

# Experimental and numerical investigation of water depths around a manhole under drainage conditions

Matteo Rubinato<sup>a\*</sup> Seungsoo Lee<sup>b</sup> Georges Kesserwani<sup>a</sup> James Shucksmith<sup>a</sup>

<sup>a</sup>The University of Sheffield, Civil and Structural Engineering Department, Sir Frederick Mappin Building, Mappin Street, S1 3JD, Sheffield, UK

<sup>b</sup>APEC Climate Center, 12 Centum 7-ro, Haenundae-gu, Busan, 612-020, Republic of Korea, 48058

---

## Abstract

This study uses a physical model to quantify shallow water depths around a scaled manhole during drainage (surface to sewer flow exchange) conditions and through a scaled manhole. A series of tests have been conducted within an experimental facility over a range of steady-state (flow exchange rate) conditions. The datasets have been used to validate both a 2D Finite Volume Model and a 2D Finite Difference Model. The results show a very close agreement between experimentally observed and numerically modelled flow depths irrespective of the flow exchange between the surface and the sewer system. The results provide increased confidence on the reliability of these two numerical methods to model surface to sewer flow under different steady state hydraulic conditions.

*Keywords:* Flow exchange, manhole, experimental modelling, numerical modelling.

---

## 1. Introduction

Climate change is likely to cause shifts in the intensity of flood events, in some regions increase the exposure of populations to severe flooding [1]. The frequency and magnitude of urban flooding events is expected to increase in the future [2, 3] hence there will be more damage in terms of loss of business, livelihoods plus increased inconvenience for citizens [4]. These potential risks underline the importance of modelling tools to evaluate flow paths in urban areas and accurately evaluate risk. Existing urban drainage systems models are commonly modelled using numerical hydraulic models. However flood modelling is often faced with the concern of how to model and reproduce the hydraulic behavior of complex structures such as manholes and gullies which are commonly used to connect the surface system to the sewer system. These structures allow water to be drained from the surface to the sewer system in “normal” conditions when the sewer is not surcharged, or during exceptional events, they become pressurized and water may flow in the opposite direction (reverse flow). The flow within these systems is highly complex and is often represented using semi empirical methods within models. Due to a paucity of full scale data the calibration and validation of such linking methodologies is challenging. It is therefore important to provide a better understanding of the flow patterns through these structures and the consequent interaction between surface and sewer flows.

Experimental studies investigating surface-sewer flow interaction via gullies and manholes are rare. However, [5] investigated the hydraulic efficiency of transverse grates within gully systems and proposed new mathematical expressions to define the hydraulic efficiency of gullies and manholes; [6,7,8] have investigated the effectiveness of the grate inlet and [9,10,11] proposed different modifications on the existing grate inlet design.

Numerical studies of gullies and manholes are limited due to the lack of experimental data for calibration/validation as well as long computational times when simulating 3D flows [12]. However some studies have been conducted: [13] analysed experimental results from a surcharging jet arising from the reverse flow out of a manhole after the sewer system became pressurized; [14] focused on surface recirculation zones formed downstream of gullies; both studies have used experimental data to model flow patterns inside gullies and manholes using CFD.

---

\* Corresponding author. Tel.: +44 (0)114 22 25768; fax: +44 (0) 114 222 5700.  
E-mail address: m.rubinato@sheffield.ac.uk

There are only three experimental facilities of which we are currently aware that at the present time can simulate both drainage and reverse (surcharging) flows through urban drainage hydraulic structures; one is located at the Kyoto University [15], one is at the University of Coimbra [13, 16] and another is the experimental facility used for this study at the University of Sheffield [17, 18].

The objective of this work is to validate two alternate numerical models (Finite Volume and Finite Difference) against experimentally observed data in the case of surface to sewer flow exchange conditions. Experimental tests are conducted within a scaled facility for 10 steady state conditions in which the exchange rate is varied via increasing the surface flow depth. Water depths are measured at nine points on the surface. One of this measurement points (downstream of the manhole, 600 mm before the surface outlet –  $P_{ds}$  in Table 1) is used to establish boundary conditions for the numerical model, the remaining eight measurements (around the manhole) are used for model validation.

The experimental installation is presented in Section 2.1 along with the numerical models used (section 2.2, a *2D Finite Volume Model* and a *2D Finite Difference Model*). Section 3 presents the numerical and experimental results and discussion followed by the conclusions (Section 4).

## 2. Models

### 2.1. Experimental Model

The experimental set-up utilised is situated in the water laboratory at the University of Sheffield (UK) [15]. It consists of a scaled model of a pipe/urban drainage system, and a shallow free surface flume linked via a scaled manhole (Figure 1). The surface flume is 4 m wide by 8.2 m long with slope of 1/1000 in the longitudinal direction. At the downstream end of the flume the flow is controlled by an adjustable weir. The pipe is constructed from acrylic pipes (inner diameter = 0.075 m). Linking the surface to the pipes is one circular acrylic manhole with 0.240 m inner diameter and 0.480 m depth.

The facility is equipped with a SCADA system (Supervision, Control and Data Acquisition) through Labview software that allows the real time operation and monitoring of flow rates, hence flow to surface and pipe networks can be controlled independently. A pumping system in a closed circuit supplies water within the entire facility. The inlet pipes of both surface and sewer system are fitted with an electronic control valve operated via Labview software.

Calibrated electro-magnetic (MAG) flow meters were installed at the upstream and downstream inlet pipes of both the floodplain and sewer systems in order to measure the system inflow ( $Q_1, Q_3$ ) and outflow ( $Q_2, Q_4$ ) and calculate the steady state surcharge rate ( $Q_e$ ). Each flow meter was independently verified against a laboratory measurement tank. Based on these tests, the exchange rate based on the sewer flow meters ( $Q_3$  and  $Q_4$ ) were found to provide the most accurate flow readings (within 2.5% of measurement tank values in all cases). Hence for the tests reported here  $Q_e$  is defined based on mass conservation principles and sewer flow measurements (Figure 1).

$$Q_e = Q_3 - Q_4 \quad (1)$$

Sixteen pressure transducers (of type GEMS series 5000) were installed to measure floodplain water depths at different locations on the surface and around the manhole (nine). The location of the transducers is presented in Figure 2. 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.

For the tests reported in this paper, there is no grate covering the manhole. This could represent the case in situations such as removal due to operational use [16] or projection of the grate during extreme reverse flow such as urban geysers [13].

Two different downstream surface boundary configurations were tested over a range of flow exchange flow rates. **Conf1**, a flat weir as a downstream boundary condition; **Conf2**, a raised weir (elevation starting point 2 cm, with increments of 4-5 mm) as a downstream boundary condition to increase water levels on the surface and around the manhole.

For each configuration flow exchange is also varied by controlling the inflow to the surface ( $Q_1$ ). For **Conf1** the inflow to sewer ( $Q_3$ ) was also varied, however it was found that the pipe flow was not sufficient to affect the flow exchange rate (i.e. free weir drainage conditions were observed for all **Conf1** cases). Table 1 provides details of the experimental conditions for each test conducted.

Table 1. Flow conditions utilized for the different experimental configurations.

Test	$Q_1$ ( $m^3/s$ )	$Q_3$ ( $m^3/s$ )	$P_{ds}$ (mm)	$Q_e$ ( $m^3/s$ )	$Fr$ (-)	$R_{ep}$ (-)
<b>Conf1</b>						
1	0.00275	0.00275	7.34	0.00047	0.216	54559
2	0.00356	0.00275	8.22	0.00061	0.247	57042
3	0.00415	0.00414	8.88	0.00066	0.264	81365
4	0.00484	0.00509	9.55	0.00073	0.283	98766
5	0.00550	0.00573	10.11	0.00075	0.303	109912
<b>Conf2</b>						
6	0.00554	0.00000	20.90	0.00189	0.178	31971
7	0.00627	0.00000	27.06	0.00502	0.137	85021
8	0.00726	0.00000	32.68	0.00668	0.117	113294
9	0.00790	0.00000	34.60	0.00719	0.116	121852
10	0.00870	0.00000	39.01	0.00766	0.105	129876

Note:  $Q_1$  = surface inflow,  $Q_3$  = sewer inflow,  $P_{ds}$  = downstream boundary conditions,  $Q_e$  = flow exchange;  $h_{surface}$  = water depth upstream manhole;  $R_{ep}$  = Reynolds number pipe;  $R_e = \rho v_p D / \mu$ ; and  $Fr$  = Surface Froude number  $Fr = v_s / (gh_{surface})^{0.5}$ ,  $v_s$  = mean velocity surface.

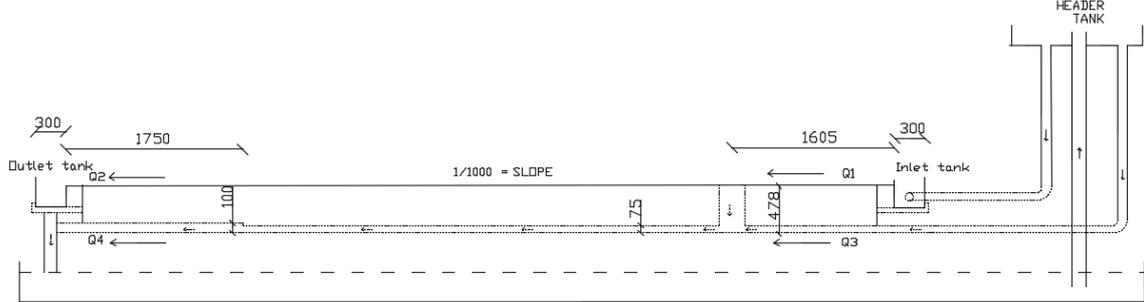


Fig. 1. Longitudinal profile of the experimental setup.

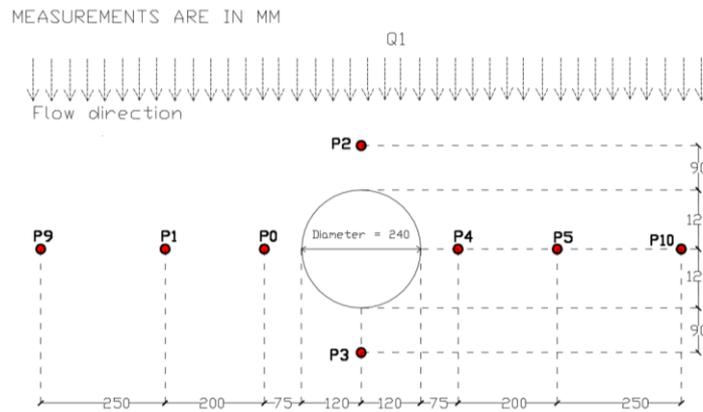


Fig. 2. Location of the measurement points around the manhole (Not in scale).

## 2.2. Numerical Models

Two numerical methods had been used for the analysis, a 2D Finite Volume Model [19] and a 2D Finite Difference Model [20]. A mesh convergence analysis suggested the use of a convergence (depth) threshold-error no bigger than  $10^{-4}$  and no less than  $10^{-6}$ . To isolate differences between the two numerical models utilized, the same boundary conditions have been applied. The experimental location of manhole was used to determine manhole meshes,  $Q_e$  was used to represent inlet discharge from surface to sewer by applying the continuity

equation.  $Q_I$  and water depth at  $P_{ds}$  were used as upstream and downstream boundary conditions, respectively. At the southern and northern boundaries (lateral), a wall boundary condition was employed (reflective).

### 3. Results and Discussion

In this section, experimental and numerical datasets are analysed. Figure 3 displays plots of predicted numerical and measured experimental depths at P0, P1, P2, P3, P4, P5, P9, P10.

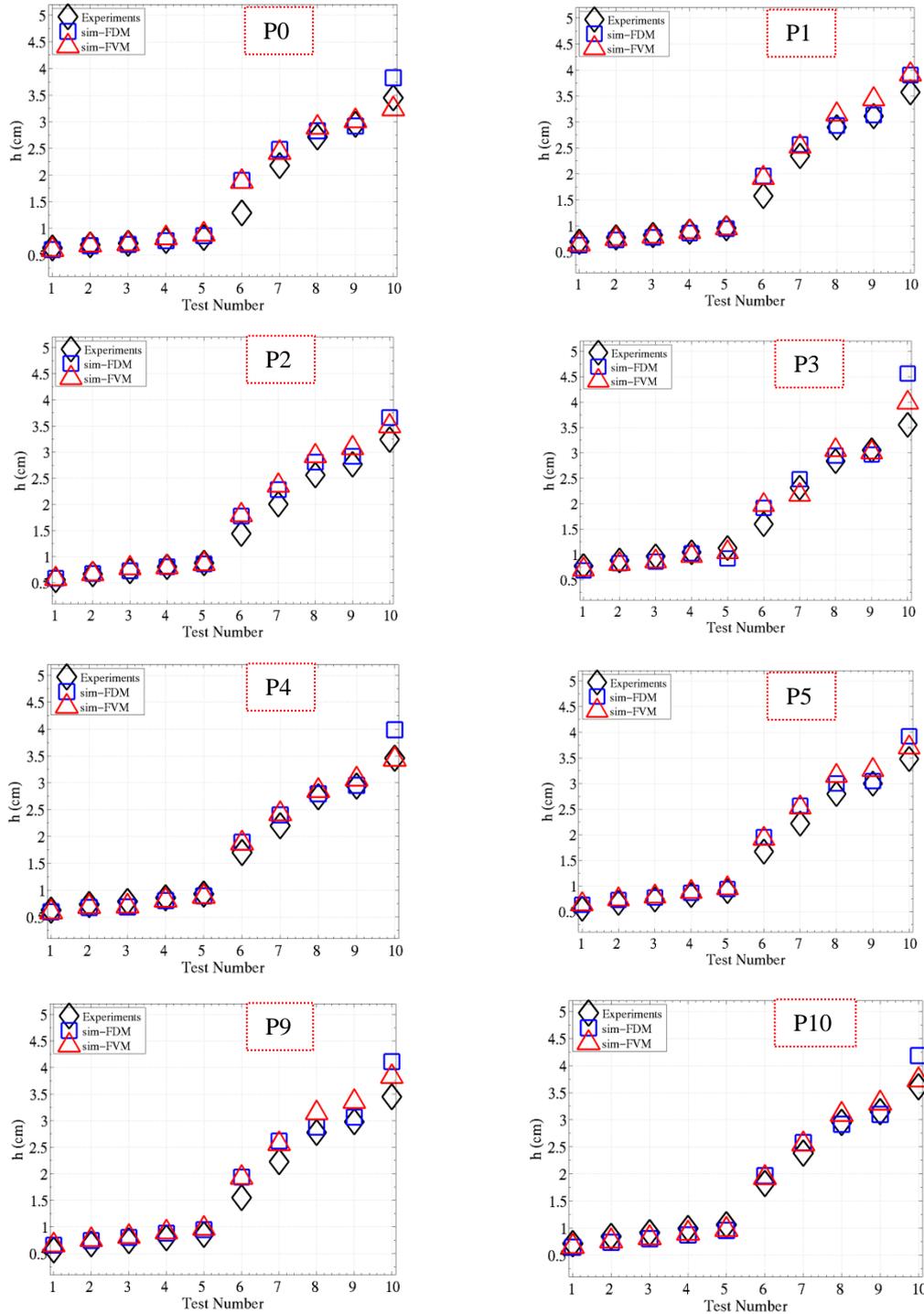


Fig. 3. Steady state numerical (FDM and FVM) and experimental depths at selected sampling points around the manhole.

At each measurement location displayed, the behaviour of the experimental observations and numerical results are seen to be quite similar (within 1 mm) for tests conducted within *Conf1*. This is due to the symmetric and stable direction of the flow entering the manhole in a uniform way as displayed in Figure 4 (left) for tests 1-5. For tests conducted with *Conf2*, 6-10, results confirm the similar trend between experimental and numerical results but the discrepancies are higher (1-3 mm). For these 5 cases, the downstream weir had been raised (as stated in section 2.1), causing an increase in water levels on the floodplain. This has initiated a higher amount of water entering the manhole that generated a vortex that was not symmetric and could justify the discrepancies due to high variations of instantaneous water depths (Figure 4, right). During the *Conf2* tests, due to the same phenomenon, the numerical steady state was not fully reached in all cases and this justifies slightly higher discrepancies obtained with FVM results in comparison with FDM results for the range of tests 6-10.

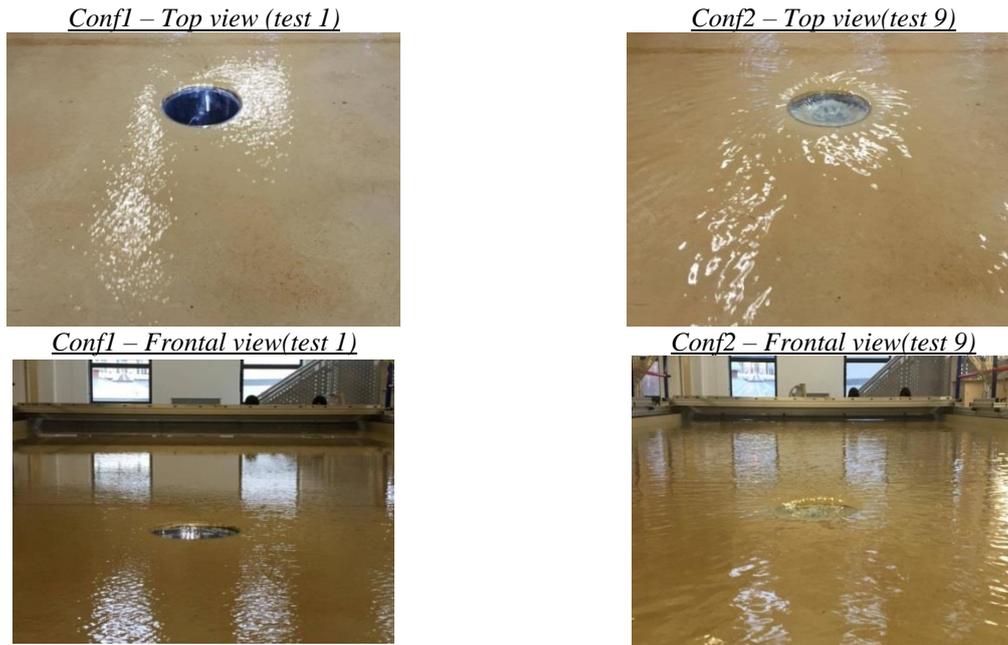


Fig. 4. Local floodplain to sewer interaction example for *Conf1* (test 1) and *Conf2* (test 9).

#### 4. Conclusions

This work has explored the numerical and experimental modelling of the floodplain to sewer flow exchange flow. A physical model, linking a slightly inclined urban floodplain to a sewer system, was used to carry out measurements under steady state flow conditions. Ten steady state experiments were conducted during which water levels at sampling points, surrounding the manhole, were measured. A finite volume numerical model was tailored to produce alternative simulation results. The numerical results have been compared with the experiments in terms of depth around the manhole at eight sampling points. Detailed comparisons between experimental results and numerical ones obtained with a *2D Finite Difference Method* and a *2D Finite Volume Method* at the sampling points show very consistent agreement between the numerical and experimental water levels (max discrepancy 5 mm). It can therefore be concluded that the proposed 2D numerical approaches are able to model sewer and floodplain interaction reliably. Future work will consider the same comparison for different hydraulic scenarios (sewer to floodplain flow) plus a Particle Image Velocimetry system will be implemented within the experimental facility to provide a better quantification of streamlines and flow patterns and local velocities in shallow urban flood flows.

#### Acknowledgments

The research has been supported by the UK Engineering and Physical Sciences Research Council (grants ID: EP/K040405/1) and Seungsoo Lee acknowledges the support from the APEC Climate Center.

## References

- [1] Leandro J., Santos B., Leitao J.P., Siekmann T., Urich C., Towards mOre Resilient Cities (ToRC). 9th Int.Conf. Urban Drain. Model. Belgrade, Serbia 1 (2012).
- [2] Flower AM, Hennessy KJ. Potential impacts of global warming on the frequency and magnitude of heavy precipitation. *Natural Hazards* (1995) , 11(3), 283–303
- [3] Hammond M., Chen A.S., Djordjevic S., Butler D., Mark O. Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12 (1), 14-29 (2015).
- [4] Ten Veldhuis, J. A. E., and F. H. L. R. Clemens. "Flood risk modelling based on tangible and intangible urban flood damage quantification. *Water Science and Technology*, (2010), 62(1), 189.
- [5] Gómez M., Russo B. Hydraulic Efficiency of Continuous Transverse Grates for Paved Areas. *J. Irrig.Drain. Eng.* (2009), 135-225.
- [6] Larson C. L. Investigation of Flow Through Standard and Experimental Grate Inlets for Street Gutters, Project Report, St. Antony Falls Hydraulic Laboratory University of Minesota (1947).
- [7] Li W. H., Geyer J. C., Benton G. S. Hydraulic Behaviour of StormWater Inlets: I. Flow into Gutter Inlets in straight Gutter without Depression. *Sewage and Industrial Wastes*, 23 (1), (1951) 34-46.
- [8] Li W. H., Goodel B. C., Geyer J. C. Hydraulic Behavior of StormWater Inlets: IV. Flow into Depressed Combination Inlets. *Sewage and Industrial Wastes*, 26 (8), (1954) 967-975.
- [9] Almedej A. O., Houghtalen R. J. Urban hydrology: hydraulics and storm water quality. John Wiley & Son. (2003)
- [10] Guo J. C. Design of grate inlets with clogging factor. *Advances in Environmental Research*, 4 (2000) 181-186.
- [11] Guo J. C. Street Storm Water Conveyance Capacity. *ASCE Journal of Irrigation and Drainage Engineering*, 126(2), (2000).
- [12] Leandro J., Lopes P., Carvalho R., Pascoa P., Martins R., Romagnoli M. Numerical and Experimental characterization of the 2D vertical average-velocity plane at the centre-profile and qualitative air entrainment inside a gully for drainage and reverse flow. *J Comp Fluids* 102, (2014) 52-61.
- [13] Lopes P, Leandro J, Carvalho RF, Páscoa P, Martins R., Numerical and experimental investigation of a gully under surcharge conditions. *Urban Water J. 1* (2013).
- [14] Djordjević S., , Saul A.J., Tabor G.R., Blanksby J., Galambos I., Sabtu N., et al. Experimental and numerical investigation of interactions between above and below ground drainage systems. *Water Sci. Technol.* 67, (2013) 535.
- [15] Bazin J-P. Flows during floods in urban areas: influence of the detailed topography and exchanges with the sewer system., PhD thesis, University of Lyon, 2013.
- [16] Martins R., Leandro J., Carvalho R.F. De. Hdraulic behaviour of a gully under drainage conditions: numerical vs . experimental. 9th Int Conf Urban Drain Model Belgrade, Serbia (2012).
- [17] Rubinato, M. 2015. Physical Scale Modelling of Urban Flood Systems. Thesis (Ph.D.) University of Sheffield, <http://etheses.whiterose.ac.uk/9270/>.
- [18] Rubinato M., Shucksmith J., Saul A.J., Shepherd W. Comparison between Infoworks hydraulic results and a physical model of an urban drainage system. *Water Sci.Technol.* 68, (2013) 372-379.
- [19] Haleem, D. A., Kesserwani, G., & Caviedes-Voullième, D. (2015). Haar wavelet-based adaptive finite volume shallow water solver. *Journal of Hydroinformatics*, 17(6), 857-873.
- [20] Lee, S. (2013). Study on Development of Integrated Urban Inundation Model Incorporating Drainage Systems. PhD Thesis, *Kyoto University*.

## Notation

- D = pipe diameter (m)  
 $h_{\text{surface}}$  = water depth urban surface (m)  
 $F_r$  = Froude number urban surface (-)  
g = gravitational acceleration ( $\text{m/s}^2$ )  
 $Q_1$  = Inflow to floodplain surface ( $\text{m}^3/\text{s}$ )  
 $Q_2$  = Outflow from floodplain surface ( $\text{m}^3/\text{s}$ )  
 $Q_3$  = Inflow to sewer pipe ( $\text{m}^3/\text{s}$ )  
 $Q_4$  = Outflow from sewer pipe ( $\text{m}^3/\text{s}$ )  
 $Q_e$  = Flow exchange ( $\text{m}^3/\text{s}$ )  
 $Re_p$  = Reynolds number pipe (-)  
 $v_p$  = velocity pipe system (m/s)  
 $v_s$  = velocity urban surface (m/s)  
 $\rho$  = density ( $\text{kg/m}^3$ )  
 $\mu$  = dynamic viscosity ( $\text{m}^2/\text{s}$ )