Co-UDlabs

Building Collaborative Urban Drainage research Labs communities

D8.3 – Report on the performance of Urban Drainage Systems under Pressure and their Recovery

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Background: about the Co-UDlabs Project

Co-UDlabs is an EU-funded project aiming to integrate research and innovation activities in the field of Urban Drainage Systems (UDS) to address pressing public health, flood risks and environmental challenges. Bringing together 17 unique research facilities, Co-UDlabs offers training and free access to a wide range of high-level scientific instruments, smart monitoring technologies and digital water analysis tools for advancing knowledge and innovation in Urban drainage systems. Co-UDlabs aims to create an urban drainage large-scale facilities network to provide opportunities for monitoring water quality, UDS performance and smart and open data approaches. The main objective of the project is to provide a transnational multidisciplinary collaborative research infrastructure that will allow stakeholders, academic researchers, and innovators in the urban drainage water sector to come together, share ideas, co-produce project concepts and then benefit from access to top-class research infrastructures to develop, improve and demonstrate those concepts, thereby building a collaborative European Urban Drainage innovation community.

The initiative will facilitate the uptake of innovation in traditional buried pipe systems and newer green-blue infrastructure, with a focus on increasing the understanding of asset deterioration and improving system resilience.

List of acronyms

Acronym	Full definition
BGI	Blue Green Infrastructure
UDS	Urban Drainage Systems
Qin	Inflow into the urban drainage system
Qout	Outflow of the urban drainage system
SCADA	Supervision, Control and Data Acquisition system
Qe	Netflow exchange from sewer to surface via manhole
Se	Sediment load
Sin	Sediment in
Sout	Sediment out
Cu	Christiansen’s uniformity coefficient
SD	Standard deviation
ET	evapotranspiration

List of project partners acronyms

Acronym	Institution
UDC	Universidade da Coruña
USFD	University of Sheffield
EAWAG	Eidgenoessische Anstalt für Wasserversorgung Abwasserreinigung und Gewaesserschutz

Executive Summary

This document is Deliverable 8.3 of the Co-UDlabs project, funded under the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008626. This deliverable is an output from Task 8.3. of Work Package 8 "Improving resilience and sustainability in urban drainage solutions". The lead beneficiary of Work Package 8 is University of A Coruña, the University of Sheffield is the responsible partner for this Deliverable.

The Deliverable is a report on the main activities and results obtained within Task 8.3. Within this task the main activities have included experimental work to quantify the transport of sediments from urban drainage systems to street surfaces during flooding/sewer surcharge conditions. The influence of different system geometries (lid grate types) and hydraulic conditions have been explored. This work has produced new experimental datasets which will inform future guidance of the performance of urban drainage systems under intense rainfall conditions. Further work in 8.3 has considered the impacts of poor maintenance on BGI's hydrological performance through a comprehensive experimental campaign under controlled conditions. These works have produced new experimental datasets which will inform future guidance of the performance of urban drainage systems under intense rainfall conditions and the long-term hydrological performance of BGI.

1 Introduction

Urban drainage systems (UDS) are under significant pressure as a combined consequence of increased urbanisation, population growth and ageing infrastructure. In addition, climate change projections indicate the likelihood of more frequent and intense rainfall events with associated implications for the frequency of urban flooding and pollution events due to a lack of local drainage capacity.

In this context is it important to increase our understanding of how UDS and their components function and perform under high flow conditions when the design capacity of the system is exceeded. For example, in such conditions, substances which pose a risk to public health may be transported from sewer networks to surface flows, and information on risks to public health are an important aspect of effectively responding and recovering from urban flood events. It is also known that blue green infrastructure (BGI) can improve the resilience of drainage systems under heavy flood events, however, like any other urban water infrastructure, BGI also require regular maintenance and upkeep to preserve their hydrological performance, an aspect which is overlooked and understudied in published literature. It is also important to understand how BGI systems perform under a range of conditions such that efficient and cost-effective maintenance regimes can be developed. Due to the difficulty in obtaining performance data from real world sites during highly intermittent and uncertain events such as urban floods, the use of innovative, large scale laboratory facilities and field sites offered by Co-UDlabs provides valuable understanding of the performance of UDS components in controlled conditions.

This deliverable presents two pieces of experimental work which produce new understanding and novel datasets concerning how UDS perform under pressure induced by heavy rainfall events. The first set of experiments conducted at USFD concerns the transport of sediments from pipe networks to urban surfaces during flood/drainage exceedance events, the second conducted at UDC by a EAWAG researcher concerns the hydrological performance of BGI systems under different maintenance regimes. Together this work offers new insights into the performance of UDS under high flow/heavy rainfall events, novel datasets to inform modelling tools and will also provide useful guidance regarding how UDS should be best managed to reduce risks, including in the post flood event recovery phase.

2 Experimental characterisation of the transport of sediments from UDS to urban surfaces during flooding/network surcharge events

2.1 Overview

Human exposure to urban floodwater poses considerable health risks due to the potential contamination from various waterborne pathogens and sediments (De man., 2014). Surface runoff contributing to floodwater can contain a range of contaminants, including chemicals and sediments sourced mainly from traffic-related activities such as combustion byproducts, corrosion inhibitors, heavy metals, hydrocarbons, as well as nitrogen and sulphur oxides (Awonaike et al., 2022). Studies have also indicated contributions of road sediments and possible contamination from dog faeces and bird droppings from paved surfaces (Monterio et al., 2021; de man, 2014). Urban flood water also carries elevated concentrations of bacteria and viruses originating from the sewer network, including faecal matter indicator organisms such as *Campylobacter* and *Cryptosporidium* (Butler et al., 2018; ten Veldhuis et al., 2010; Thupaki et al., 2013). These contaminants can be transported, in either soluble or sediment/particulate form, from the sewer networks to the surface during flood events through interaction structures such as gullies and/or manholes (Beg et al, 2020). Sediments serve as carriers for contaminants during surcharged flows from manholes and gullies, facilitating their transportation and deposition through floodwater onto the surrounding surfaces, potentially serving as a source of pathogenic contamination (Beg et al., 2018).

Consequently, sewer sediment entrained within urban floodwater has the potential to contain human enteric pathogens sourcing from crude sewage water, such as *E.coli* and *Cryptosporidium* (Noble et al, 2006; de man, 2014), potentially inducing symptoms such as vomiting and fever, and whilst usually of short and mild duration, it can result in hospitalisation and even death to vulnerable population groups, such as those aged 65 and over. One study conducted by Ten Veldhuis et al (2010), sampled and analysed floodwater samples from three urban flood events in the Hague, the Netherlands. Notably, these areas are served by combined urban drainage systems. The samples indicated faecal contamination, with concentrations akin to raw sewage under high-flow conditions, with *Campylobacter* detected in all samples. However, the host factors that influence the risk of these enteric pathogens are not well understood, with epidemiological data lacking regarding the human health impacts from mixed source of faecal contamination, such as floodwaters (Tam C et al, 2013; Warish et al, 2019).

Notably, there is a lack of research into the extent of the exchange of pollutants during surcharged flood events, and their transport and fate in shallow urban floodwater (Beg et al 2020; Rubinato 2022). Contaminants present in wastewater can infiltrate surface flows through manhole surcharges in the sewer network (Djordjevic et al, 2013). However, there exists a gap in the understanding of the interaction of these contaminants between pipe to surface flows during surcharge flow conditions. Therefore, it can be seen of importance to investigate these interactions, to then evaluate the health risks associated with urban floods. Understanding the transportation and deposition of harmful pollutants within urban floodwaters from hydraulic structures is challenging, yet essential for understanding the associated health risks. Furthermore, this understanding allows informed decisions on the necessary mitigation strategies required, including the potential alterations in sewer network designs and identification of high-risk areas and districts with which to focus post flood public health resources (Mostafa et al, 2016; Rubinato et al, 2022). Beg et al (2020), used 3D CFD modelling to analyse soluble pollutant transport through manhole structure during surcharge sewer to surface flows. The findings affirm the CFDs models' ability to accurately describe the surface flow partitions and the soluble pollutants transportation processes through the manhole. The study developed initial relationships to describe the degree of solute exchange to the surface as a function of time and flow characteristics. However, this study does not consider the influence of manhole coverings/grates or the changes of structure geometry and shape for the flow partitions, transportation, or deposition processes. Additionally, the study only considered soluble pollution rather than sediments, hence it does not capture the potential variability in contamination concentrations or the quantities and nature of contaminated materials during urban flood events. In a more recent study, Rubinato et al (2022) investigated the flow exchange, energy losses, and pollutant transport in surcharging manholes linked to street profiles. The results revealed a significant soluble pollutant exchange from sewer to surface, ranging between 28% and 39% (Rubinato et al, 2022). This range indicates a potential risk to individuals exposed to contaminated urban floodwater, which could potentially be transporting water borne pathogens that are a risk to human health (de man 2014). However, there remains a notable gap in this research area, as no studies have explored the exchange of sediments from sewer to surface flows during surcharged flood events via manholes equipped with various manhole grate geometries.

Addressing the research gap related to sediment transportation and deposition during surcharged flow conditions is essential for comprehending and managing urban drainage systems, along with mitigating the potential associated risks. Additionally, investigating geometric changes within hydraulic structures, such as different grate covers and inlets, is important for advancing our understanding their influences on the sediment's behaviour and the flow exchange. This study therefore aims to provide a new experimental dataset describing the exchange of sediments from piped drainage networks to surface systems within an experimental scale model. It is anticipated that this dataset will be of value for model development testing and validation, providing increased confidence in model predictions when applied to full scale UDS. These efforts will collectively contribute to a wider understanding of the associated health risks from contaminated floodwater from urban drainage systems.

2.2 Experimental Setup/Methodology

This section describes the experimental scale model urban drainage system, sediment injection and measurement system at USFD, and the grate geometries tested in this research as well as the measured hydraulic conditions for the experimental tests conducted.

The experimental tests described here utilise a 1:6 pipe/manhole/surface scale model at USFD. It links a model surface floodplain to an urban drainage system via a manhole shaft (see Figure 1). The floodplain surface is 4 m width, 8.2 m length, with a longitudinal slope of 1/1000.

Connecting the surface to sewer pipes, the manhole shaft is made from vertical acrylic pipe, has a 0.478 m height, and an inner diameter of 0.24 m. Directly beneath the floodplain, connected by the manhole shaft, is the drainage system made from horizontal acrylic pipes, with an inner diameter of 0.075 m. The facility has been used for a number of previous studies of pipe/surface flow interaction, and more details can be found in, for example, Rubinato et al. (2017). A pumping system in a closed-circuit supplies water within the facility. With inflows to the upstream pipe being set independently by automated control valves operated via Labview software and both inflow and outflows (Qin, Qout) to the manhole monitored with in line magnetic flow meters. The facility is equipped with a SCADA system (Supervision, Control and Data Acquisition) through Labview software that permits the monitoring and logging of the flow rates and other sensor readings within the sewer system. Flow at the sewer outlet can also be controlled by a manual value. Given sufficient flow at Qin and applying a partial restriction to Qout via the manual valve, results in net flow exchange (Qe) from the sewer to the surface.

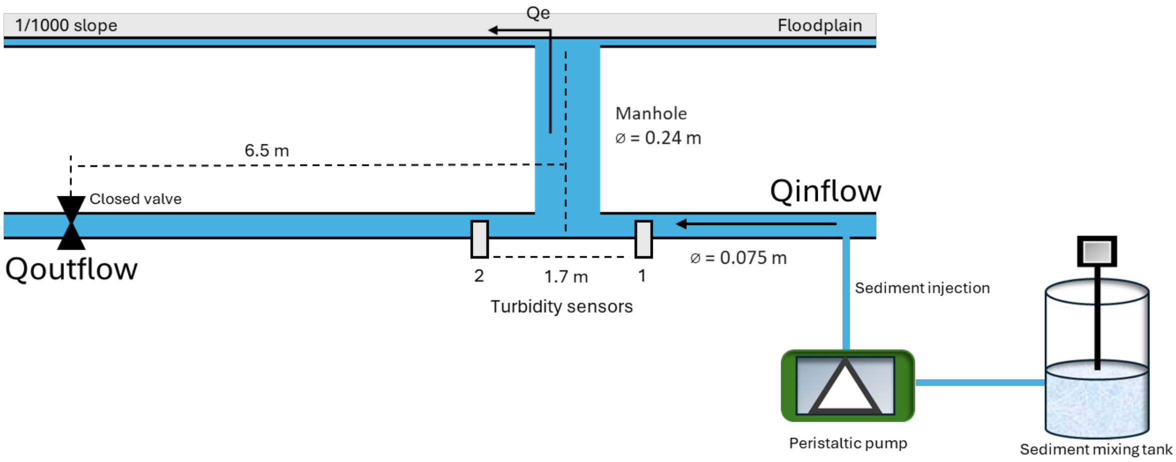


Figure 1. Experimental setup at USFD. Tests were conducted in steady state hydraulic conditions under a range of flow exchange (Qe) rates and manhole lids. Sediment load is injected 9.47 m upstream of the manhole (also upstream of the flow meter), with concentrations monitored in the pipe network using turbidity probes.

For the purposes of these experiments the system has been modified to allow the study of the transport of sediments within the pipe system and the potential transfer to surface flow. The adjustments involve the installation of a sediment injection system that suspends sediments in water within a storage tank (using a continuous stirring system), connected to the sewer inflow pipe (Qin) 9.47 m upstream of the manhole via a calibrated peristaltic pump (Figure 2), allowing the injection of sediment loads with particle sizes representative of road sediments (d50 between 150 and 600 µm). An additional settling tank has also been incorporated, connected to the sewer outflow pipes to prevent the sediments from re-entering the water supply. This settling tank utilises sediment bags to capture and contain the sediment particles. Turbidity monitors (Cyclopes 7F from Turner Designs) have been installed both 0.85m upstream and downstream of the manhole centre. Continuous monitoring of the turbidity of the flow into and out of the manhole can be directly related to the sediment concentration within the flow via a calibration relationship (see section 3.2.1). Given a measurement of the steady flow rate into and out of the manhole, the sediment load passing through the manhole can also be calculated and used to consider the net sediment load (Se) passing to the surface via a mass balance when the system is in surcharge conditions (+ve Qe).

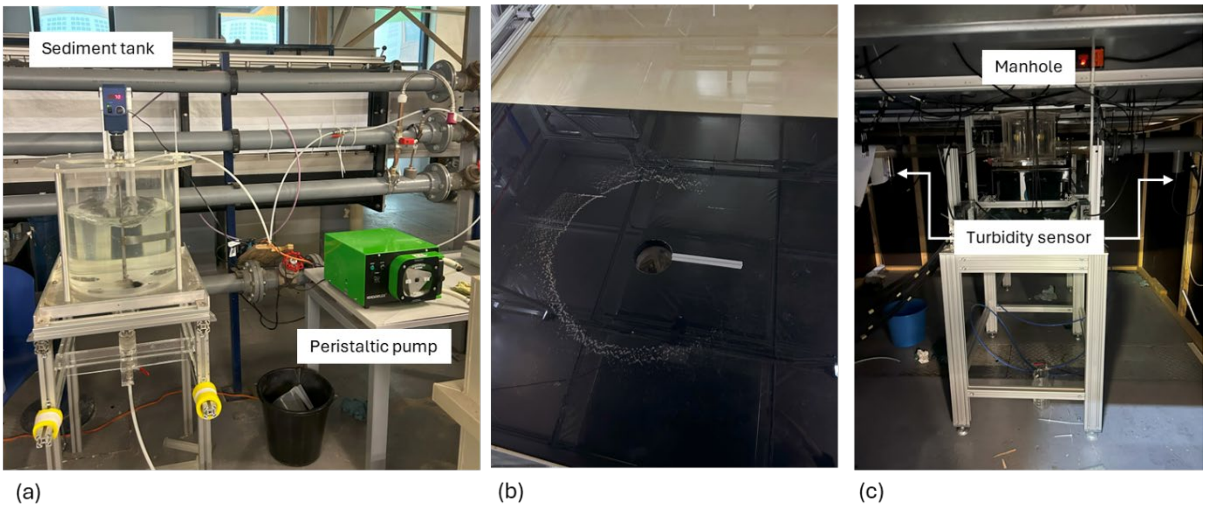


Figure 2. (a) showing the sediment mixer tank and peristaltic pump injecting into sewer inflow pipe (b) birds eye view of the manhole on floodplain surface, grey tape marking 40 cm (c) showing manhole and turbidity sensors location below floodplain.

A series of experiments were conducted to determine proportion the sediment load transferring to the surface flows under several different hydraulic conditions (i.e. by adjusting the pipe inflow valve to achieve different surcharge flow rates). Further, experiments have been repeated with several different manhole grate types (Figure 3), the characteristics of these are presented in Table 1. This allows the work to consider the influence of system geometry on the sediment load being transported to the surface flow.

Table 1. Grate characteristics, including void ratio of empty space to full manhole opening and total effective perimeter of filled/unfilled space.

Grate	Area of empty space (m^2)	Void ratio (%)	Effective perimeter (m)
No grate (NG)	0.0452	100	0.753 (manhole circumference)
A	0.0145	32.1	3.0364
B	0.0079	17.48	1.3880
C	0.0061	13.5	2.2586
D	0.0067	14.11	1.2428

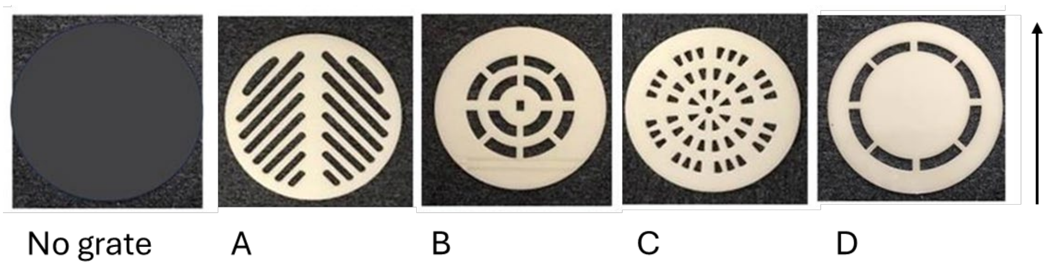
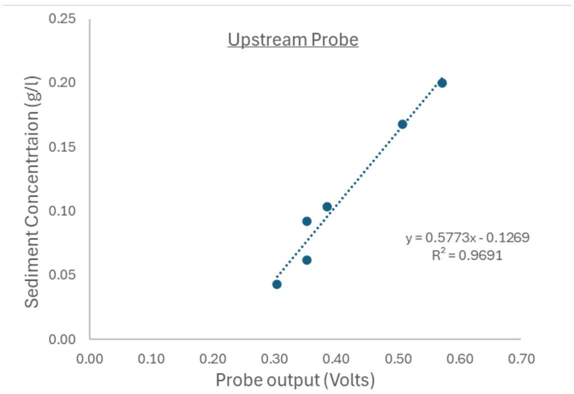


Figure 3. Grates applied on top of manhole. Black arrow shows orientation of grates (direction of flow).

2.2.1 Turbidity Probe Calibration Procedure

A careful calibration procedure was carried out to determine the relationship between in situ turbidity probe response (Volts) and sediment concentration (g/l) at the measurement positions upstream and downstream of the manhole. The mixing tank was filled with 20 l of water and a known mass of sediment (150g - 200 g depending on the test). The peristaltic pump was set to a known flow rate and the sediment/water mixture was pumped from the tank into a series of three beakers before being connected to the Qin pipe inflow for a period of 5 mins during non-surcharge (Qe = 0, Qin = Qout) conditions. Following the measurement of the response of the turbidity probes to the sediment injection, the pipe was again sequentially diverted to three further beakers. The sediment and water in each of the beakers was then filtered to quantify the sediment mass and water volume and given the known pump and sewer pipe flow rate, the mean sediment concentration during each calibration test could be derived. This was repeated for several sediment concentrations and flow rates to develop a known relationship between sewer pipe sediment concentration and the resulting in-situ response of the turbidity probes. The resulting calibration plots for the turbidity probes are presented in fig.4



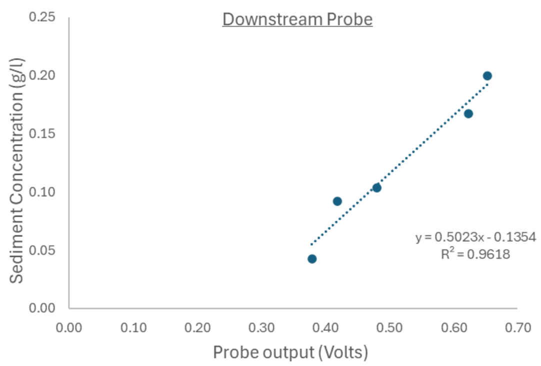


Figure 4. Calibration relationships for turbidity probes upstream (left) and downstream (right) of the interaction manhole.

2.3 Results

Results of all 32 experiments (over a range of hydraulic conditions and grate types) are presented in Table 2 and Figures 5-6. Each test is run in steady state hydraulic conditions (flow rates are left to stabilise for 3 minutes before sediment is introduced into the system), all resulting in a different degree of flow/sediment exchange from the pipe network to the surface. Pipe inflow and outflow (Qin, Qout, l/s) values are measured using the facility flow meters and represent a temporal average of 3 minutes of data. Flow exchange to the surface (Qe, l/s) is calculated based on a mass balance considering the measured pipe inflow and outflow to the manhole (Qe = Qin – Qout). Inflow and outflow sediment load (Sin, Sout, g/l) is based on a 3-minute temporal average of the turbidity measurements, applying the calibration relationships presented in 3.2.1 and measured flow rate. The flow rate and sediment concentration are used to calculate the sediment load at the inflow and outflow and hence the net sediment load transferred out of the manhole to the surface via a mass balance calculation (Se, g/l). This result is also presented non dimensionally as a fraction of the inflow sediment load which is transferred to the surface flow (Se/Sin).

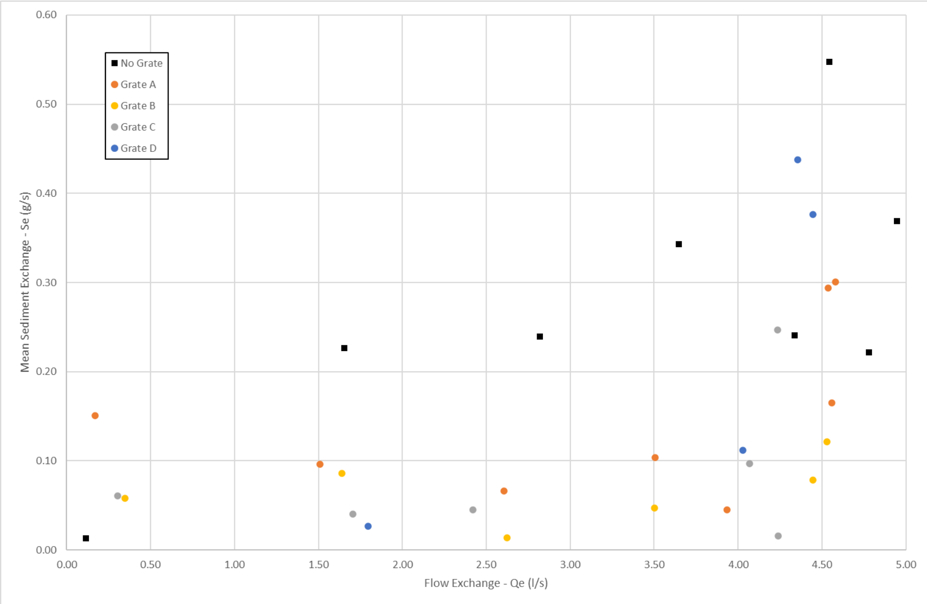


Figure 5. Measured mean sediment transport rate from pipe network to surface (g/s) as a function of flow exchange (surcharge) from pipe to surface (l/s) for all grate types.

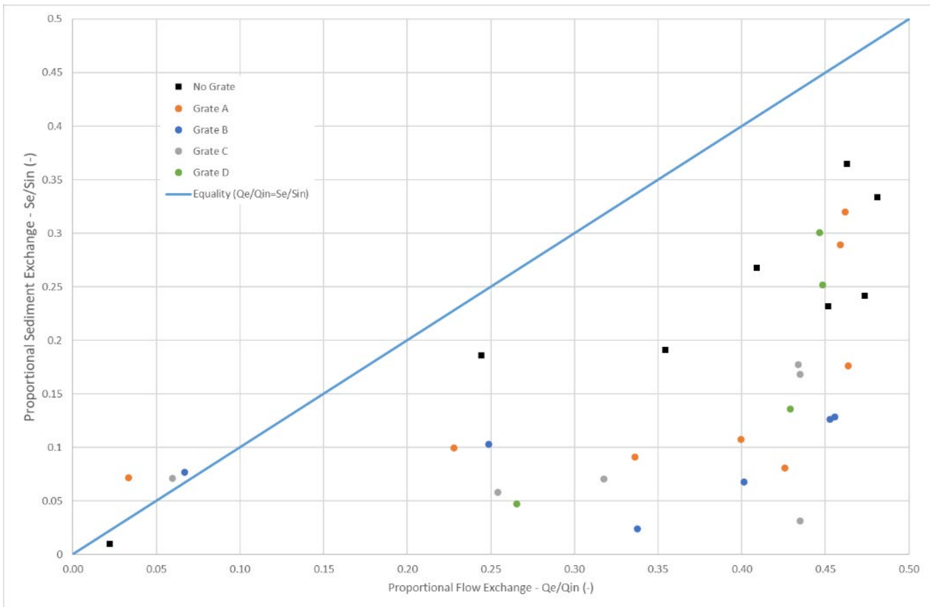


Figure 6. Non dimensional mean sediment transport rate from pipe network to surface (g/s) as a function of flow exchange (surcharge) from pipe to surface (l/s) for all grate types. The line of equality (Proportional Flow exchange = Sediment Exchange) is also shown

Results demonstrate a broad increase in sediment exchange from the pipe network to the surface as the flow rate (surcharge) increases. This is as expected as higher velocities increase the ability of the flow to transport sediment vertically through the manhole chamber. Overall sediment exchange is observed to be higher in the open manhole/no grate condition, hence the addition of a manhole lid is effective in reducing the sediment exchange to the surface flow, especially when the flow exchange is relativity low (> 4 l/s or 40% of the inflow). In these cases, the proportion of sediment exchanged to the surface remains below 10% when a grate is included (compared to up to approx. 20-25% in the case of no grate). After 4 l/s the proportion of sediment reaching the surface increases rapidly for all grate types (A-D), moving closer to (although not reaching) equivalency with the proportional flow exchange, and converging with the 'no grate' results. Again, this is likely due to the overall higher velocities and turbulent flow structures inside the manhole being able to vertically transport and keep in suspension a greater proportion of the sediment load including the higher grain sizes. For the grates tested in this work there is little conclusive difference in performance between the different grate designs.

Table 2. Experimentally measured mean sediment loads transported to surface through different grate types (NG, A,B,C,D) under varying sewer surcharge flow rates. Values are time averaged results from 3-minute tests.

Grate/ Test No.	Flow Exchange, Qe (l/s)	Proportional Flow exchange, Qe/Qin (-)	Mean Sediment Exchange, Se (g/s)	Proportional Mean Sediment Exchange, Se/Sin (-)
NG 1	0.12	0.022	0.01	0.010
NG 2	1.65	0.244	0.23	0.186
NG 3	2.82	0.354	0.24	0.191
NG 4	3.65	0.409	0.34	0.268
NG 5	4.34	0.452	0.24	0.232
NG 6	4.54	0.463	0.55	0.364
NG 7	4.78	0.474	0.22	0.242
NG 8	4.95	0.481	0.37	0.334
A 1	0.17	0.033	0.15	0.072
A 2	1.51	0.228	0.10	0.100
A 3	2.61	0.336	0.07	0.091
A 4	3.50	0.399	0.10	0.107
A 5	3.94	0.426	0.04	0.080
A 6	4.54	0.459	0.29	0.289
A 7	4.56	0.464	0.17	0.176
A 8	4.58	0.462	0.30	0.320
B 1	0.35	0.067	0.06	0.077
B 2	1.64	0.249	0.09	0.103
B 3	2.62	0.338	0.01	0.024
B 4	3.50	0.401	0.05	0.067
B 5	4.45	0.453	0.08	0.126
B 6	4.53	0.456	0.12	0.129
C 1	0.31	0.059	0.06	0.071
C 2	1.70	0.254	0.04	0.058
C 3	2.42	0.318	0.05	0.070
C 4	4.07	0.435	0.10	0.168
C 5	4.24	0.435	0.02	0.031
C 6	4.24	0.434	0.25	0.177
D 1	1.79	0.265	0.03	0.047
D 2	4.03	0.429	0.11	0.136
D 3	4.36	0.447	0.44	0.301
D 4	4.45	0.449	0.38	0.252

2.4 Conclusions

Sediments within urban floodwater which originate from UDS are likely to pose a significant risk to public health. There are currently no available experimental datasets describing the transport of sediments from pipe systems to surface flows during urban flood situations. Such information is likely to be useful for UDS in understanding risks as well as coordinating and mitigating post flood risks and recovery operations when considering public health. The experiments described here represent the first available datasets describing the behaviour and transport of sediments during flood/sewer surcharge conditions, utilising an experimental scale model. This is expected to be of immediate value to researchers wanting to develop and validate hydrodynamic urban flood models which include sediment transport processes. As expected, overall results confirm the proportion of sediment exchanged to the surface from the pipe network increases with the degree of flow surcharge. The addition of a manhole grate is shown to be effective in reducing the transported sediment load for smaller surcharge rates, although in this case as the proportion of flow surcharge increased past 40% of the manhole inflow, the effect of the grate on sediment exchange relative to an open manhole became negligible. To reduce health risk to the public during more frequent, less severe floods it is therefore recommended that manhole lids are secured such that they remain in place during surcharge events and can therefore reduce overall sediment load transferred to the surface.

3 Understanding the influence of leaf litter and sand on the water balance composition of blue-green infrastructure

3.1 Introduction

From centralised, end-of-pipe-based "grey" infrastructure, urban stormwater strategies have increasingly embraced decentralised, blue-green infrastructure (BGI) such as bioretention cells, porous pavements, or green roofs. BGI offer various hydrological, ecological, aesthetic, and societal benefits as part of their multifunctional design, due to which urban water engineers and planners are increasingly proposing their implementation, with or without pipe-based drainage systems in the mix. From an urban hydrological perspective, BGI reduce runoff volume by storing rainwater on-site (water retention) (Stovin et al., 2013). BGI also temporarily store water to lower the peak flow rate, slow runoff concentration time, or control the outflow rate (water detention) (Stovin et al., 2017).

Many studies have focussed on BGI planning and designing requirements and strategies, but less on their maintenance requirement, which is generally overlooked and understudied (Blecken et al., 2017). It is hypothesised that BGI will have reduced hydrological benefits in the long-term without regular upkeep to preserve their hydrological performance.

Against this context, the results of an experimental study to establish the maintenance requirements of BGI are presented. The study's general objective was to understand the impacts of poor maintenance on BGI's hydrological performance. Here, the effects of incremental leaf litter and sand accumulation on a green roof are depicted, assuming that the expected effects are similar in other BGI as well. The specific objectives, in relation to the green roofs' hydrological performance, were to:

1. Quantify the changes in the water detention characteristics
2. Quantify the changes in the underdrain flow volume and characteristics

3.2 Methodology

3.2.1 Overview

The tests were conducted at CITEEC in the University of Coruña (UDC), Spain, which is equipped with an indoor rainfall generator (Figure 7a) (Naves et al., 2020), and three BGI boxes (Figure 7b), of which only Boxes 1 and 2 were used for the study. The boxes were each equipped with tipping buckets to quantify the underdrain flow (Figure 7c) and soil moisture sensors to measure soil water content (not visible in Figure 7c). The green roofs' composite layers (tray arrangements) are shown in Figure 7d that shows the surface layer on top of bottom storage layers.

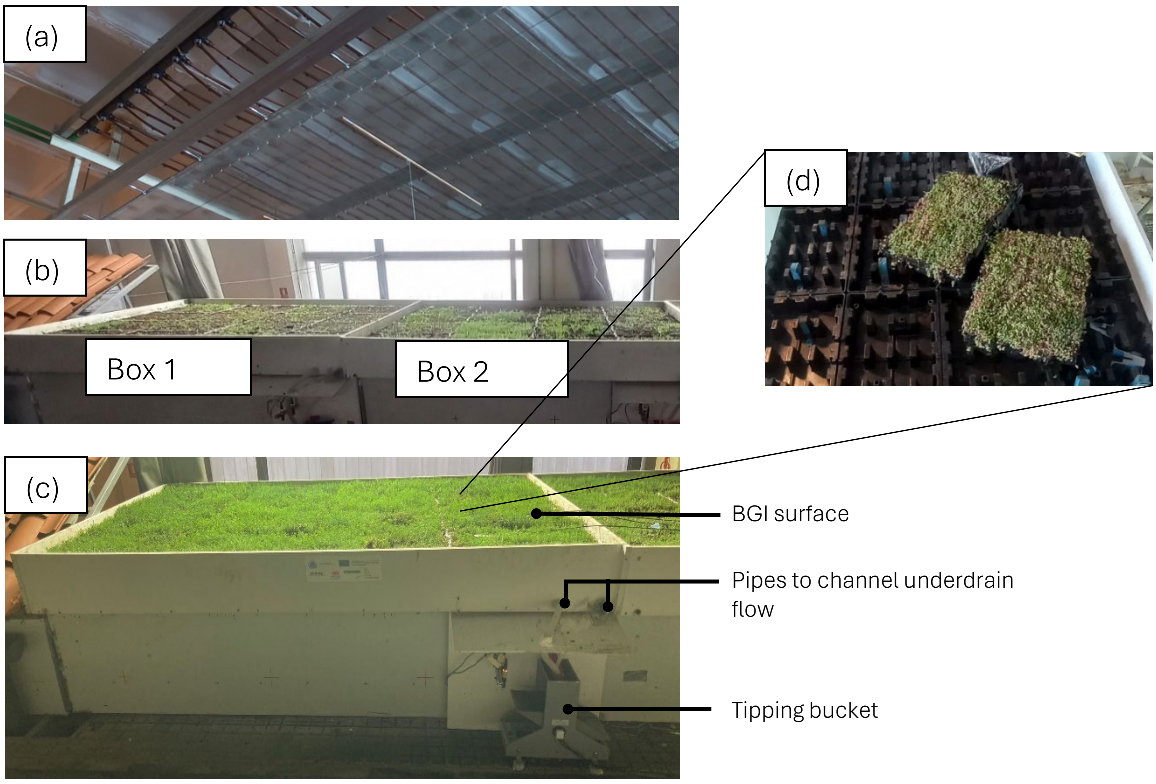


Figure 7. Overview of the rainfall generator and the BGI housed in boxes with tipping buckets to measure underdrain ow. (a) Rainfall generator; (b) Two BGI boxes showing the arrangement of trays; (c) Front view of one of the roofs with the tipping bucket to measure underdrain flow; (d) Tray arrangements

3.2.2 Rainfall generator

The rainfall generator, which was initially capable of producing 30, 50, and 80 mm/h (Naves et al., 2020), was adapted by lowering the water pressure to generate less intense values so as not to limit the study to extreme events. In doing so, it was ensured that the pressure was enough to produce a uniformly distributed rainfall across the two boxes. For a given rainfall intensity, rainwater was collected in sixteen collecting vessels on each of the two boxes for 15 minutes. The “new” intensity of rainfall was then computed by averaging the weight of the collected rainwater in the vessels. On the other hand, the uniformity of the rainfall was quantified using the Christiansen’s uniformity coefficient (Cu) (Christiansen, 1942).

The total volume of rainfall was also confirmed by removing all the trays and leaving only the boxes and collecting all the rainwater in the box. The sum was then divided by the total area and duration to obtain the rainfall intensity. This process was repeated three times such that we obtained a mean value (expressed in mm/h) and the corresponding standard deviation (SD) for the two boxes.

3.2.3 Green roof scenarios: no interference (reference condition)

To establish the baseline (reference) condition against which the other scenarios were to be compared, the tests were first conducted without any interventions (i.e. no sand or leaves) on the BGI surface. To simplify the tests and ensure that the major hydrological response was only in the underdrain flow, the tests were simplified by:

1. supplying fixed amount of rainfall (fixed intensity and duration).
2. neglecting the evapotranspiration (ET) as the facility was in indoor condition, which had high relative humidity.
3. preventing the generation of surface overflow by sealing the trays and supplying relatively low intensity rainfall.
4. running the tests in wet conditions, i.e. when the substrate was close to its field capacity. Doing so ensured controlling the initial soil moisture condition and also minimising that the soil storage, which, in turn, allowed that the response of the scenarios was discernible in the underdrain flow only.

3.2.4 Green roof scenarios: incremental sand accumulation

Sand at a rate of 2, 4, 8, 4 kg/m^2 was added incrementally on Box 1 such that the cumulative sums were 2, 6, 14, and 18 kg/m^2, respectively (Figure 8). To ensure a uniform distribution, the sand was spread using a mesh during each addition.

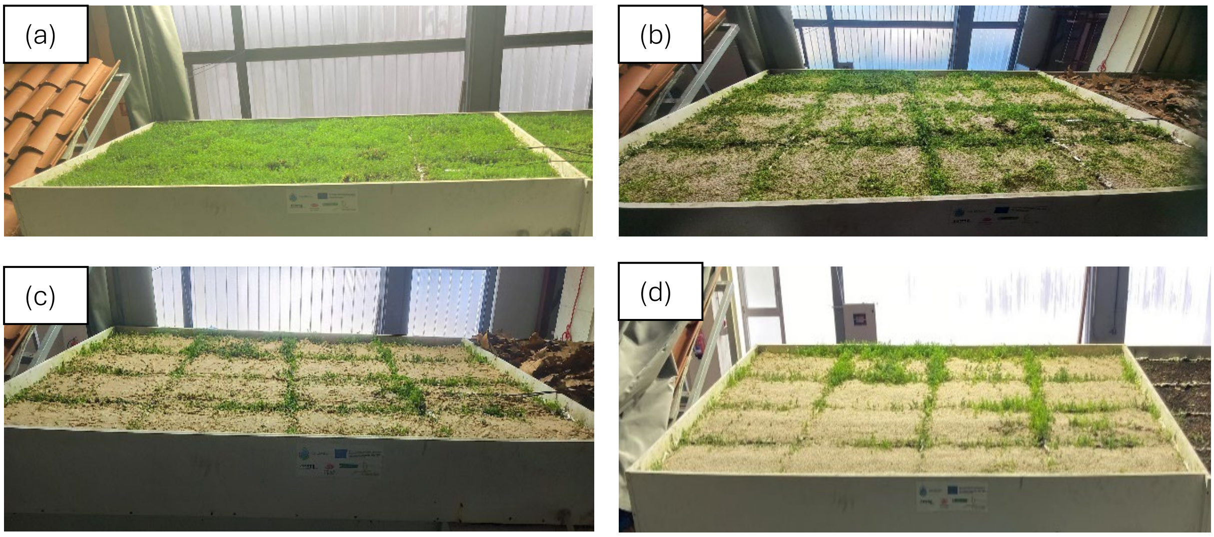


Figure 8. Sand accumulation scenario in Box 1. Total sand amount [kg.m^{-2}]: (a) 2; (b) 6; (c) 14; (d) 18

Once a specific amount of “dry” sand was added, the rainfall (16.66 mm/h for 30 minutes) was supplied, and the hydrological response recorded. Then, more sand was added for another iteration after a delay of at least 24 hours to allow the soil and sand to dry. For some weights, we also conducted tests with “wet” soil in which another test was run after ~4 hours from the first test under dry conditions.

3.2.5 Green roof scenarios: incremental leaf litter accumulation

Leaf litter was added 300, 1200, and 1725g (total) and distributed it randomly –albeit uniformly-- across the BGI surface of Box 2 (Figure 9). Once a specific amount of “dry” leaves was added, rainfall (18.66 mm/h for 30 minutes) was supplied, and the underdrain response recorded. Following the “dry” test, another test was subsequently performed (after ~4 hours by which time the underdrain flow had already ceased), with the same amount of leaves to compare the performance of wet leaves against dry ones.

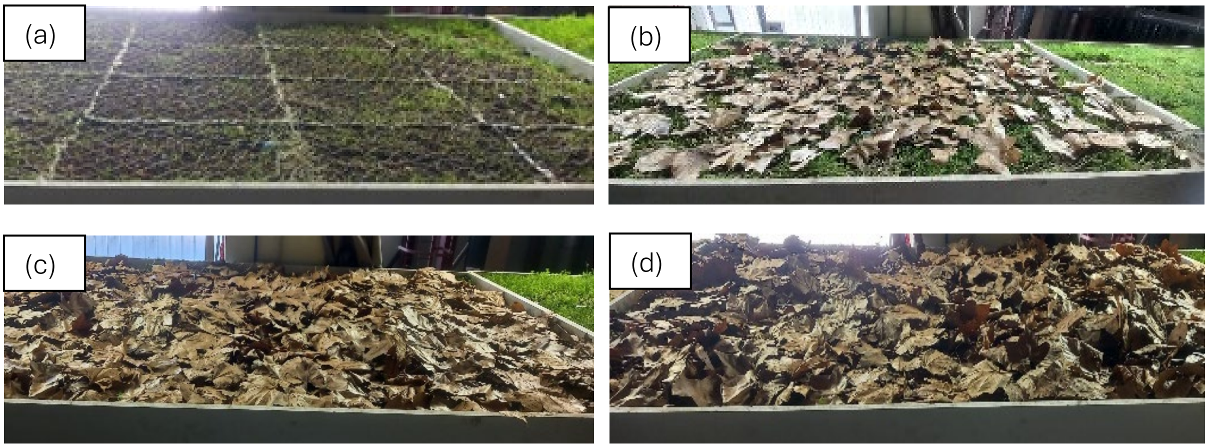


Figure 9. Leaf litter accumulation scenario in Box 1. Total leaf litter amount [g]: (a) 0; (b) 300; (c) 1200; (d) 1725.

3.3 Results

3.3.1 Sand accumulation increased BGI retention in the short term and delayed the onset of underdrain flow

In general, sand accumulation delayed the onset of underdrain flow and attenuated peak flow (Figure 10a and 10b and increased the rainfall retention amount (Figure 10b and 10d). The magnitude of the effect varied with the amount and the wetness of the sand, as shown in Figure 10.

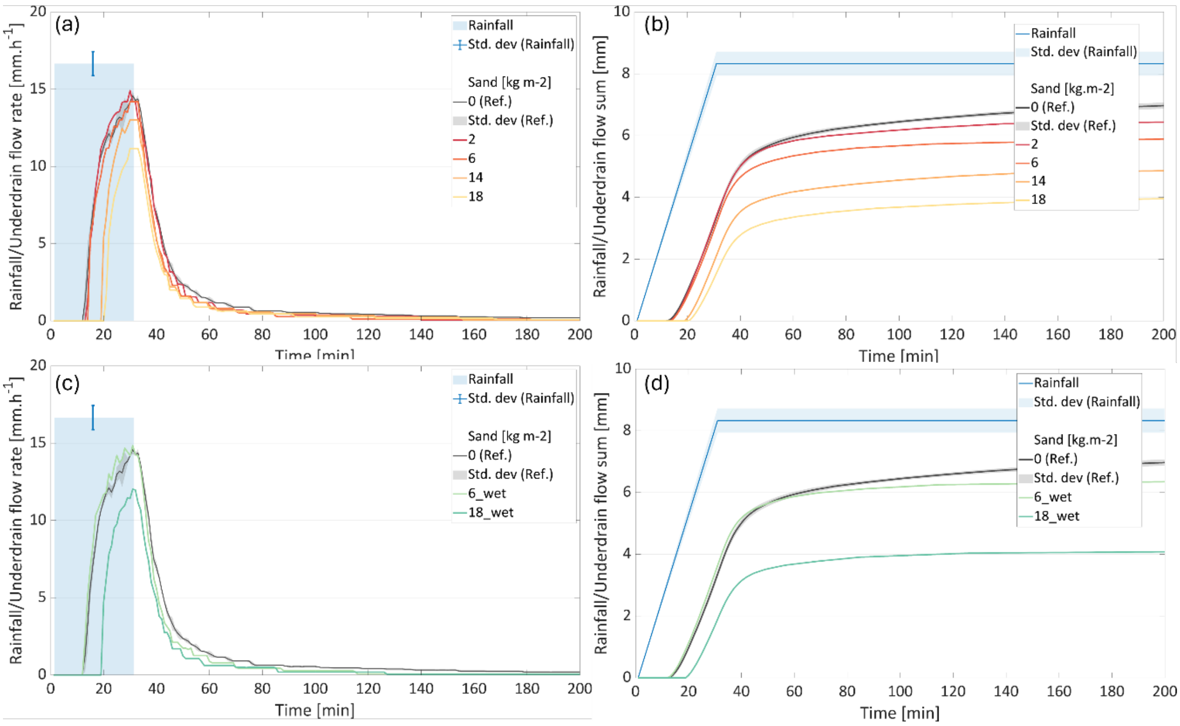


Figure 10. Underdrain flow time series (c) and (d) and cumulative sums (a) and (b) for dry and wet sand, respectively.

Adding 2 kg/m² of dry sand caused the peak to attenuate by ~10%, slightly less than the reference condition, but it delayed the underdrain flow onset to roughly 12 minutes. The rainfall retention also increased to ~23%.

When the sand amount was increased to kg/m², the underdrain flow started only 13 minutes after the rainfall began while the peak attenuation increased to ~13%. More than 29% of rainfall was retained.

However, when the sand was wet, the retention amount was ~5% less than the dry sand, which was still ~8% higher than the reference condition (for 6 kg/m²). However, for this amount of sand, the wetness of sand only led to a marginally quicker onset of underdrain flow (~11min) and lower peak attenuation (~11%).

When more dry sand was added such that, the total amounted to 14 and 18 kg/m², the peak attenuation drastically improved to ~21 and ~32%, respectively. More importantly, the rainfall retention amounts increased to ~42% and ~52%, respectively. Eighteen kg/m² of wet sand had more and quicker underdrain flow than when it was dry but was still considerably slower and lower than the reference condition.

3.3.2 Leaf litter reduced the underdrain flow volume

With the 300 g dry leaf litter, the hydrograph characteristics were similar to that of the reference condition: the underdrain flow started around 11 minutes after the rainfall started, which peaked (~14.8 mm/h) around the end of the rainfall (Figure 11a. The total underdrain flow volume was ~7.6 mm (Figure 11b).

Increasing the dry leaf litter amount to 1725 g, however, had a discernible effect on the hydrograph properties. To begin with, the underdrain flow onset was only at around 15-minute mark, and although the peak flow rate (~15.7 mm.h-1) was slightly higher than the reference condition, the total underdrain flow volume (~6 mm) was considerably lower.

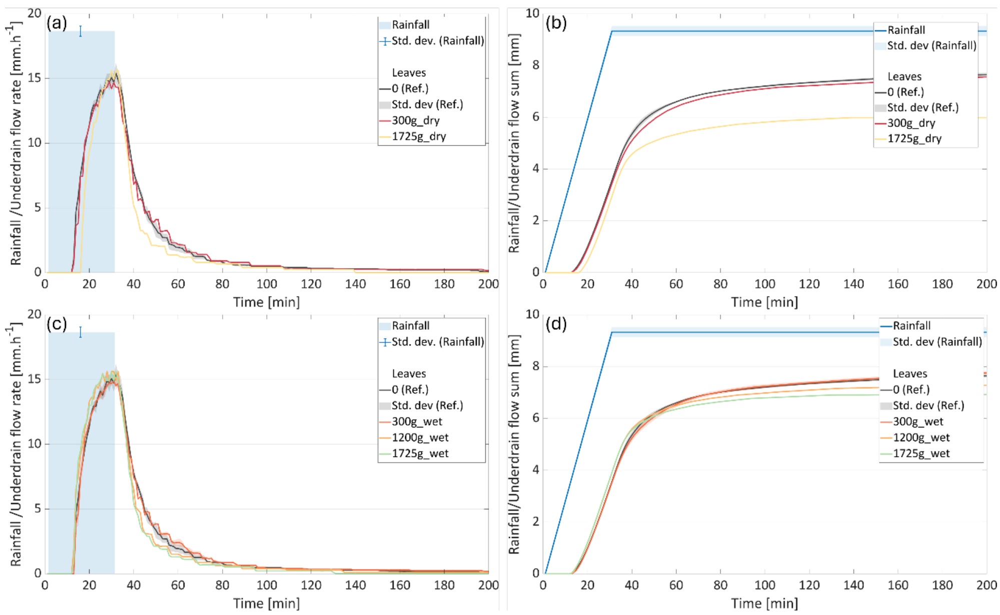


Figure 11. Underdrain flow time series (c) and (d) and cumulative sums (a) and (b) for dry and wet leaves, respectively.

Figures 11c and 11d depict that the wetness of the leaves had only marginal effect for the 300 g weight – comparable hydrograph characteristics, onset time (12 minutes), and total volume (~7.7 mm) – but for higher weights, the time to underdrain flow peak seem to be quicken and the total underdrain flow volume to be higher than for dry leaves. Data for dry 1200 g was not available, so it was excluded from the comparison. It was also noted that while peak attenuation was largely unaffected by the wetness of leaves, dry leaves (1725 g) had a slower onset of underdrain flow by ~3 minutes in comparison with wet leaves. Dry leaves also retained more water; for 1725 g again, the retention was at least 10% higher than for wet leaves of the same weight.

3.4 Conclusions

We presented the results of an experimental campaign to understand the hydrological performance of poorly maintained BGI by adding sand and leaf litter to a green roof and comparing the generated underdrain flows with those generated by a reference green roof. The results showed that sand accumulation increased BGI retention in the short term and delayed the onset of underdrain flow and that leaf litter reduced the underdrain flow volume. These experiments provide insights into understanding BGI dynamics and helping to emphasise that their maintenance is crucial to ensure their optimal hydrological performance.

4 Conclusions and contribution towards the objectives of Co-UDlabs

This deliverable presents two detailed experimental studies of key components of UDS and their performance under pressure, specifically high flow/flooding events as well as understanding the impacts of varying maintenance regimes. The first study conducted at USFD has considered the transport of sediments though traditional UDS during urban flood events, specifically considering the transport of sewer sediments from pipe networks to surface flows during sewer surcharge events. This is of relevance to the understanding of the public health risks posed by urban floods, as sediments are highly likely to contain harmful pathogenetic of chemical substances. The work presents new experimental dataset of significant value for model validation and risk evaluation, as well as presenting new evidence concerning the significance of manhole lids/grates on retaining sewer sediments within pipe networks during flood/surcharge events.

Ultimately this information will assist UDS operators in post flood recovery operations via a better understanding of urban areas and under what flow conditions which there may be of higher risk of negative health outcomes from urban flood inundations. The second study conducted at UDC by researchers from EAWAG considers the hydrological performance of poorly maintained BGI. The study provided specific performance changes relative to a reference case under varying degrees of accumulation of both sand and leaf litter, providing specific information on how reduced maintenance and cleaning of BGI can affect the hydrological performance and hence flood risk.

Taken together these studies provide valuable new insights into the performance of UDS infrastructure under high flow events. This will enable us to provide increased confidence in modelling tools for risk evaluation and the targeting of public investment and post flood recovery resources, as well as provide more specific recommendations regarding UDS maintenance regimes to reduce societal risks of heavy rainfall events.

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