allows simultaneous processing of multiple data streams and actuator commands, which is essential for real-time performance. The controller evaluates current water levels and weather forecasts to determine the operational state. If both indicators suggest a high risk of overflow, the system initiates a controlled pre-release of water to maximize available storage.

Edge Computing and Sensor Fusion Edge computing plays a pivotal role in reducing the system's reliance on cloud infrastructure for every decision. By placing microcontrollers near the data source, the system can process and respond to sensor inputs locally, minimizing latency and improving efficiency. This is particularly valuable in time-sensitive scenarios where immediate action is necessary to prevent flooding.

Sensor fusion techniques are applied to refine and validate incoming data. Multiple sensors feed information into the system, and techniques such as Kalman filtering are used to eliminate noise caused by environmental factors like wave motion or debris. The processed data is then transmitted to the cloud platform for higher-level analytics, ensuring that only accurate, reliable information is used for decision-making. This layered approach to data processing strengthens the RTAC system's ability to function under diverse and challenging urban conditions.

These data inputs are fed into control units, typically programmable logic controllers or embedded microcontrollers, that serve as the decision-making core of the RTAC system. These units execute algorithms to determine when and how water should be retained or released. Actuators such as motorized valves, pumps, and mechanical gates then implement these decisions in the physical environment. Valves regulate outflows from water tanks, while pumps transport water to elevated storage or treatment facilities when needed. Gates and barriers can be used to manage the flow in larger stormwater systems.

Communication between all system components is supported by reliable, energy-efficient wireless technologies. Low-power wide-area networks (Zigbee, LoRaWAN, and NB-IoT) enable seamless data transmission between devices even across large urban settings. These protocols offer the benefit of long-range operation and low bandwidth requirements, making them ideal for dispersed sensor networks. Localized data processing through edge devices further reduces the need for constant data transmission, freeing up network capacity and speeding up system responsiveness.

Once processed at the edge, data is transmitted to a centralized cloud platform, where it is aggregated, stored, and analyzed. This platform supports advanced analytics and visualization tools, offering operators insights into system performance and enabling remote control when necessary. As these systems depend heavily on connectivity and automation, cybersecurity measures such as encryption, secure transmission protocols, and role-based access control are essential to protect against potential threats.

A crucial part of RTAC's predictive capability is its analytical modeling for future rainfall and runoff. The system uses a mass balance model that incorporates historical rainfall data, forecasts, and reserved capacity to determine storage requirements and guide water release decisions. One of the key metrics used in this model is the recovery capacity factor (*M*), which quantifies the available storage between storm events (Meng, 2018; Meng, et al., 2023):

$$M_{\_current} = Volume_{\_previous} - Rain\_forecast_{\_previous} - Rain\_forecast_{\_current} - Storage_{\_for\_use}$$

Rainfall forecasting is carried out using a PyTorch-based Long Short-Term Memory (LSTM) model, trained on historical and real-time atmospheric data. This model processes temporal data to generate probabilistic rainfall predictions, which feed into the control logic of the system to inform decision-making.

<u>CASE STUDIES</u>

In 2019, a pilot study was conducted in Brisbane to test the effectiveness of the RTAC system in a practical environment. The pilot project aimed to assess the performance of the RTAC model in real-world conditions and identify potential limitations that may impact its effectiveness. The RTAC system comprised a 500L water tank, a water tank level sensor, a Wifi control water valve, and an innovative adaptive control system designed to manage precipitation forecast information and evaluate the storage capacity in the RTAC model.

The selection of Brisbane as the testing location was a carefully considered decision. The city is situated in a region that experiences more rainfall, especially during the months of January to

March, which was the period selected for this project's study. Additionally, Brisbane is known for having overland flow flooding issues and more flooding damages compared to other cities, making it an ideal location for testing the water tank level sensor and control valve.

Fig. 2 presented the logic of the connection of the project. The water tank utilized in this project had a capacity of 500L and was fitted with an ultrasonic water tank level meter sensor. The installation of the sensor was done at the top of the water tank to enable it to measure the water level accurately. The water tank level meter sensor employed an ultrasonic transmitter unit to measure the water level, ensuring high accuracy and reliability. The system had an intuitive interface that displayed the measured water level on a bar graph, allowing individuals to monitor the water level in real-time. Additionally, the system allowed users to set alarms for specific water levels, such as high and low levels or when the tank was empty, ensuring that the water storage requirements were met.

To manage stormwater runoff in real-time, this pilot project utilized a WiFi-controlled valve, which allowed them to control the release amount of water from the water tank remotely. The valve was connected to the computer system through an Android application program, which enabled remote control of the valve from anywhere using a smartphone. The WiFi-controlled valve was designed to be easy to install and safe to use, as it did not require any plumbing work and could be easily fitted over the existing levered ball valve. The valve adopted standard WiFi protocol, ensuring that it was compatible with most devices. Additionally, the valve had a high reliability rate and was designed with an automatic feature that turned off the water valve and sent a notification to the smartphone app when it detected water level reached to 400L level, ensuring the available capacity in the system (Fig. 2).

This project implemented an Android control system to manage rainfall data and control the water valve's release from the tank. The software was developed to provide an intuitive interface that allowed individuals to monitor rainfall data and control the valve remotely through the application program. The software was straightforward to operate and efficient, rendering it a suitable solution for managing the stormwater runoff in real-time.

The water tank level sensor and control valve system utilized in this project were designed to provide an efficient solution for managing stormwater runoff in real-time. The system was easy to install, safe to use, and highly reliable, rendering it a suitable solution for urban planners looking to manage the stormwater runoff in their cities. Additionally, the system had a smart control system, allowing individuals to monitor the water level in real-time and set alarms for specific water levels, ensuring that varying water storage requirements were met.

This pilot project is the first time to test the RTAC control system in the RTAC model to control Runoff Water Dynamically Through a Wifi based System, which enabled the model to adapt to changing weather conditions and adjust the system in real-time. The RTAC model can accurately calculate the reduced amount of runoff, which is critical in managing stormwater runoff effectively, particularly in high-runoff, low-drainage-capacity zones.

The three-month test for the RTAC model started on 1st January 2019, during which the project used a 12-hour rainfall forecast to analyze the release water amount from the water tank. As the rainfall in the first and second months was very limited, the real test started from the middle of March 2019. On 16th, 17th, and 18th of March, the RTAC system released three times 300L water from the tank (the release amount is set as 300L per time as the default), resulting in the balance in the tank being 385L, 474L, and 303L after each release, respectively.

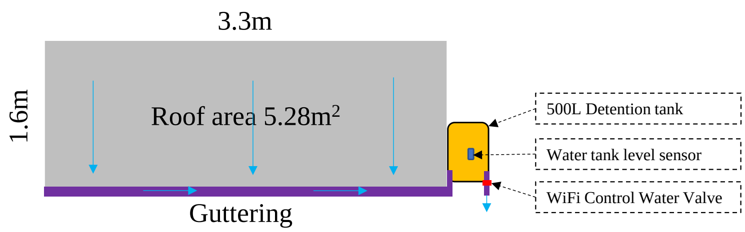

Figure 2 Conceptual model for the experimental design conducted in 2019 (Meng, 2019)

In this study, the model can calculate the reduced amount of runoff in different scenarios, including 12EY (exceedances per year), 6EY, 4EY, 2EY, and 1EY, enabling urban planners to design effective stormwater management systems and reduce the risk of flooding. The RTAC model can also analyze precipitation forecast information to calculate the accurate release amount from the water tank based on the forecast, enabling urban planners to predict the amount of runoff and adjust the system accordingly. By analyzing precipitation forecasts, the model can optimize the release amount from the water tank, reducing the risk of flooding.

In the Sydney case study, a more extensive RTAC deployment was implemented across a network of water tanks. This system integrated multiple sensors and forecasting models to manage stormwater runoff on a community-wide scale (Meng, et al., 2023). The RTAC system dynamically adjusted water releases based on real-time weather data, reducing the risk of flooding and easing the burden on the city's stormwater infrastructure (Meng, et al., 2022; Meng, et al., 2023).

One of the most critical insights is the importance of real-time data in driving effective decision-making. The systems' ability to respond to rapidly changing weather conditions enabled efficient use of stormwater detention facilities and minimized the likelihood of overflows. Predictive modeling further enhanced this capability by allowing preemptive adjustments based on anticipated weather events.

The integration of IoT-based sensors and edge computing proved vital for system responsiveness. Local data processing meant that control actions could be executed without delay, a key requirement in flood-prone scenarios where every second counts. Nevertheless, challenges such as sensor accuracy and data consistency emerged, often due to environmental interferences. Addressing these issues will require ongoing refinement of sensor fusion techniques, sensor calibration, and algorithm robustness.

Scaling RTAC systems to larger urban areas presents additional complexity. Bigger cities often involve more intricate infrastructure, diverse environmental conditions, and larger datasets (Meng, 2022). Managing multiple stormwater assets simultaneously demands sophisticated control logic capable of coordinating complex, real-time responses without sacrificing performance. This scaling effort will also require more extensive sensor networks, reliable communication protocols, and scalable cloud infrastructure.

DISCUSSIONS

The case studies in Brisbane and Sydney have offered valuable insights into RTAC's capabilities and the broader implications for urban stormwater management. Both projects showcased how RTAC can manage stormwater flows more effectively, reduce flooding risks, and optimize water reuse strategies.

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Fig. 3 presented the difference between the conventional and RTAC model in the stormwater storage management. The RTAC system is designed to optimize the management of stormwater harvesting facilities in developed areas. The key component of the system is the control logic, which uses real-time data to make decisions about how to manage the flow of water through the system.

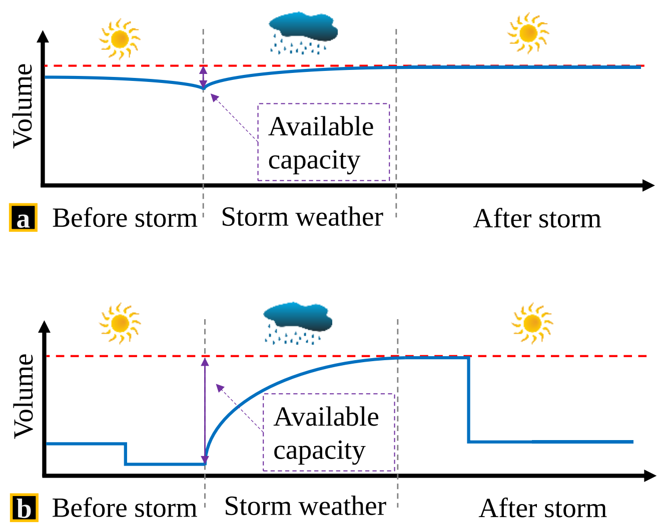

Figure 3 Water storage performance of individual stormwater storage facilities in the (a) conventional model and (b) RTAC model during very frequency rainfall events

The control logic is configured to perform several functions that are critical to the efficient management of stormwater harvesting facilities. One of the key functions is to discharge water in advance of storm events if necessary to create storage capacity. This enables the system to ensure that the system is prepared to capture and store as much runoff as possible during a storm event. Another key function of the control logic is to minimize discharge during storm events. This enables the system to reduce the amount of runoff that enters the urban drainage network, which can help to alleviate the pressure on the network during heavy rain events. By minimizing the amount of discharge during a storm event, the system can also retain more water for future use, such as for irrigation or other non-potable uses.

Water reuse from stormwater storage tanks provides numerous advantages that contribute to sustainable water management and address pressing water-related challenges. By harnessing the potential of captured stormwater for non-potable uses, there are unlock a range of benefits.

One of the primary advantages of water reuse is the reduction in demand for freshwater resources. By utilizing stored stormwater for non-potable purposes such as irrigation, industrial processes, or toilet flushing, lessen the reliance on traditional freshwater sources. This reduction in freshwater demand helps to conserve valuable water supplies, especially in regions where water scarcity is a significant concern. It also reduces the strain on existing water infrastructure, including water treatment plants and distribution networks (Meng & Kenway, 2018).

Moreover, water reuse from stormwater storage tanks promotes water sustainability by alleviating the burden on water treatment and supply infrastructure. Traditional water treatment processes require significant energy and resources, and they often involve complex treatment methods to ensure water quality and safety. By utilizing captured stormwater for non-potable purposes, the system can reduce the amount of water that needs to undergo extensive treatment, thus reducing energy consumption and the associated environmental impact. This, in turn, contributes to the overall sustainability of the water supply system.

In areas facing water scarcity or experiencing drought conditions, water reuse from stormwater storage tanks becomes particularly valuable. These regions often struggle with limited water availability, increased competition for water resources, and the need to implement strict water conservation measures. By reusing captured stormwater, communities can alleviate the strain on local water sources and mitigate the impact of drought. This enables the system to ensure a more reliable water supply for essential non-potable uses, such as landscaping, industrial processes, or firefighting. The subsequent study will aim to provide clarification on the effective utilization of stored water from these storage systems.

In addition to minimizing discharge during storm events, the control logic is also designed to withhold water directly after storm events to allow the downstream stormwater trunk drainage system to regain capacity. This is important because the downstream drainage system can become overwhelmed with runoff during a heavy rain event, which can lead to flooding and other problems. By withholding water from the stormwater harvesting system after a rain event, the downstream drainage system has time to recover, which helps to prevent flooding and other issues. Once the downstream drainage system has regained capacity, the control logic can then release water from the stormwater harvesting system. This approach ensures the system is prepared for the next rain event, and that it has sufficient capacity to capture and store runoff.

Overall, the control logic of the RTAC system is designed to optimize the management of stormwater harvesting facilities in developed areas. By using real-time data to make decisions about how to manage the flow of water through the system, the RTAC system can help to reduce the impact of stormwater runoff on the urban drainage network, while also maximizing the use of captured runoff for non-potable uses .

Looking ahead, RTAC systems are poised to benefit from advancements across several domains. Integration with smart city technologies could facilitate data sharing across infrastructure systems, creating more efficient and resilient urban environments. Improvements in machine learning and artificial intelligence will enhance predictive accuracy, especially when combining diverse data sources such as satellite imagery and socio-economic data.

The progression toward autonomous control and decision-making is another promising development. As AI capabilities mature, RTAC systems could independently optimize water release strategies, minimizing the need for human intervention. Additionally, incorporating climate change projections into predictive models will allow RTAC systems to anticipate and adapt to long-term environmental shifts, such as increased rainfall variability or rising sea levels.

CONCLUSION

RTAC systems offer a robust, data-driven solution for modern urban stormwater management. By harnessing real-time data and advanced predictive modeling, RTAC enhances the efficiency of stormwater storage and release, thereby reducing flood risks and supporting water conservation. The positive outcomes of the Brisbane and Sydney case studies highlight RTAC's potential to transform urban stormwater infrastructure. As cities confront the dual challenges of climate change and urban growth, RTAC systems stand out as a critical tool for building resilient, sustainable urban environments.

REFERENCES

Meng, X., 2018. *Water sensitive infill development - A Case Study for the Norman Creek catchment using water mass balance,* Brisbane: University of Queensland.

Meng, X., 2019. *The real-time adaptive control (RTAC) research and practical applications,* Brisbane: unpublished.

Meng, X., 2022. Understanding the Effects of site-scale Water Sensitive Urban Design (WSUD) in urban water cycles – a review. *Blue-Green Systems,* 4(1), pp. 45-57.

Meng, X. & Kenway, S., 2018. Analysing water sensitive urban design options - Using water mass balance to analyse hydrological performance of water sensitive urban design options in infill development. *Water e-Journal,* 3(4), pp. 1-18.

Meng, X. et al., 2023. Impacts of site real-time adaptive control of water-sensitive urban designs on the stormwater trunk drainage system. *Journal of Water Process Engineering,* Volume 53, p. 103656.

Meng, X. et al., 2023. Assessing the effectiveness of site real-time adaptive control for stormwater quality control. *Journal of Water Process Engineering,* p. 104324.

Meng, X. et al., 2022. Improved stormwater management through the combination of the conventional water sensitive urban design and stormwater pipeline network. *Process Safety and Environmental Protection,* Volume 159, pp. 1164-1173.