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Water Sensitive Urban Design performance in Singapore: monitoring with low-cost sensors

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SUMMARY

The ABC Waters Programme, with its design based on Water Sensitive Urban Design (WSUD), has successfully implemented stormwater control systems across Singapore for 15 years. Yet, there is relatively little attention paid to monitoring ABC Waters features' medium to long-term performance. Compared with traditional monitoring system, low-cost sensors' technology presents economic advantages and flexibility for operation and communication. In this study, we aim to 1) analyse the potential of low-cost sensors for medium to long-term monitoring of WSUD in Singapore; 2) propose a monitoring protocol that can be promoted and used widely. The monitoring system we present is composed of low-cost sensors and Arduino platform. Several kinds of sensors have been identified from a literature review, and lab testing for sensors is in progress. After completing the testing, the monitoring system will be established in site to monitor the performance of WSUD in improving water quality and reducing runoff.

KEYWORDS

ABC waters Programme, Low-cost sensors, Monitoring system, Water sensitive urban design

1 INTRODUCTION

Cities worldwide are currently facing numerous water-related challenges, such as water scarcity, poor water quality, and floods, which have enormous human and economic impacts (O'Donnell & Netusil, 2021). Low Impact Development (LID) and Water Sensitive Urban Design (WSUD) are widely used urban water management approaches around the world, providing a unified method for integrating the interactions between the water cycle and the water utilities systems to create multi-functional landscapes and infrastructures in cities (Gleason, 2021). The effectiveness of WSUD has been extensively studied, including stormwater runoff reduction (Li et al., 2021), water infiltration (Gunnell & Mulligan, 2019), and water purification (Tang et al., 2021). Many studies are conducted based on hydrological and ecological models, such as SWMM, MUSIC, MOUSE, SUSTAIN, HEC-RAS, CADDIES (Elliott & Trowsdale, 2007; Guidolin et al., 2016), which need to be calibrated by using observation data obtained from field investigation (Yin et al., 2021).

However, studies often lack empirical validation, especially in the Global South and Southeast Asia (Hamel & Tan, 2021). Relatively few studies have attempted to measure and quantify the medium to long-term performance of WSUD in runoff reduction and pollution mitigation, which can be explained by limited resources as traditional monitoring systems can be costly and time-consuming (Bertrand-Krajewski, 2021). Thus, it is urgent to develop low-cost, real-time, and autonomous monitoring network for existing WSUD systems. Compared with traditional monitoring equipment, low-cost sensors are affordable, typically have similar operation and maintenance requirements, and, by allowing a large decentralised spatial monitoring, have a great potential in environmental monitoring and emerging in many fields such as air quality, air temperature, and agriculture (Cherqui et al., 2020; Sun, Kato, & Gou, 2019). Such sensors have benefitted from recent technological advances regarding falling costs, miniaturisation, ease-of-access, modularity, and open-source programming.

Singapore has launched the Active Beautiful Clean (ABC) Waters Programme in 2006, promoting WSUD features in the city-state (Lim & Lu, 2016). The relatively limited monitoring efforts restrict the ability of public agencies and private developers to provide adequate maintenance for existing systems and to optimize the design of new systems (Hamel & Tan, 2021; Lim & Lu, 2016). In this study, we aim to 1) establish a continuous and autonomous water monitoring system by adopting low-cost sensors and assessing their performance, 2) monitor the medium to long-term performance of WSUD. The specific objectives are to: 1) collect information of low-cost sensors, and identify traditional and equivalent low-cost sensors for water quantity and quality monitoring, 2) test (in laboratory and in situ) and compare the multi-criteria performance of traditional and low-cost sensors, and 3) develop an experimental protocol to assess the performance (water quantity and quality) of WSUD systems.

2 METHODS

2.1 Selection of low-cost and traditional sensors

Some of the co-authors (Zhu et al., Review of Low-cost Sensors for Monitoring Stormwater Control Measures, under review, 2021) have reviewed the existing literature on low-cost sensors and compared the performance (range, resolution, response time, price range, previous uses and experiences) of different low-cost sensors in monitoring air humidity, conductivity, flow or velocity, nitrogen, pH, phosphorus, rainfall, soil moisture, solar radiation, turbidity, water level, and wind speed. Our candidate low-cost sensors are selected based on the findings from this review.

2.2 Lab testing of low-cost and traditional sensors

First, we tested low-cost water level sensors in the laboratory and compared them with the baseline (provided by a sensor that is widely used, with good accuracy and stability). Three widely used low-cost water level sensors (laser-ranging, ultrasonic-ranging, and pressure) and one baseline sensor (PLS, pressure transducer) were tested. The performance of these sensors was assessed in terms of range, accuracy, precision, and sensitivity to the environment. In addition, a low-cost meteorological monitoring station is also currently tested and compared with traditional sensors. In the next step, more types of low-cost sensors and traditional sensors will be systematically tested in the laboratory for final selection before being implemented on site.

2.3 Field experiment

2.3.1 Experimental site

The first pilot site is the cleansing biotope 2 in Yunnan Garden of Nanyang Technological University, located in the southwest of Yunnan Garden (Figure 2.1). The cleansing biotope 2 has a typical design including plants, cleansing layer (filter media inside), transition layer (for preventing filtration media from entering the drainage layer), drainage layer (for assisting in the drainage of the effluent), and geotextile layer. Through water recirculation, the cleansing biotope purifies water pumped through pipes from Yunnan Garden Wetland, and discharges the treated water back to the wetland and then to the nearby canal along the Expressway. In addition, part of the runoff from North-East of South Spine Catchment Area will also be purified by cleansing biotope 2 (Figure 2.1b).



Figure 2.1 The location (a) and water circulation (b) of cleansing biotope 2 in Yunnan Garden

2.3.2 Experimental protocol

The planned location of monitoring systems is shown in Figure 2.2. For the water quality, monitoring systems will be established in locations A/C and B in November 2021 (when the lab testing has been completed). For the water level and flow velocity, monitoring system will be established in locations D and C, respectively. Water quantity indicators include water level and flow velocity. Water quality indicators include nitrogen, phosphorus, turbidity and total suspended solids (TSS), pH, and conductivity.

For the data transfer, we use the Arduino Nano which sends sensor data to a nearby computer every minute through a USB cable. These data are recorded on the computer in a csv file. To ensure that the system is running continuously, a measure is sent online every 15 minutes and a remote control is installed on the computer. The lack of new data triggers an alert (email) and it is then possible to remotely control the computer and the setup.

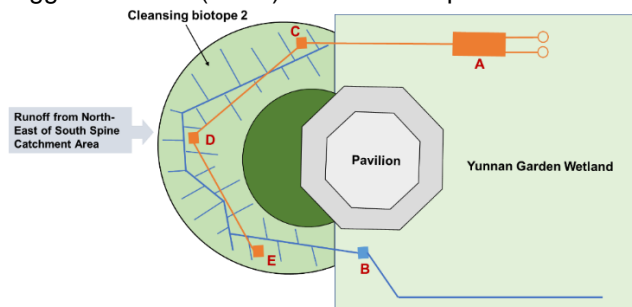


Figure 2.2 The planned locations of monitoring systems in cleansing biotope 2

3 RESULTS AND DISCUSSION

3.1 Review of low-cost sensors

The review of low-cost sensors provided the following recommendations: **1) For water level:** The JSN-SR04T (ultrasonic sensor) offers the best performance to price ratio with an accuracy of ± 7 mm in the range 0.225 ~ 1.9 m, and other pressure transducers, sold under different names (including KIT0139 from Gravity), provide similar levels of performance. **2) For flow or velocity:** There are two main methods to monitor water flow or velocity at a low cost. One is image-based method, another method uses Doppler velocity radar. For both methods, cameras and radars all showed a certain degree of accuracy in the field but all lack long-term experimental results. Preliminary research suggests that the ER sensor and flow sensor perform best. **3) For pH:** Three brands of pH sensors were found in the literature: Global Water WQ201, SensoreX S8000 and Atlas Scientific. In general, pH sensors from Atlas Scientific and SensoreX have the most potential. **4) For conductivity:** There are three commonly-used sensors for measuring conductivity: Atlas Scientific, DFRobot Gravity, and YL-69 (soil moisture sensor). In general, all of them deserve further testing. **5) For turbidity and TSS:** SEN0189 has good performance but its enclosure is not satisfactory for in situ usage, so it is important to find a way to protect it in water for a long-term. Solitax is a good sensor to work as a reference. **6) For**

nitrogen and phosphate: In general, the off-the-shelf nitrogen and phosphate sensors found in the literature were not low-cost, and they are more than 100 EUR or even 10,000 EUR. There are still some interesting low-cost sensors under development. As nitrogen and phosphate low-cost sensors are still under development, they will not be implemented in the first phase of the project, but will be considered again later when progress will have been reported about their applicability and availability.

3.2 Laboratory testing of low-cost sensors

Laboratory tests are in progress at the time of writing the abstract. The following table illustrates the water level low-cost sensors and the reference sensor that have been assessed by some of the authors (Table 3.1) (Cherqui et al., 2020). These results will be updated with the Singapore based laboratory testing. In addition, some of the authors (Zhu Q., 2021) are currently testing a low-cost meteorological monitoring station (rainfall intensity, air temperature and humidity, wind speed and direction, solar radiation) with positive results after 5 months of operation.

Table 3.1 Characteristics of the reference sensor and the low-cost sensors assessed according to the manufacturer. Testing results showed that the laser-ranging sensor VL53L0X is not suited for application with a required accuracy of ± 20 mm and the ultrasonic-ranging sensor JSN-SR04 T offers the best performance to price ratio.

	Reference sensor		Low-cost sensors		
Brand	OTT	STMicroelectronics	Unknown	TE	Several
Model	PLS	VL53L0X	JSN-SR04T	MS5803-01BA	KIT0139 (Gravity) or YB-2J-F
Price range	~ \$1,000 USD	< \$5 USD	< \$10 USD	< \$30 USD	< \$50 USD
Type	Pressure transducer	Laser-ranging module	Ultrasonic-ranging module	Pressure transducer	Pressure transducer
Meas. time	2s	< 200m	100ms ^b	8ms	unknown
Accuracy	$\leq \pm 2$ mm	$\leq \pm 36$ mm ^c	± 10 mm ^b	± 15 mm	unknown
Range	[0-4m]	[0-1.2] m ^c	[0.02-6] m ^b	[10-1300] mbar ^d	[0-5] m

3.3. Preliminary field results

The systems will be established in November 2021 after completion of the laboratory tests to select the best sensors. If accepted, the paper will share preliminary results from the experiment.

4 CONCLUSIONS

Though low-cost sensors have great potential in environmental monitoring, there is still little information on their real performance and use in urban water systems. In this study, we have conducted a literature review of different types of low-cost sensors, and we are currently testing the performance of three low-cost water level and meteorological sensors in the laboratory. Based on these works, we plan to test more types of low-cost sensors in lab and in situ in the next two months, and establish the low-cost sensors monitoring system at the cleansing biotope 2 in Yunnan Garden. If accepted, the paper will share preliminary results from the lab testing and on-site monitoring.

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