Present and future hydrologic performance assessment of a Water Sensitive Urban Design (WSUD) system using low-cost monitoring: A case study in Singapore

Évaluation de la performance hydrologique présente et future d’une technique alternative à l’aide d’un système de suivi à faible coût : Cas d’étude à Singapour

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RÉSUMÉ

La conception urbaine sensible à l’eau (WSUD) est au cœur de la gestion intégrée de l’eau en milieu urbain dans le monde entier, soulignant la nécessité d’un suivi fiable. Grâce à leur faible coût et à leur flexibilité en matière d’exploitation et de communication, les systèmes de capteurs à bas coût présentent un fort potentiel pour généraliser la gestion numérique de l’eau. Cependant, les implications liées à l’utilisation de données inexistantes, de données de faible qualité ou de données hydrologiques de haute qualité pour l’évaluation des dispositifs WSUD et le développement de modèles restent mal comprises. Cette étude a utilisé un modèle hydrologique (PCSWMM) pour évaluer un système WSUD à Singapour en comparant un modèle non calibré, un modèle calibré avec des données provenant de capteurs à bas coût et un modèle calibré avec des données issues de capteurs traditionnels sous les climats actuel et futur. Le modèle non calibré sous-estimait généralement la hauteur d’eau, le ruissellement et les volumes d’écoulement, tout en surestimant la réduction du ruissellement et de l’écoulement d’environ 2 % à 6 %. Ces biais ne sont pas universels et dépendent des conditions du site et de la configuration du modèle. Le capteur à bas coût a montré des performances comparables à celles du capteur traditionnel pour la calibration du modèle et l’évaluation de la performance hydrologique. Dans l’ensemble, l’étude souligne la valeur des capteurs à bas coût pour fournir des données empiriques et améliorer la modélisation hydrologique dans l’évaluation des dispositifs WSUD sous les climats actuel et futur.

ABSTRACT

Water Sensitive Urban Design (WSUD) is central to integrated urban water management worldwide, underscoring the need for reliable monitoring. Being economical and flexible for operation and communication, low-cost sensor systems show great potential to mainstream digital water management. Yet, the implications of using no data, low-quality data, or high-quality hydrologic data for WSUD assessment and model development remain unclear. This study used a hydrologic model (PCSWMM) to evaluate a WSUD system in Singapore by comparing the uncalibrated model, model calibrated with low-cost sensor data, and model calibrated with traditional sensor data under present and future climate. The uncalibrated model generally underestimated water depth, runoff, and outflow volumes, while overestimating runoff and outflow reduction by about 2%–6%. These biases are not universal and depend on site conditions and model configuration. The low-cost sensor performed comparably to the traditional sensor in model calibration and hydrologic performance assessment. Overall, the study highlights the value of low-cost sensors in providing empirical evidence and improving hydrologic modelling for WSUD evaluation under present and future climate.

KEYWORDS

Low-cost Sensor, Personal Computer Storm Water Management Model (PCSWMM), Rain Garden, Hydrologic performance, Water Sensitive Urban Design

INTRODUCTION

Water Sensitive Urban Design (WSUD), developed since the 1990s in Australia, integrates structural measures such as green infrastructure with non-structural strategies like water-efficiency policies to mitigate the hydrological impacts of urbanisation (Fletcher *et al.*, 2015; Kuller *et al.*, 2017). However, recent reviews show that WSUD performance assessments, especially in Southeast Asia, generally overlook uncertainties, rarely conduct sensitivity or uncertainty analyses, and lack transparent calibration, resulting in low confidence in reported WSUD effectiveness (Hamel and Tan, 2021; Pons *et al.*, 2023). Continuous monitoring is further constrained by budget limitations, technical expertise, and restricted knowledge sharing, particularly in developing regions where long term and standardised datasets are still lacking (Mao *et al.*, 2019; Chan *et al.*, 2021). These gaps highlight the need for improved monitoring systems, stronger calibration and validation practices, and cost-effective approaches such as low cost, open-source sensors to support robust, evidence-based evaluation of WSUD performance (Zhu *et al.*, 2023; Hamel *et al.*, 2024). To address these challenges, this study pursues three main objectives: 1) to assess the performance of a real-time low-cost water level monitoring system, 2) to calibrate and validate a hydrologic model using field observations, and 3) to assess the uncertainties in the evaluation of the hydrologic performance of the WSUD system using the low-cost and traditional monitoring system, under present and future climate conditions. Through these objectives, the study seeks to demonstrate how empirical data can enhance the accuracy and reliability of hydrologic modelling for WSUD assessment and provide stronger insights for urban stormwater management.

METHODOLOGY

2.1 Case study

The study site is the NIE rain garden in Singapore, a system jointly developed by PUB, AECOM, Greenearth Consultants Pte Ltd., and the National Institute of Education, and officially launched in 2017. Located in an equatorial tropical rainforest climate with consistently warm, humid conditions and frequent short-duration, high-intensity convective storms, Singapore faces stormwater challenges typical of many Southeast Asian cities, including rapid rainfall variability, limited storage capacity, and recurrent flash-flood risks (Public Utilities Board (PUB) Singapore, 2018; Sun *et al.*, 2019). The rain garden has a conventional four-layer configuration comprising vegetation and ponding, a loamy-sand filter layer, a sand transition layer, and a gravel drainage layer with perforated pipes (**Figure 1**). It receives water from direct rainfall, a nearby drain, a staircase drain, and surface runoff from an 880 m² catchment, and discharges through an underdrain outlet sump and an overflow sump designed for a 3-month storm. The core filter area is 66 m² with a total landscaped area of 140 m², enabling the system to manage stormwater and regulate flows to the adjacent drainage network.

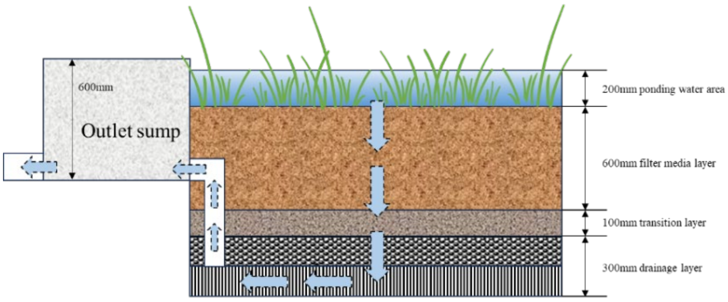

Figure 1. The cross section of the NIE rain garden shows its four functional layers. Blue arrows represent the water infiltration and percolation processes within the rain garden. Adapted from PUB & AECOM, 2015.

2.2 Real-time low-cost sensor monitoring system

The real-time field monitoring station was installed in the outlet sump of the NIE rain garden in June 2023. **Figure 2** illustrates the field setup of the monitoring station. The low-cost water level sensor KIT0139 and the traditional water level sensor OTT PLS were vertically mounted inside the outlet sump, secured to the wall using U clamps and screws. The bottoms of both sensors were positioned at the base of the sump. The low-cost digital temperature sensor DS18B20 was installed near the traditional OTT PLS sensor. The

Figure 2. Field setup of the real-time water-level monitoring station at the NIE rain garden.

DIY PCB board, which houses all the electrical connections, was placed inside a waterproof enclosure. Additionally, a V-notch weir was installed at the outlet pipe to maintain water levels above 0.05 m, thereby enhancing the reliability of the low-cost sensor measurements, as discussed in (N. Ding et al., 2025). The system measures water level and temperature and transmits real-time data at 5-minute intervals.

2.3 PCSWMM modelling setup and calibration

The PCSWMM 2023 Professional 2D model version: 7.6.3695 (64-bit), SWMM version: 5.0.013 - 5.2.4 was used for the modelling in this study. The entire catchment area is divided into five sub-catchments, labelled S1 through S5. Among these sub-catchments, S3 represents the core area of the rain garden, which serves as the primary zone for filtering and treating stormwater and runoff. This sub-catchment is fully occupied by the rain garden and designated as its main functional area. The rain garden was designed as a Bio-Retention Cell in the LID control editor, mimicking its four main layers: surface, soil, storage, and underdrain. The model simulation used 5-minute rainfall data from January 2023 to December 2024. Calibration involved refining parameter uncertainty ranges with the Sensitivity-Based Radio Tuning Calibration (SRTC) tool, followed by a two-stage process: 1) optimising the full-period NSE through parameter adjustments, and 2) manually fine-tuning parameters using the calibration event with the highest NSE to ensure close hydrograph agreement with observations.

2.4 Climate scenarios

Climate projections were requested from Singapore's Third National Climate Change Study (V3), including the 2 km convection-permitting SINGV-RCM outputs at 10-minute temporal resolution. Three CMIP6 emissions pathways were considered: SSP1-2.6, SSP2-4.5 and SSP5-8.5, representing low, medium and high emissions futures. Two future time windows are analysed, 2040–2060 for mid-century and 2080–2100 for end-century, consistent with IPCC AR6 climatological periods.

RESULTS

3.1 Performance of the low-cost sensor monitoring system in the field

The linear correlation between the low-cost sensor measurements and the traditional sensor measurements was examined using the dataset collected from 28th June 2023 to the end of November 2024 (about 18 months). Over the 18-month monitoring period, the traditional sensor (OTT PLS) provided reference water level measurements from June 2023 to August 2024 before the traditional sensor malfunctioned. Results showed that 9 out of 15 months, the low-cost sensor measurements showed strong linear relationship with traditional sensor measurements ($R^2 > 0.9$, $p < 0.001$). Manual water level measurements have been collected as reference measurements since May 2024. The results demonstrate a strong linear relationship between the raw readings from the low-cost sensor and the manual measurements over the measurement range (0.05–0.115m), with an R^2 value of 0.99 and a statistically significant p-value (< 0.001). In practice, it requires regular recalibration (monthly three-point calibration) to ensure MAE within 10 mm (except for January 2024 and April 2024) under field conditions, and frequent maintenance to address potential electrical disconnections and sediment buildup. **Figure 3** presents an example time series of measurements from the traditional sensor and the calibrated low-cost sensor, including the 95% prediction interval, for July 2023.

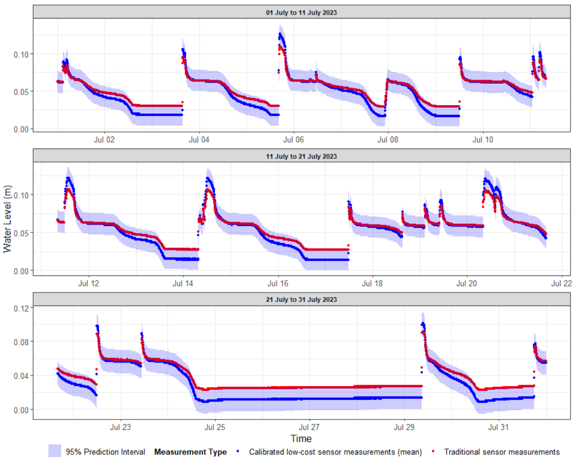

Figure 3. Time series plot for the traditional sensor and calibrated low-cost sensor measurements with 95% prediction interval in July 2023. Note that the prediction intervals for values below 0.05m may be underestimated due to the known sensor inaccuracy below that water level.

3.2 Performance of rain garden and uncertainties under current and future climate

The NIE rain garden's stormwater retention was evaluated using peak runoff, total runoff, and total outflow. The uncalibrated model generally underestimated these values but overestimated their reduction rates, with peak runoff reduced by ~2% and total runoff and total outflow by ~6% compared to the calibrated models. Assessment across six calibration events showed similar trends (**Figure 4**), underscoring the importance of calibration. Calibrated models using low-cost and traditional sensors produced comparable results including similar ranges of values and reduction rates, confirming the comparable effectiveness of both sensor types for model calibration.

Calibrated models showed that the NIE rain garden reduces runoff and outflow by roughly 11%–16% of the catchment. This is lower than the 21%–72% reduction reported for other WSUD units in Singapore (Tan *et al.*, 2019), likely due to over seven years of operation with lack of effective routine maintenance, high soil moisture from successive storms and frequent precipitation typical in Singapore, and its small size, with a core area of 66 m² (about 7.5% of the 880 m² catchment) designed for a 3-month storm. Modelling with future climate data is ongoing due to delays with data acquisition. The updated results will be reported at the conference.

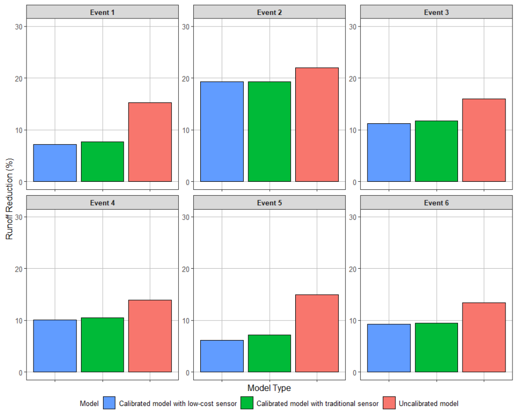

Figure 4. Total runoff reduction (%) of the NIE rain garden across six calibration events for three model types: 1) uncalibrated model; 2) calibrated model with low-cost sensor; and 3) calibrated model with traditional sensor.

CONCLUSIONS

Using the NIE rain garden as a WSUD case site, this study examined the contribution of field observations from both low-cost and traditional sensors to the performance of the hydrologic model (PCSWMM) in modelling the WSUD system, as well as to the assessment of the WSUD system's performance for stormwater retention under current and future climate. The uncalibrated model generally underestimated outlet water depth and overestimated runoff and outflow reduction, though such biases may vary with site conditions, data quality, and parameter choices. Models calibrated with either low-cost or traditional sensors achieved similarly strong performance, accurately reproducing water-depth dynamics and improving key error metrics. Despite lower field accuracy, the low-cost sensor provided sufficiently consistent data for reliable calibration and hydrologic assessment. Both calibrations substantially enhanced the model's ability to simulate realistic runoff and outflow outcomes compared to the uncalibrated model. Overall, the study shows that consistent low-cost sensor data can offer benefits comparable to traditional sensors, supporting cost-effective evaluation of WSUD performance. Future research may extend this approach to multiple WSUD types and sites to validate its applicability at larger scales.

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