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FIELD DATA ANALYSIS OF HOME-BASED STORMWATER ON-SITE DETENTION SYSTEM

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Abstract: This paper describes the field test of a stormwater detention system which is a system designed to hold a specific volume of water and release it slowly over time, in this test case precast concrete modular units are assembled in a residential car porch and connected to a partial roof catchment via a downpipe. Stormwater is held and stored temporarily within the chambers created by the precast concrete pieces. Rainfall and flow data associated with the detention system in terms of the inflow, outflow and water levels data are collected and verification process are performed by comparing the collected data to design data for the intended system. Analyses of five storm events confirm that the estimated design inflow, outflow and water levels in response to 5- and 10-minute 10-year Average Recurrent Intervals (ARI) design rainfall are safe against the actual rainfall and actual detention and discharge performances.

Keywords: Car porch, StormPav, inflow, outflow, sustainable development, urban runoff, water level.
Abbreviations: Average Recurrent Interval (ARI), On-site Stormwater Detention (OSD), Research and Development (R&D)

Introduction

A field test analysis is a process of drawing conclusion based on data gathered in practical, real-world scenarios. It starts with the data collection from the test site. The lack of field data for stormwater systems is often reported in the available literature (Kohlsmith *et al.,* 2021; Zhang *et al.,* 2021). The test site, in this paper, refers to a field test of a stormwater detention system specifically tailored for use at home (Figure 1).

Figure 1: Field test for home-based StormPav green pavement system

A stormwater detention system is a man-made structure designed to hold stormwater so that the attenuation of running surface water in urban areas can be achieved (Hamel *et al.,* 2013; Prudencio & Null, 2018). The pre-cast concrete pieces in Figure 1 is the StormPav green pavement (StormPay) system a product that is still in its research and development (R&D) phase (Mannan *et al.,* 2016). One modular unit comprises three pieces, namely two hexagonal plates and one hollow cylinder (Figure 2).

The intention of this paper is to share the findings of the R&D of a university team on this product. Unlike any other commercial product available in the market, the product owners of StormPay are treating their data as a trade secret and publishers are unwilling to publish articles on the product.

First designed as a permeable road the modular units are easy to put together, it is (Bateni *et al.,* 2019). The hexagonal plate that forms the top layer can be used for pavement surfaces or in other applications such as walkways, parking lots and patios. Studies by Ngu *et al.* in 2016 and 2019 proposed the use of the StormPav system in residential car porches and conducted a small-scale laboratory experiment with computational fluid dynamic simulations. Extending from the same study, a full-scale field test with a set up depicted in Figure 3 is the focus of the current study.

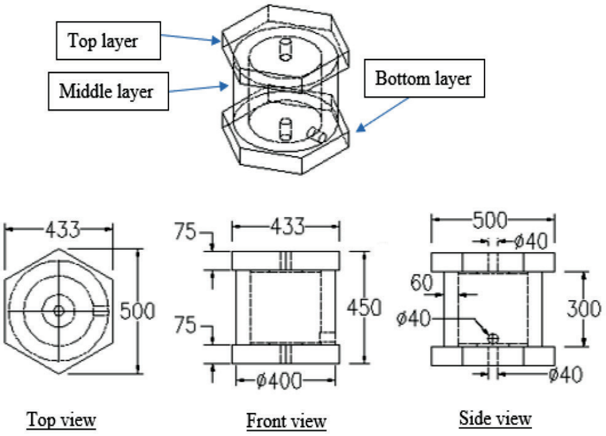

Figure 2: StormPav green pavement system

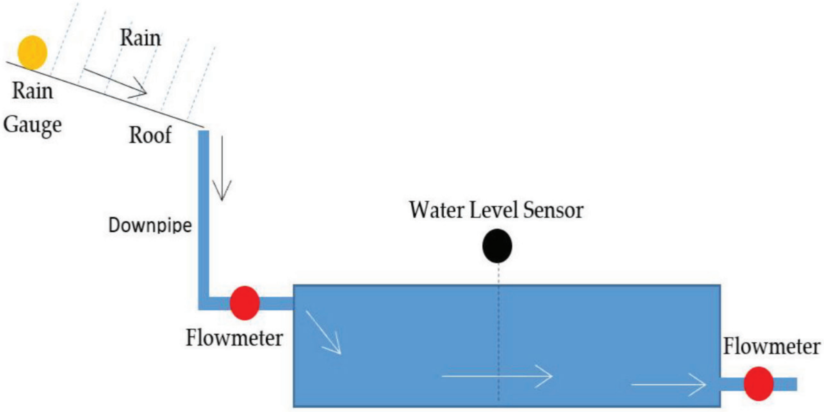

Figure 3: Schematic of field test set up

As set out in Mah *et al.* (2020), the field test was constructed in a house lot of a volunteer who agreed to be a part of the study has and allowed for a water-proof tank to be fitted under the side canopy of the house. Originally designed to be installed underground, the system was erected aboveground instead to allow for easier disassembly when the experiment was concluded. The 20.68 m^2 tank was filled with about 120 modular units of StormPav. The surface area of the system covers a two-car garage area that is common in most Malaysian households. The depth of the tank is 0.45 m. Its and its effective storage was estimated at 3.92 m^3.

A rain gauge was installed to record the rainfall on the 95 m^2 roof catchment area. A 0.1 m-diameter downpipe was connected to a flowmeter before entering the tank filled with StormPav. The detained water in the tank was then measured by the water level sensors on either side of the tank. Another flowmeter was installed at the 0.05 m diameter outlet pipe.

Materials and Methods

Engineering Design

According to DID (2012), the field test in a residential area is classified as a minor system that should be designed to meet 10-year ARI rainfall specifications. Due to the small size of roof catchment area, the duration of storms should range between 5 and 15 minutes.

Once the rainfall intensity and depth are determined, the peak runoff generated from a catchment can be calculated using the Rational Method formula (Equation 1) below. This runoff is also treated as the inflow for the detention system:

$$Q = C\,I\,A/360 \qquad (\mathbf{1})$$

where:

Q = Peak runoff generated (m^3/s)
C = Runoff coefficient (unitless)
I = Design rainfall intensity (mm/hr)
A = Catchment area (ha)

Meanwhile, the outflow is usually controlled by an orifice, therefore formula for flow through the orifice below is applied:

$$q = C_d A_o \sqrt{2gh} \qquad (\mathbf{2})$$

where:

q = Flow through orifice (m^3/s)
C_d = Coefficient of discharge (unitless)
A_o = Area of orifice (m^2)
g = Acceleration from gravity (m/s^2)
h = Pressure acting on the centre line (m)

The parameter h in Equation 2 is related to the water level due to detained water and storage volumes in the detention system. The critical design data are summarised in Table 1.

Field Data

According to Abang Uthman and Selaman (2017) and Bong and Richard (2019), the field test site lies in a flat alluvial coastal plain and it is confronted by the northeast monsoons from November to February annually. Therefore, the data collection period was December 2019 during the aforementioned monsoon season. Presented in Figure 4, the hourly rainfall data are distributed throughout the month. The total rainfall recorded on the spot is 687.3 mm.

Table 1: Calculated data for 10-year ARI design rainfall

Storm Duration (minutes)	**5**	**10**	**15**
Rainfall intensity (mm/hr)	278	214	183
Rainfall depth (mm)	23	36	46
Roof runoff volume (m^3)	2.2	3.4	4.4
Roof peak runoff (m^3/s)	0.0073	0.0056	0.0048
Orifice outlet flow (m^3/s)	0.0005	0.0006	0.0007

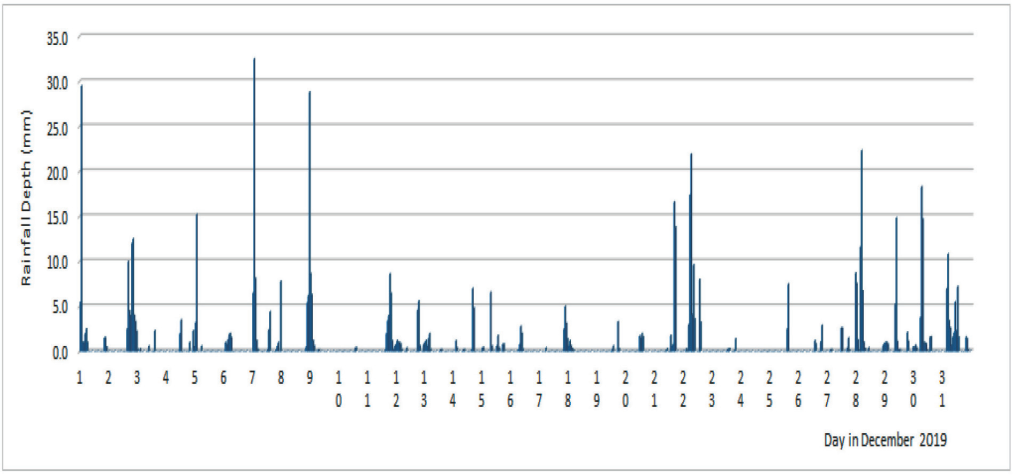

Figure 4: Hourly rainfall in December 2019

There were 58 storm events recorded during the data collection period, the duration of each storm ranged between 1 hour and 15 hours as tabulated in Table 2. The rainfall events with the highest frequency are the 2-hour storm (36%), followed by 1-hour and 3-hour storms (both 16%). The mean value stands at 4.8 hours, median value at 2 hours and mode stands at 2 hours.

In terms of rainfall depth in Table 3, majority (91%) are below 20 mm that are classified as low intensity rainfall. Only 5 events (9%) were found to have a rainfall depth of more than 20 mm.

The five highest storm events were selected for analysis. Referring to Table 4, two events were found to come close to the 5-minute 10-year ARI design specifications (23 mm) while three events were near the 10-minute 10-year ARI design specifications (36 mm). It indicates that the remaining 53 events are below all the design rainfall levels and could be taken as insignificant storm events.

Results and Discussion

This section describes the field hydrographs as compared with the design flows. The two groups that match the 5- and 10-minute 10-year ARI design rainfall levels are presented in Figure 5 and Figure 6, respectively.

Table 2: Classification according to storm duration

Hour	1	2	3	4	5	6	7	8	9	10	11	15
Frequency	9	21	9	3	5	1	2	2	2	2	1	1

Table 3: Classification according to rainfall depth

Rainfall Depth	**Number of Event**	**Percentage (%)**
More than 20 mm	5	9
10 mm – 20 mm	6	10
Below 10 mm	47	81
Total	58	100

Table 4: Selected storm events

Date	Peak Rainfall (mm)	Storm Duration (hour)	Remarks
22 December 2019	21.9	8	Near to 5-minute 10-year ARI
29 December 2019	22	9	
8 & 9 December 2019	28.8	8	Near to 10-minute 10-year ARI
1 December 2019	29.5	7	
7 December 2019	32.5	5	

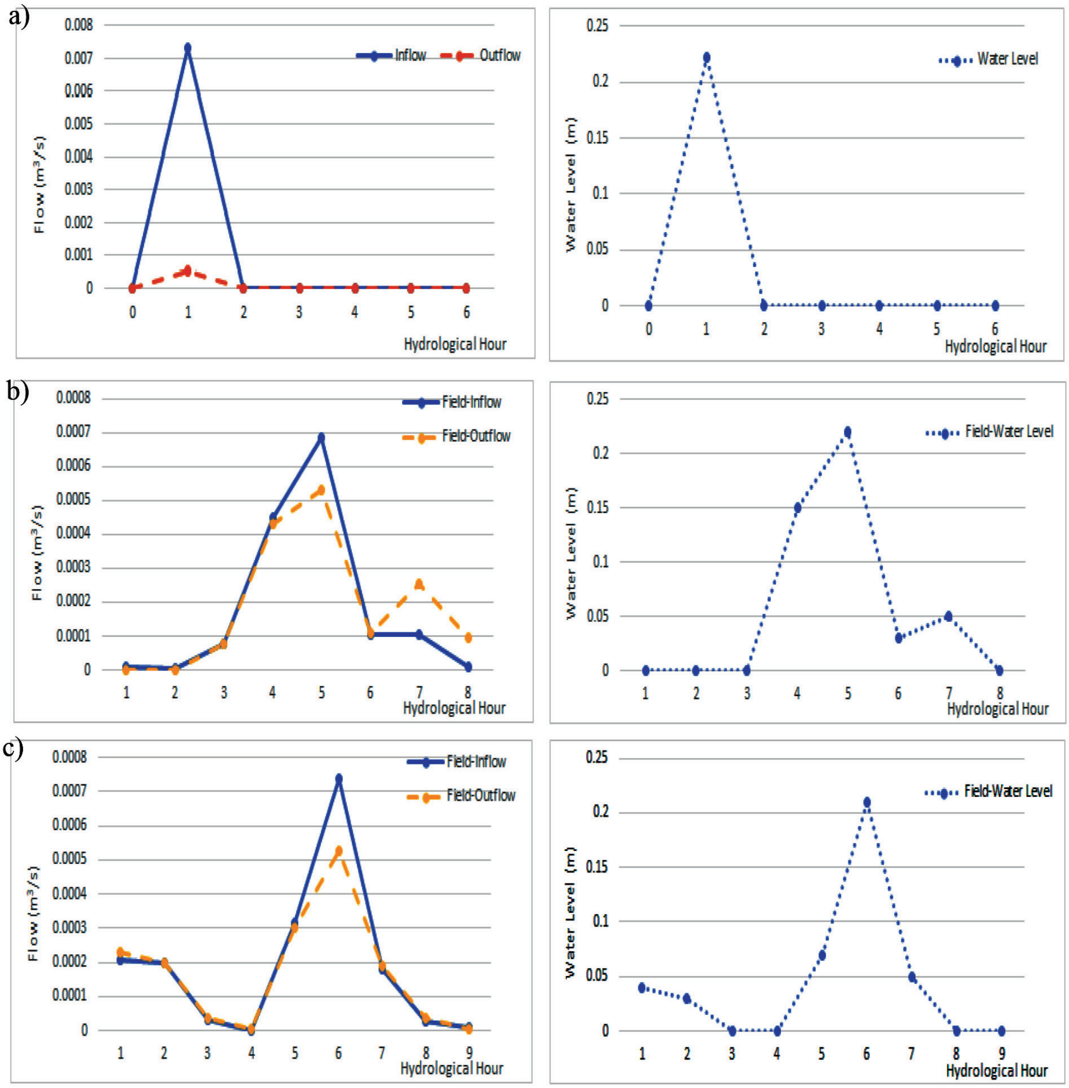

Figure 5: Inflow, outflow and water level hydrographs for (a) design flow, (b) 22 December 2019 storm and (c) 29 December 2019 storm

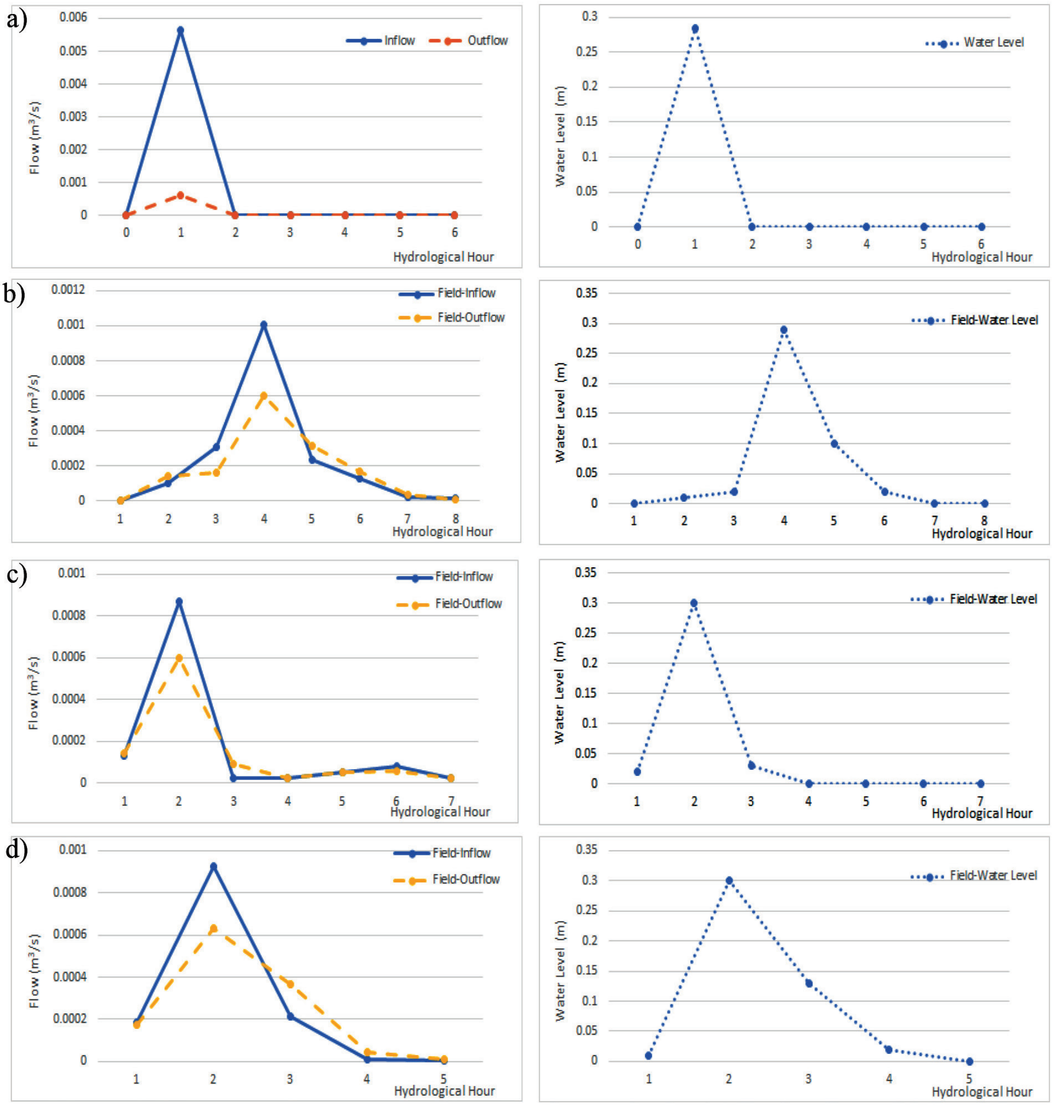

Figure 6: Inflow, outflow and water level hydrographs for (a) design flow, (b) 8 and 9 December 2019 storm, (c) 1 December 2019 storm and (d) 7 December 2019 storm

The graphs below describe the field hydrographs as compared with the design flows. The two groups that equivalent to 5- and 10-minute 10-year ARI design rainfall are presented in Figure 5 and Figure 6, respectively.

The design flow data resulted by the 5-minute 10-year ARI design rainfall are depicted in Figure 5 (a), the highly intense rainfall of 278 mm/hr or a depth of 23 mm is expected to fall continuously for 5 minutes. By allowing stormwater detention, the attenuation of the inflow and outflow peaks is expected to have a difference of 93%.

On the other hand, the design flow data resulted by the 10-minute 10-year ARI design rainfall is as depicted in Figure 6 (a). The slightly less intense rainfall of 214 mm/hr is expected to last longer, for a duration of 10 minutes continuously to cause a higher rainfall depth of 46 mm. The attenuation is expected to be 89%. The longer the storm duration, the lower the attenuation is expected to be.

Actual rainfall depth varies over time in a manner that is different from that seen in the design approach. Actual rainfall does not stay at a constant intensity over a specified time. This is the factor that causes the observed data to differ in peak inflows for example while the 5-minute design rainfall has estimated a peak inflow of 0.0073 m^3/s, both the two observed events (on 22 and 29 December) have a peak of 0.0007 m^3/s (a difference of 90%). The 10-minute design rainfall has an estimated a peak inflow of 0.0056 m^3/s but the three observed events (8 and 9 December, 1 December and 7 December) have a peak of around 0.001 m^3/s (a difference of 82%).

This variance is understandable as the design approach considers the worst-case scenario and therefore, estimates higher intensity levels for safety purposes. With the lower observed inflow peak, the attenuation is lowered as well. The attenuations for the 5-minute group are 23% for 22 December event and 29% for 28 and 29 December events while the 10-minute group are 40% for 8 and 9 December event, 31% for 1 December event and 32% for 7 December event. These findings are contradicting with the design approach that the field data shows the longer the storm duration, the more attenuation is achieved.

The outflow, on the other hand, is not influenced by the varied actual rainfall. It has a constant linked to the outlet pipe size and depends on the pressure in the detention system which is influenced by the water level.

The outflow peaks of all observed cases matched the design approach, in which the 5-minute group is observed with 0.0005 m^3/s and the 10-minute group is observed with 0.0006 m^3/s. There is no lag time between the inflow and outflow peaks due to the short distance between the roof and the detention system. This is evidenced in all cases in Figure 5 and Figure 6. This observation also points out there may be a need to reduce the outlet pipe size to promote larger attenuation. With larger attenuation, larger detention volumes can be expected.

As the depth of the detention system is 0.45 m, water levels that exceed that level are indicative of flooding. Therefore, the water level in the detention system is important so as not to cause an overflow. Observed water levels are found to conform to the levels that the design can handle. In the 5-minute group, whether in the design or the observed cases is indicated a level of about 0.2 m. The 10-minute group indicated a level of 0.3 m. These levels are safe from flooding. As such, with the matching of water levels in both the design and observed rainfall levels, the water detention system has been confirmed as dependable.

Conclusion

A field test was carried out on a stormwater detention system in a residential setting. Two events in December 2019 were found to match the 5-minute 10-year ARI design and another three events were found to match the 10-minute 10-year ARI design. The datasets allowed for an insight into how well the estimated design flow data of the stormwater system held up in real world testing. An analysis of the observed datasets showed that the outflow and water level data conformed to the design data. However, the observed inflow data was lower than that allowed for in the design data. This is due to the fact that there are varied rainfall depths in the real world, which is different from the constant rainfall depth assumption made by the design rainfall approach.

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Appendix

Appendix A: Observed data for 22 December 2019 storm event

Time (hour)	Rainfall (mm)	Inflow (m^3/s)	Outflow (m^3/s)	Water Level (m)
0200-0300	0.3	0.000008	0.000002	0.00
0300-0400	0.1	0.000003	0.000001	0.00
0400-0500	3.0	0.000079	0.000078	0.00
0500-0600	17.4	0.000449	0.000431	0.15
0600-0700	21.9	0.000686	0.000531	0.22
0700-0800	4.1	0.000106	0.000111	0.03
0800-0900	9.6	0.000106	0.000252	0.05
0900-1000	3.6	0.000011	0.000096	0.00

Appendix B: Observed data for 29 December 2019 storm event

Time (hour)	Rainfall (mm)	Inflow (m^3/s)	Outflow (m^3/s)	Water Level (m)
2300-0000	8.7	0.000206	0.000229	0.04
0000-0100	7.5	0.000198	0.000197	0.03
0100-0200	1.3	0.000032	0.000036	0.00
0200-0300	0.1	0.000000	0.000005	0.00
0300-0400	11.6	0.000317	0.000303	0.07
0400-0500	22.3	0.000739	0.000524	0.21
0500-0600	6.7	0.000179	0.000187	0.05
0600-0700	1.0	0.000026	0.000036	0.00
0700-0800	0.3	0.000008	0.000003	0.00

Appendix C: Observed data for 8 and 9 December 2019 storm event

Time (hour)	Rainfall (mm)	Inflow (m^3/s)	Outflow (m^3/s)	Water Level (m)
2100-2200	0.5	0.000000	0.000003	0.00
2200-2300	5.4	0.000106	0.000142	0.01
2300-0000	6.2	0.000311	0.000164	0.02
0000-0100	29	0.001003	0.000602	0.29
0100-0200	8.6	0.000238	0.000314	0.10
0200-0300	6.3	0.000132	0.000167	0.02
0300-0400	1.2	0.000026	0.000038	0.00
0400-0500	0.6	0.000016	0.000010	0.00

Appendix D: Observed data for 1 December 2019 storm event

Time (hour)	Rainfall (mm)	Inflow (m^3/s)	Outflow (m^3/s)	Water Level (m)
0100-0200	5.5	0.000132	0.000145	0.02
0200-0300	29.5	0.000871	0.000600	0.30
0300-0400	1.0	0.000026	0.000092	0.03
0400-0500	1.0	0.000026	0.000024	0.00
0500-0600	2.0	0.000053	0.000053	0.00
0600-0700	2.5	0.000079	0.000061	0.00
0700-0800	1.0	0.000026	0.000024	0.00

Appendix E: Observed data for 7 December 2019 storm event

Time (hour)	Rainfall (mm)	Inflow (m^3/s)	Outflow (m^3/s)	Water Level (m)
0100-0200	6.5	0.000185	0.000172	0.01
0200-0300	32.5	0.000924	0.000631	0.30
0300-0400	8.1	0.000211	0.000367	0.13
0400-0500	1.2	0.000013	0.000046	0.02
0500-0600	0.2	0.000005	0.000008	0.00