Experimental investigation of the influence of manhole grates on drainage flows in urban flooding conditions

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Summary

Climate change and urbanization have recently increased the number of flooding events in urban areas. Urban flood modelling tools commonly utilize the weir and orifice equations to quantify the drainage flow from the surface flood flow into a sewer system through a manhole or gully. The calculation of drainage flow exchange is a function of the surface flow depth, the geometrical properties of the manhole/gully opening and the discharge coefficient. This paper presents a series of experimental tests conducted within a unique experimental facility built in the water laboratory at the University of Sheffield that features a model sewer system linked to an urban surface/floodplain via a scaled manhole. Tests to investigate the influence of manhole grates with different geometrical configurations on the drainage flow between surface and sewer flows have been conducted. Head-discharge relationships for six different grates are presented in addition to a fully open (i.e. no grate) condition. Discharge coefficients for each grate type have been derived based on the weir and orifice equations.

Keywords

Experimental Modelling, Drainage, Discharge Coefficients, Manhole, Grates.

Introduction

Flooding and inundation in urban areas may occur due to river flooding, levee breaches or heavy localised rainfall (Bazin et al, 2014). During heavy rainfall/flood events, water commonly enters drainage systems via gully and manhole structures. Accurate quantification of drainage flow through these structures during flood events is therefore of importance for the performance of hydraulic models. Within urban flood models (e.g. Chen et al., 2007; Djordjevic et al.; 2005; Leandro et al., 2009; Martins et al., 2016) this drainage flow is commonly calculated using equations originally derived for flow over a weir or through an orifice (Lopes et al., 2017) with length/area parameters based on the geometrical properties of the drainage structure and driving head based on the flow characteristics (i.e. surface flow depth). However, little guidance currently exists for the selection of appropriate discharge coefficients in urban flood conditions. Moreover, the influence of different drainage cover grates types on flow exchange and discharge coefficients is yet to be fully investigated.

Field datasets of water depths and flow discharges for both the surface and the subsurface can be considered as calibration/validation data for flood models (Mark et al, 2004) but unfortunately accurate, high resolution field data sets are scarce and difficult to obtain (Rubinato, 2015). More commonly physical scale models are used to quantify the performance of urban drainage hydraulic structures. To date, studies have been completed to: i) determine drainage efficiency for grated inlets [Larson et al., 1947; Li et al., 1951; Russo and Gómez, 2011; Gómez et al., 2016; Sabtu et al., 2016]; ii) determine the efficiency of continuous transverse gullies [Russo and Gómez, 2009; Russo et al., 2013; Lopes et al., 2016]; iii) propose different modifications on the existing grate inlet design [Almedeij et al., 2003; Guo, 2000a; Guo, 2000b].
This work presents new experimental datasets of drainage flows through different grate types from a scale model of an urban surface linked to a sewer system through a manhole. Tests were conducted to i) quantify the variation in steady state head/drainage flow relationships through seven different opening conditions (six different installed grates as well as a fully open condition) and ii) quantify weir and orifice equation discharge coefficients for the different opening types for use within urban flood modelling tools.

Methods

The experimental set-up utilised (Fig. 1) was constructed at the water laboratory of the University of Sheffield (UK) (Rubinato, 2015). It consists of a scaled model of an urban drainage system/floodplain linked via a manhole. The floodplain surface (4 m, width, by 8.2 m, length) has a longitudinal slope of 1/1000. The urban drainage system is constructed from horizontal acrylic pipes directly underneath the surface (inner diameter = 0.075 m). Linking the surface to the pipes is one circular acrylic manhole with 0.240 m inner diameter and 0.478 m height. Previous studies have focused on the validation of numerical models to represent flow depths around a surcharging manhole (Martins et al., 2017) and a review of the above/below ground flood model linking equations in a no grate condition (Rubinato et al., 2017). The facility is equipped with a SCADA system (Supervision, Control and Data Acquisition) through *Labview*^{TM} software that allows the operation and monitoring of flow rates into the surface and sewer systems independently. A pumping system in a closed circuit supplies water within the facility. The inlet pipes of both surface (V_1) and sewer systems (V_{is}) are fitted with an electronic control valve operated via *Labview*^{TM} software. The surface downstream outlet is a free outfall which contains an adjustable height weir.

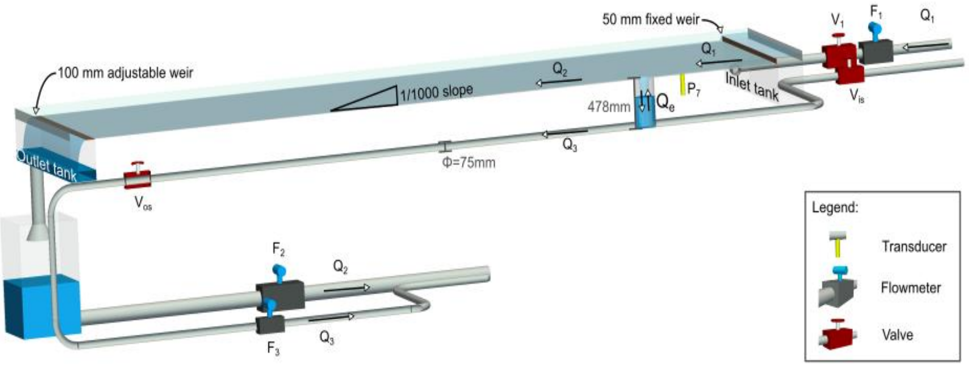

Fig. 1. *Scheme of the experimental facility.*

Calibrated electro-magnetic (MAG) flow meters (F_1, inlet floodplain; F_2, outlet floodplain; F_3 outlet sewer) were installed at the upstream and downstream inlet pipes of both the floodplain and sewer systems in order to measure the system inflow (Q_1) and outflow (Q_2, Q_3) and calculate the steady state drainage rate through the manhole. Each flow meter was independently verified against a laboratory measurement tank. For the tests reported here, the sewer inflow was not used (sewer inflow = 0) and all flow therefore entered the facility via the surface inlet weir (Q_1). Drainage flow passed via the manhole to the sewer outlet (Q_e = Q_3), with the remaining flow passing over the downstream surface weir (Q_2). Flow depth on the floodplain was measured via a pressure sensor (of type GEMS series 5000) fitted upstream of the manhole (460 mm from the centerline). To ensure reliable depth and flow rate quantification for each test, flows were left to stabilise for 5 minutes before flow rates and depths were recorded. Each reported depth/flow measurement is a temporal average of 5 minutes of recorded data after flow stabilisation such that full convergence of measured parameters is achieved.

Initial tests were completed without the application of any grate on the top of the manhole to be used as a reference case. Six different manhole opening/grate types were installed within the manhole structure and tested under steady drainage conditions in order to obtain depth/discharge relationships. The grate opening types were selected based on common types used in six different countries, and are presented in table 1 and fig 2. For each opening type the area of empty spaces (A_e) and effective perimeter (P_v) were obtained from the *AutoCAD* drawings prior to fabrication. For each test, surface inflow (Q_1) was varied between 4.290 and 9.290 l/s using the upstream valve. A flat weir was used as the downstream floodplain boundary in all cases, and the downstream pipe flow was with free surface in all cases. The hydraulic conditions for each test are detailed in table 2.

In order to quantify discharge coefficients for each opening type the weir (1) and orifice (2) equations were used. In the no-grate condition these are commonly defined as the following (Rubinato et al., 2017) within flood modelling applications:

$$Q_e = \frac{2}{3} C_w \pi D_m \sqrt{2g} (h_s)^{\frac{3}{2}} \quad (1)$$

Where Q_e (m^3/s) the drainage flow, D_m is manhole diameter (m), h_s is depth of the surface flow (m). C_w is the weir discharge coefficient.

$$Q_e = C_o A_m \sqrt{2g} (h_s)^{\frac{1}{2}} \quad (2)$$

Where A_m is the area of the manhole and C_o is the orifice coefficient.

Tab. 1. *Technical details of the grates.*

Grate	Area Manhole (m^2)	Area filled (m^2)	Area Empty spaces, A_e (m^2)	Void Ratio, V	Effective perimeter, P_v (m)
A	0.0452	0.0435	0.0017	0.04	0.513
B	0.0452	0.0421	0.0031	0.07	1.252
C	0.0452	0.0391	0.0061	0.13	2.258
D	0.0452	0.0373	0.0079	0.17	1.388
E	0.0452	0.0353	0.0099	0.22	2.379
F	0.0452	0.0307	0.0145	0.32	3.036
NO GRATE	0.0452	0	0.0452	1	0.754

For each of the tests conducted using grates, equations 2 and 3 were modified to account for the total length of the weir within each grate design.

$$Q_e = \frac{2}{3} C_i P_V \sqrt{2g} (h_s)^{\frac{3}{2}} \quad (3)$$

$$Q_e = C_o A_e \sqrt{2g} (h_s)^{\frac{1}{2}} \quad (4)$$

Where P_v is the effective perimeter of the voids specific for each manhole design considered, and A_e is the correspondent area of empty spaces for each grate type (Table 1). In addition, for each manhole grate configuration the efficiency (E) was quantified using equation 5 (adapted to the standard equation used by Russo et al., 2013 to include geometrical parameters and make it transferable):

$$E = \frac{Q_e/P_v}{Q_1/floodplain\ width} \qquad (5)$$

This parameter indicates the percentage of water that is trapped in the manhole and it should be dependent only on the geometry of the grate and street (length, void area and shape) and on the hydraulic conditions of the inlet flow (Russo et al., 2013).

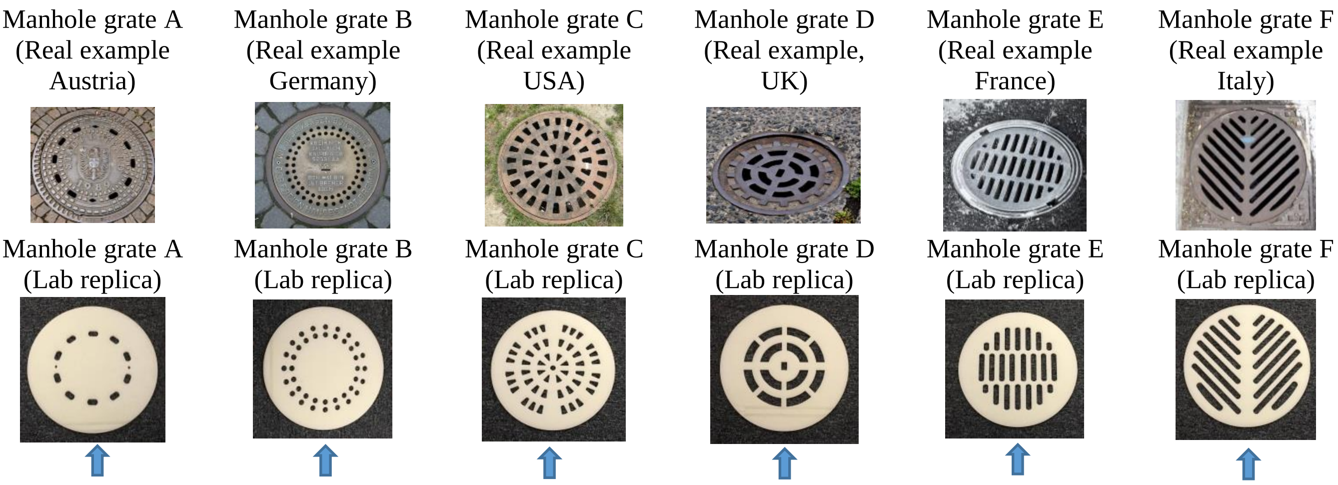

Fig. 2. *Grates applied on the top of the manhole (Blue arrows shows the direction of the flow Q_1 and hence the orientation of each manhole grate).*

Tab. 2. *Hydraulic parameters measured (Q_1, Q_3 and h_s) and calculated (Fr) for the tests conducted.*

Grate	Q_1 (l/s)	Q_e *(l/s)*	h_s *(mm)*	Froude Surface *(/)*		Q_1 (l/s)	Q_e *(l/s)*	h_s *(mm)*	Froude Surface *(/)*
	4.263	0.387	7.25	0.176		4.287	0.426	7.53	0.167
	4.965	0.438	7.96	0.178		4.975	0.545	8.16	0.172
	5.661	0.476	8.68	0.178		5.661	0.631	8.91	0.172
Grate A	6.294	0.520	9.35	0.177	Grate D	6.317	0.715	9.53	0.173
	6.921	0.580	9.82	0.181		6.952	0.739	10.10	0.174
	7.514	0.655	10.30	0.183		7.544	0.802	10.60	0.176
	8.186	0.679	10.77	0.187		8.209	0.876	11.14	0.178
	9.224	0.702	11.57	0.189		9.282	0.969	11.91	0.182
	4.290	0.499	7.26	0.177		4.230	0.431	7.72	0.159
	4.985	0.592	7.92	0.180		4.956	0.589	8.40	0.164
	5.671	0.683	8.60	0.181		5.694	0.701	9.24	0.163
Grate B	6.326	0.761	9.15	0.184	Grate E	6.296	0.717	10.11	0.158
	6.932	0.823	9.63	0.187		6.965	0.801	10.72	0.160
	7.523	0.886	10.12	0.188		7.490	0.824	11.18	0.161
	8.184	0.913	10.64	0.190		8.190	0.961	11.70	0.165
	9.221	0.942	11.42	0.193		9.245	1.087	12.49	0.169
	4.218	0.483	7.60	0.162		4.329	0.552	7.28	0.178
	4.932	0.610	8.27	0.167		4.998	0.665	7.89	0.182
	5.627	0.715	9.01	0.168		5.660	0.761	8.50	0.184
Grate C	6.261	0.796	9.61	0.169	Grate F	6.321	0.862	9.09	0.186
	6.872	0.842	10.05	0.174		6.932	0.929	9.49	0.191
	7.515	0.943	10.50	0.178		7.513	0.939	10.05	0.190
	8.208	1.032	11.01	0.181		8.218	1.055	10.60	0.192
	9.224	1.129	11.75	0.184		9.290	1.194	11.36	0.195

Results

Figure 3 shows (a) the relationship between the water depth and the corresponding flow exchange for each flow condition; (b) weir equation (3) vs the measured drainage flow; (c) the orifice equation (4) vs the measured drainage flow.

In terms of flow exchange, the geometry of each void area in the grates influences the flow entering the manhole. As expected, comparing results for similar inlet hydraulic conditions as shown in Figure 3 (a), *Grate A* (lowest V) is the grate that enables the lower exchange while *Grate F (*highest V*)* is the configuration that allows the higher exchange between the hypothetical surface and the sewer system.

By analysing Figure 3(a), it is also possible to highlight the effect of the different grates on the water depths recorded for similar inlet conditions. This phenomenon requires further investigation via the collection of velocity data of the approach flows.

This could help understand phenomena such as water accumulation and dispersion and separation of stream flows with a consequent rise in water levels, due to the different geometries considered for the grates.

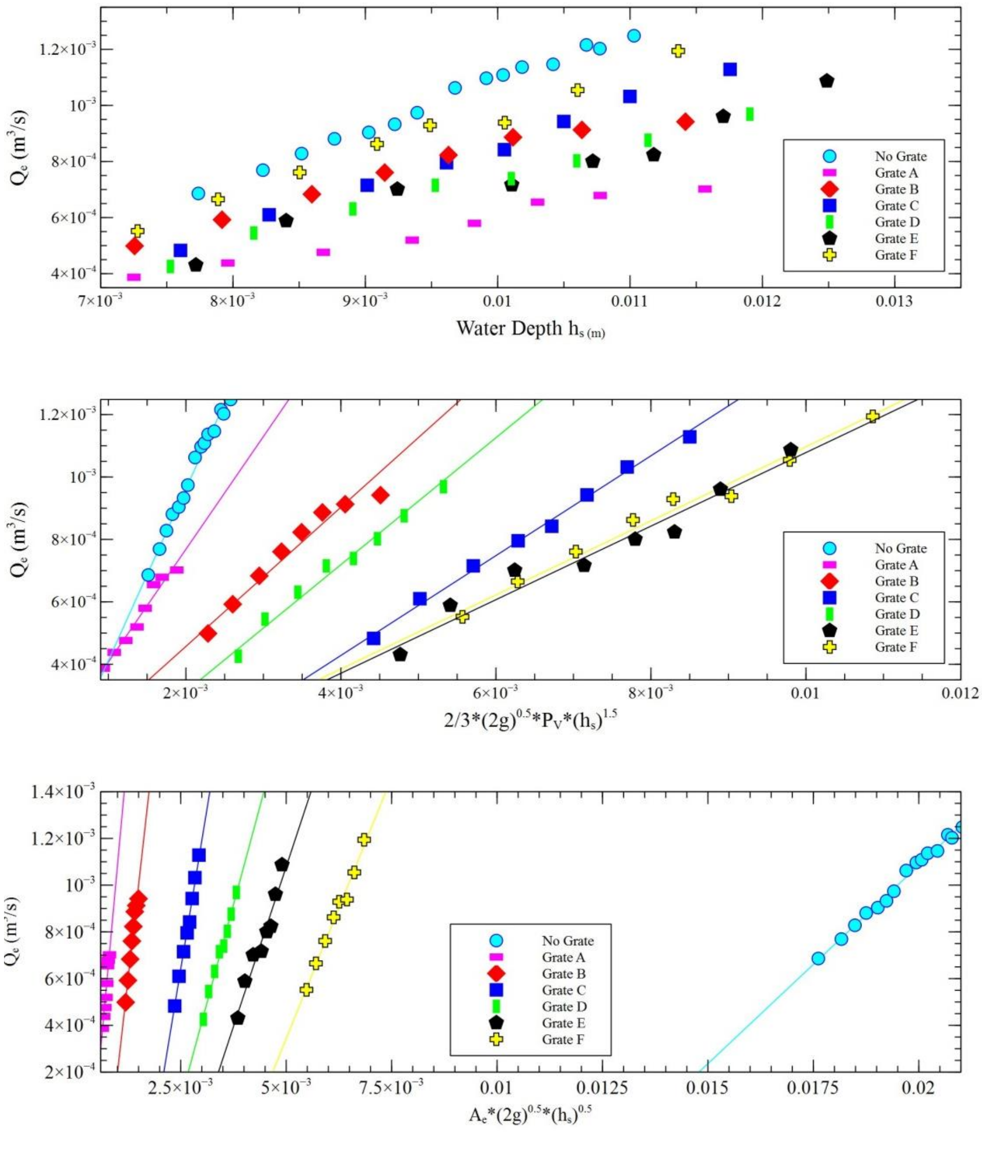

Fig. 3. *a) The relationship between the water depth recorded for each flow condition tested vs the correspondent flow exchange; (b) the modified weir equation (3) vs the flow exchange; (c) the modified orifice equation (4) vs the flow exchange.*

The applicability of the modified weir equation (3) is confirmed by the results displayed in Fig.3 (b) and the obtained linear correlations (R^2>0.951 for all cases). Calibrating equation (3) against the experimental results provides a discharge coefficient C_w in the range 0.115 - 0.540 based on the variety of grates applied (Table 3). By using equation (4), the range of discharge coefficients C_o for typical drainage conditions varies between 0.170 - 2.038 obtained from the linear correlations displayed in Fig.3 (c) (Table 3, R^2>0.950 for all cases).

Tab. 3. *Discharge coefficient obtained by using equation (3) and equation (4) with their correspondent R^2 values.*

Manhole Grate type	Discharge Coefficient Weir C_w	Weir R^2	Discharge Coefficient Orifice C_o	Orifice R^2
Grate A	0.363	0.968	2.038	0.967
Grate B	0.208	0.951	1.546	0.974
Grate C	0.157	0.995	1.115	0.994
Grate D	0.194	0.985	0.657	0.991
Grate E	0.115	0.957	0.552	0.950
Grate F	0.115	0.984	0.447	0.987
NO GRATE	0.540	0.988	0.170	0.992

A clear trend was found between effective perimeter P_v *vs* discharge coefficients C_w (R^2=0.960) and void area A_e *vs* C_o (R^2=0.868). Future work is required to further elucidate this relationship via the collection of velocity data around the manhole and detailed hydrodynamic modelling.

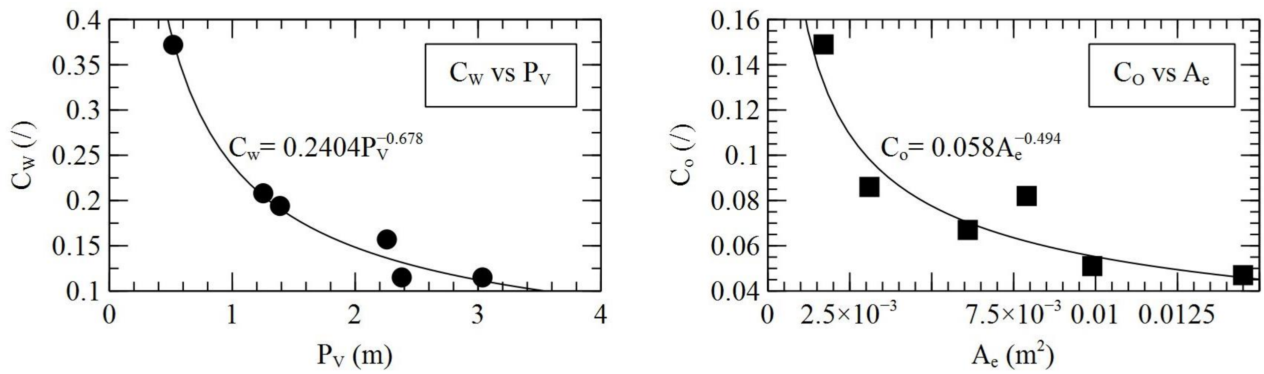

Fig. 4. *The relationship between discharge coefficients used for equations (3) and (4) and geometrical parameters specific for each grate used and described in Table 1.*

Furthermore, the efficiency (E) has been calculated using equation (5) for each grate and results confirm Russo et al., 2013 hypothesis previously stated. To support design criteria, a new relationship (R^2 = 0.864) was obtained to link values of efficiency (equation 5) associated to each grate with known parameters such as water depth recorded and perimeter of voids, specific for each grate geometry (Figure 5).

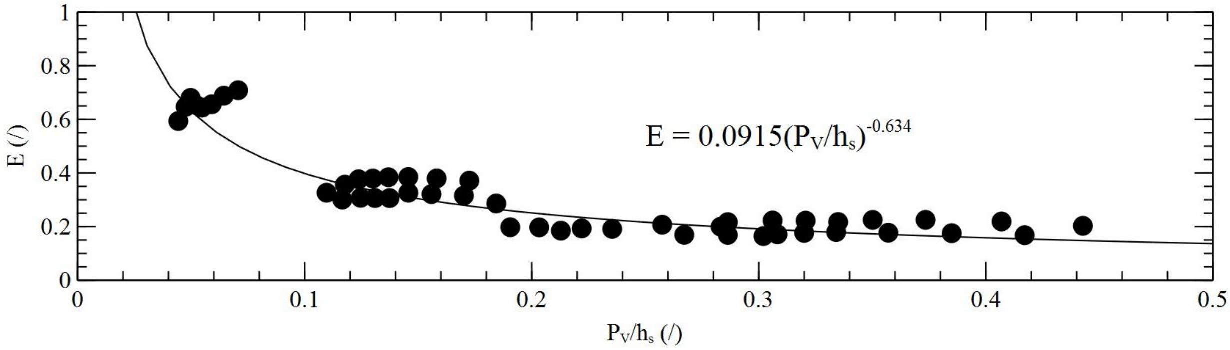

Fig. 5. *Relationship between the efficiency (E) for each grate and the correspondent geometries (P_V) and hydraulic parameters (h_s).*

Conclusions

In this work, experimental tests have been conducted to investigate the effect of different manhole grates on the head/drainage flow relationship and discharge coefficients commonly used in the weir/orifice equation to estimate the drainage flow during flooding conditions. The main findings of the research are summarised as:

- The presence of the grate on the top of the manhole influences the amount of flow entering the manhole. *Grate A* (lowest V) is the grate that enables the lower exchange while *Grate F (*highest V*)* is the configuration that allows the higher exchange between the hypothetical surface and the sewer system;
- The validity of weir and orifice equations has been verified for the hydraulic drainage conditions and the application of manhole grates. Discharge coefficients have been defined in the range of 0.115 - 0.540 calibrating equation (3) against the experimental results and in the range of 0.170 - 2.038 by using equation (4) ($R^2 > 0.950$ for all the cases);
- Trends have been identified between i) the discharge coefficient C_w and the void perimeter P_v and ii) the coefficient C_o and the void area A_e. Further detailed experimental and modelling work is required to further elucidate these relationships.
- A trend between drainage efficiency (equation 5) and P_v/H_s has been identified ($R^2 = 0.864$).

Future work will focus on the characterization of the velocity fields around the manhole to provide novel datasets for further understanding of drainage flows and the validation of numerical models.

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