

Experimental study of pollutant washoff on a full-scale street section physical model

Juan Naves, Zurab Jikia, Jose Anta, Jerónimo Puertas, Joaquín Suárez and Manuel Regueiro-Picallo

ABSTRACT

This study analyses the mobilization of total suspended solids (TSS) for different spatial distributions of sediment load located over the roadway surface of a full-scale street section physical model. At the sewer network outlet, flow discharges were measured and TSS pollutographs were determined with manual grab samples and inferred from turbidity records. In all the tests, the rain duration was 5 min and its averaged intensity was 101 mm/h. In addition, solids that were not washed off at the end of the experiments were collected from the street surface, gully pots and pipes and the mass balance error was checked. The experiments were configured to assess the influence of the initial load, spatial distribution method, distance from gully pot and distribution area dimensions on the TSS washoff. The study showed that sediment initial load and distribution cannot explain completely pollutant washoff processes because other variables such as the spatial rainfall distribution or the runoff depth also affect to the outlet pollutographs and system mass balances.

Key words | runoff pollution, sediment transport, urban drainage, washoff

Juan Naves (corresponding author)
 Zurab Jikia
 Jose Anta
 Jerónimo Puertas
 Joaquín Suárez
 Manuel Regueiro-Picallo
 Universidade da Coruña,
 Water and Environmental Engineering Group
 (GEAMA),
 Elviña,
 A Coruña 15071,
 Spain
 E-mail: juan.naves@udc.es

INTRODUCTION

The contemporary trend of fast urbanization and population migration to cities and towns has resulted in the development of more impervious surfaces such as urban areas, roads and parking lots. Some of the consequences of this trend are greater hydrograph runoff volumes and flow velocities and shorter concentration times. The result is an overall increase in pollution levels (Butler & Davies 2010). Pollutants such as sediments, nutrients, organic matter, heavy metals, hydrocarbons or pesticides are accumulated over impervious surfaces during dry days and washed into water bodies through surface runoff during rainfalls (Gastaldini *et al.* 2013). This causes significant environmental impacts and constitutes a great problem in urban areas, as it has been demonstrated in several studies (e.g. Anta *et al.* 2006; Zafra *et al.* 2008; Miguntanna *et al.* 2010). An understanding of pollutant washoff and transport process in sewer systems is essential to estimate the mobilization of

pollutants and to improve treatment techniques to minimize their impact on the environment.

Wind and rain characteristics, surrounding land uses, traffic conditions, catchment characteristics or street sweeping and other human activities are presented by different authors as key factors that affect pollution build-up and redistribution of particles (see among others Deletic *et al.* 1997; Vaze & Chiew 2002; Herngren 2005). Therefore, total load distribution of sediment across the road is not uniform and is influenced by the existence of natural or artificial barriers like vegetation, footpaths or curbs as shown by Deletic & Orr (2005). As part of the given study, sediment collected from sampling sites with different distances from the curb were analysed showing that load and particle sizes decrease with distance from the curb, and two-thirds of these solids were presented within 0.5 m from the curb. Earlier studies (Sartor & Boyd 1972; Grottker 1987) reported the same phenomenon with a higher percentage of solids near the curb. As regards washed sediment sizes, a broad spread of data has been observed in previous quality runoff studies (Charters *et al.* 2015). In the work of Anta *et al.* (2006), a d_{50} mean value of 38 μm was obtained and only 10% of

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY-NC-ND 4.0), which permits copying and redistribution for non-commercial purposes with no derivatives, provided the original work is properly cited (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

doi: 10.2166/wst.2017.345

solids were greater than 150 μm . These values are close to the overall average values reported by the work of [Charters *et al.* \(2015\)](#). Furthermore, studies such as developed by [Chebbo & Gromaire \(2004\)](#) reported that most of the pollutants are associated with the finest fraction of the sediments, which are the most difficult particles to eliminate by sedimentation techniques. Thus, in order to analyse washoff and sediment transport processes, these finest fractions of the surface sediments are considered the most interesting ones.

Urban washoff water quality models are usually based on empirical equations like the developed one by [Sartor & Boyd \(1972\)](#); such equations are implemented in most of the commercial codes like SWMM ([Rossman 2015](#)). Antecedent dry days and total runoff volume are the main relevant variables for describing build-up and washoff processes ([Wang *et al.* 2011](#)). Nevertheless, most of the approaches do not consider other aspects like the sediment characteristics, the definition of a threshold shear stress for particle movement or the influence of raindrops energy ([Tomanovic & Maksimovic 1996](#)), and the equations are often roughly approximate compared to the complexity of the physical phenomena ([Bertrand-Krajewski 2006](#)). In order to design and calibrate numerical models, several studies have been developed to characterize build-up and washoff process in urban catchments of different sizes. For instance, [Egodawatta *et al.* \(2007\)](#) suggest that an isolated storm event has the capacity to wash only a fraction of pollutant and this fraction was related to rainfall intensity, the kinetic energy of rainfall and characteristics of the pollutants. In addition, different empirical approaches to build-up and washoff processes were proposed by authors such as [Wijesiri *et al.* \(2015\)](#), [Chow *et al.* \(2015\)](#) or [Morgan *et al.* \(2016\)](#).

The main objective of this work is to analyse how accumulation and dispersion of pollutants affect the washoff

process on a street section at the scale of 1:1. This facility has been used previously for hydraulic validation and calibration of the Water and Environmental Engineering Group (GEAMA) MODUS 2D-1D urban drainage model ([Fraga *et al.* 2015a, 2015b](#)).

MATERIAL AND METHODS

Experimental setup

The laboratory installation consists of a full-scale street section built in the Hydraulic Laboratory of the Centre of Technological Innovation in Construction and Civil Engineering (CITEEC) at the University of A Coruña. The physical model geometry and overview of the installation are shown in [Figure 1](#). The model consists of a concrete tile pavement and a concrete roadway linked to a sewer drainage network. Three gully pots, two of them at the roadway and a third one at the end of the lateral outflow channel with a rectangular cross section, collect the runoff to the sewer network which includes six circular pipes with two different diameters: 0.085 m (Pipe 1 and Pipe 2) and 0.19 m (Pipes 3, 4, 5 and 6). The surface has an average transversal slope of 2% to the 0.15 m high concrete curb and a 0.5% longitudinal slope to the outflow channel. The sewer network characteristics and a detailed bathymetry of the model can be consulted in [Fraga *et al.* \(2015b\)](#).

Four nozzles of Fulljet 3/4HH71WSQ (Spraying System Co., Wheaton, IL, USA) located 2 m above the surface generate the rainfall in the model. The kinetic energy of falling raindrops is a key variable in the washoff process because it affects the degree to which pollutants are detached from the surface on impact. Therefore, nozzles have been selected taking into account raindrops' fall velocity (7.62 m/s) and

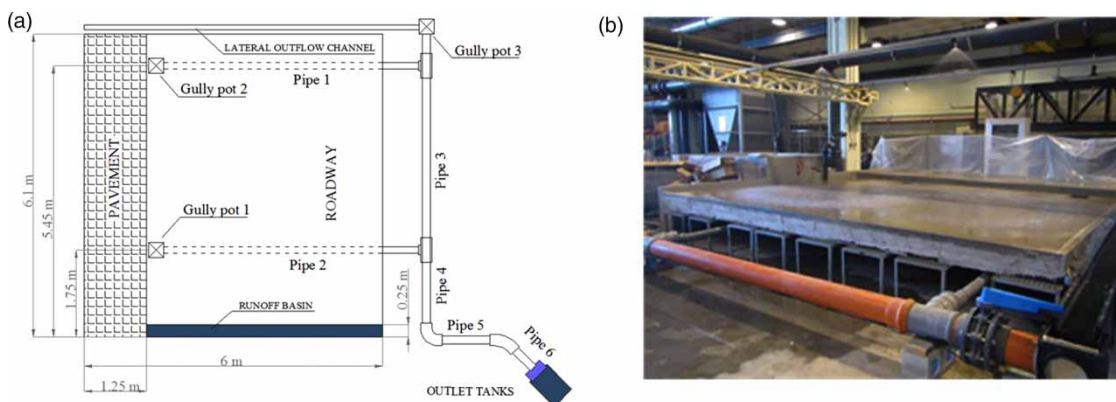


Figure 1 | Geometry (a) and photograph of the experimental setup (b).

mean size (0.0028 m), in order to reproduce faithfully real rain characteristics (Hudson 1963). The rain intensity distribution at the roadway and pavement surface was measured by the volume of water collected in a 0.25 m grid of test tubes during 3 min of rainfall. Rain intensity map (Figure 2(a)) shows that intensity is higher in two opposite areas for each diffuser and where they overlap. Average rainfall intensity (101.44 mm/h) corresponds to a high intensity of real rain.

Two tanks located at the sewer network outlet were used to measure turbidity and discharge volume (Figure 2(b)). A turbidity probe (Solitax) was installed in the first tank, which has a reduced volume (0.16 m diameter and 0.4 m length), allowing measuring the turbidity records with sufficient depth. The turbidity was measured with a 5-s frequency and a measurement accuracy of ± 0.01 FNU (Formazin Nephelometric Unit). This tank drains into a bigger reservoir (0.5 \times 0.6 m²) where discharge was measured by a triangular weir. In addition, discharge was redundantly measured by a flowmeter installed at the rainfall generation system. The error between both measurements was less than 2%.

An industrial dust with $d_{50} = 40 \mu\text{m}$ and 200 μm maximum size was chosen to simulate runoff pollution according to the results from Anta *et al.* (2006). It has a suitable grain size and it also has excellent properties for a total suspended solids (TSS) analysis. This dust is not cohesive, it does not form floccules and it does not dissolve, so the sediment transport is completely in suspension allowing a greater control over solid discharges and mass balances.

Experimental procedure

Different build-up configurations were placed over the roadway surface before the beginning of the experiments. Once the sediment deposits were distributed, a constant rain was simulated for 5 min. During each experiment, turbidity and flow discharge were monitored continuously at the sewer network outlet. As both parameters were measured at different reservoirs, time shifts have been noticed at the beginning and at the end of the hydrograph caused by the retained volume in the outlet tank (Figure 2(b)). In order to compensate these time shifts (20 s maximum), the hydrograph was routed in the outlet of the turbidity probe reservoir from the discharge measured with a triangular weir and a variation of the outlet tank volume. The total amount of sediment mass from the runoff was determined from the hydrograph and pollutograph integration.

In the course of each test, 12 manual grab samples were collected with 250 mL vessels at the turbidity probe tank outlet as part of the runoff characterization. The purpose of sampling was to correlate TSS concentrations with the turbidity probe signal. The first 6 samples were collected every 10 s after the beginning of the flow discharge in order to record the peak of the pollutograph accurately. The next 6 samples were collected every 60 s with the aim of having data from the whole pollutograph. TSS values were obtained from samples following the APHA (1995) method. By means of a linear regression, the turbidity probe signal was converted to TSS concentration values. As suggested by Torres & Bertrand-Krajewski (2008), an individual trend line was obtained for each test, resulting

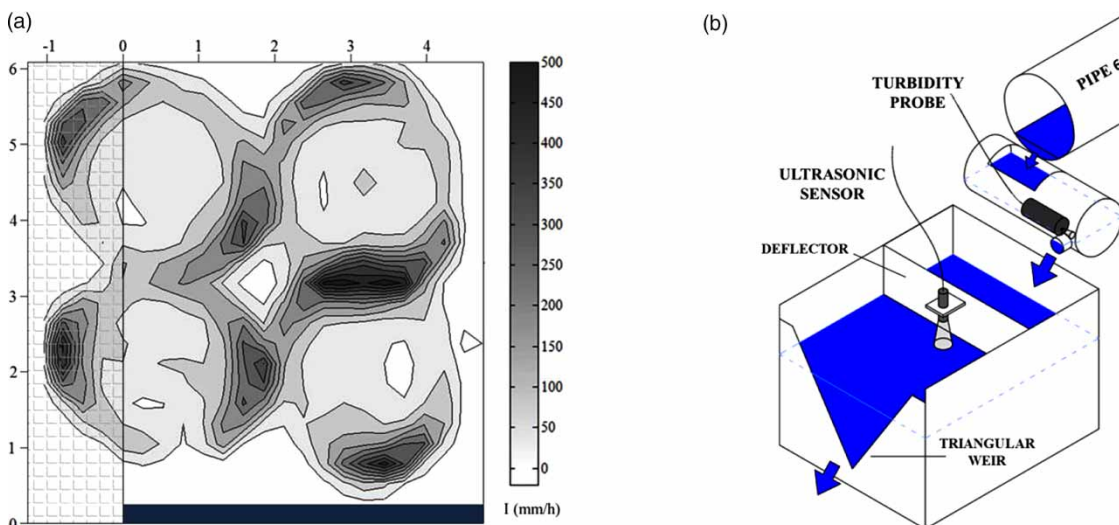


Figure 2 | Rain intensity map over street surface (a) and scheme of sewer outlet tanks (b).

in determination coefficients (R^2) above 0.96 for all experiments (Figure 3). All manual grab samples volumes were added to the measured flow hydrograph.

At the end of each test, a percentage of the initial sediment load remained deposited over the pavement. In addition, some dust was retained inside gully pots and pipelines. These sediment fractions were recovered in order to calculate a sediment mass balance and assess the global accuracy of each test. Firstly, dust remained over the surface and inside gully pots it was collected with an industrial vacuum sweeper with a 98% sweeping efficiency. Some cement dust particles from the pavement surface were also collected in a small portion during this process. Sweeping blank experiments (without sediment loads over the surface) were performed to consider these particles in mass balances. Later, pipes 1, 2 and 3 were cleaned with a 1 L/s flow. TSS concentrations and flow discharge were measured in cleaning processes in order to calculate the mass associated with pipe sediment bed deposits.

Relative error in the mass balance of each test (ϵ_M) was obtained as the difference between the initial sediment load placed over the roadway surface (M_0) and the amount of mass recorded at the sewer outlet (M_{outflow}), the amount of mass recovered by the industrial sweeper at the pavement surface (M_{surface}) and gully pots (M_{gully}), and the sediments deposited in pipeline inverts (M_{pipes}) in accordance with Equation (1). In this equation the small fraction of cement dust particles (about a 2% of M_0) recovered by the vacuum sweeper has also been taken into account ($M_{\text{cement dust}}$).

$$\epsilon_M = \frac{1}{M_0} [M_0 - (M_{\text{outflow}} + M_{\text{surface}} + M_{\text{gully}} + M_{\text{pipe}} + M_{\text{cement dust}})] \quad (1)$$

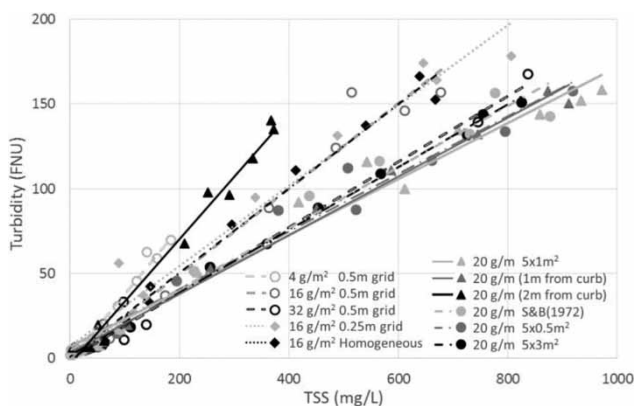


Figure 3 | Individual turbidity (FNU) and TSS (mg/L) regressions.

Following this methodology, eleven experiments grouped into four sets of tests were performed. Figure 4 shows the sediment distribution and initial load for each test. The experiments were configured to assess the influence of the initial load, the spatial distribution method, the distance from the curb and the distribution area dimensions on the TSS washoff.

- Initial surface sediment load tests:** Several build-up studies, mentioned in the introduction section, were reviewed in order to select the most suitable initial load. Due to the wide range of variation of the initial sediment load, it became interesting to analyse how this parameter affects the mobilization of TSS. Therefore, in the first set of experiments called initial load tests (Figure 4(a)), three experiments with different pollutant loads of 4, 16 and 32 g/m² and the same distribution over the roadway surface were carried out. In all cases, dust was distributed in a 0.5 m grid on a total surface of 4 m². In these tests, sediment was deposited between the gully pots because runoff from this area is completely drained into gully pot 2 and sediment transport conditions are more controlled.
- Sediment distribution method tests:** Using a grid to distribute sediment in small rectangular piles (with an area of 0.0025 m²) allows us to easily repeat and compare different tests, but this distribution method gets away from the way that pollutant appears over real roadways. This set of experiments was performed to study the influence of the sediment distribution, with the same initial sediment load (16 g/m²) placed over the roadway (Figure 4(b)). In addition to the 0.5 m grid distribution of the first round of experiments, a 0.25 m grid and a homogeneous distribution were placed over a total surface of 4 m².
- Distance from the curb tests:** In the third set of experiments, sediment was distributed along 5 m of the curb in 1-m-wide strips. For these tests, the strip was placed attached to the curb and 1 and 2 m away from it (Figure 4(c)). The purpose of these experiments was to compare the resulting pollutographs for different separations of the sediment strip from the gully pots.
- Curb accumulation tests:** Real roadway sediment accumulates near the curb (Grottker 1987; Deletic & Orr 2005). Therefore, in the last set of tests, a 20 g/m initial sediment load was attached along the curb with a 5-m-length strip with different widths for each experiment

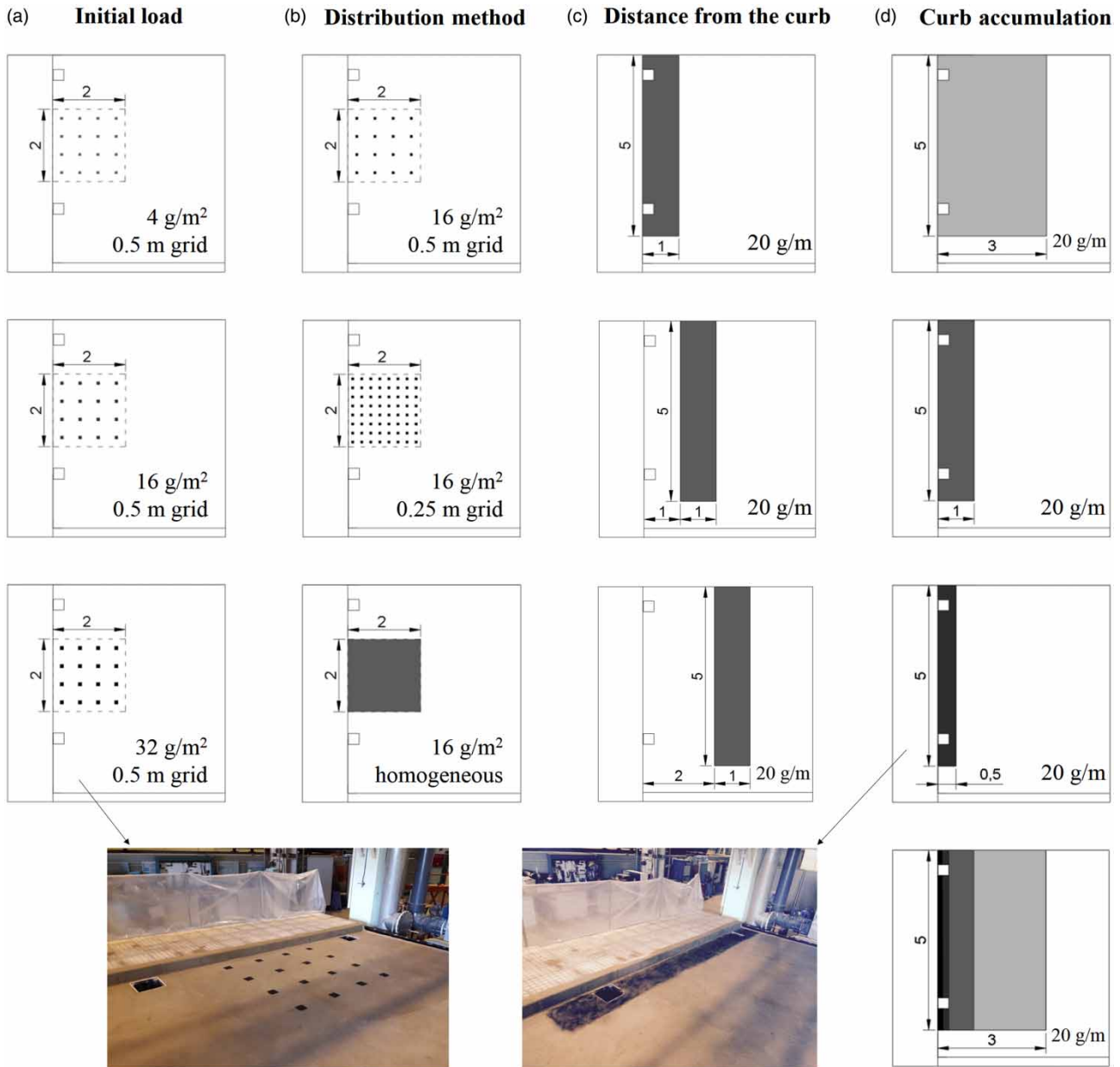


Figure 4 | Distribution of the initial dust deposited over roadway surface in performed experiments. Two photographs from initial load and curb accumulation test are also included.

(Figure 4(d)). Firstly, dispersed load tests were performed with surface sediment widths of 0.5, 1 and 3 meters. In the last experiment, a more realistic distribution of the initial sediment load was placed following Sartor & Boyd (1972) measurements. This study concluded that 78% of the initial sediment load over a roadway surface was found within the first 0.15 m from the curb, then 10% and 9% over the next 0.15 and 0.70 m, respectively, and finally 3% over the rest of the surface up to the road median.

RESULTS AND DISCUSSION

Initial surface sediment load tests

Figure 5 shows the pollutographs and discharges measured during the initial load tests and mass balance results. A good agreement between turbidity derived pollutographs and manual samples was found. The TSS peak value measured increases in an approximately linear trend as the initial sediment load over roadway surface increases,

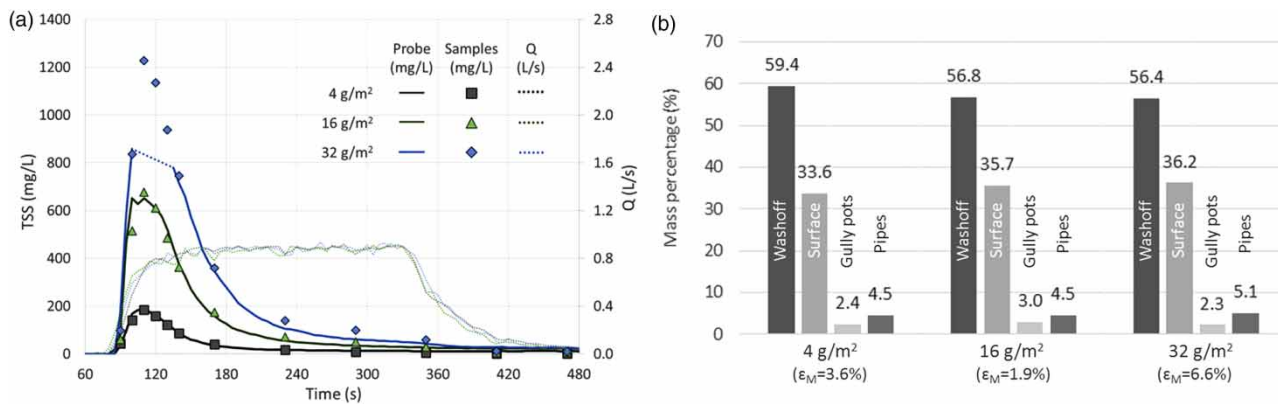


Figure 5 | Samples and turbidity signal derived TSS pollutographs and discharges at the sewer outlet (a) and mass percentage final distributions (b) for sediment loads of 4, 16 and 32 g/m² over a 4 m² surface in a 0.5 m grid. Values in parentheses indicate the mass errors balance (ϵ_M).

without TSS peak temporal shift, so results can be extrapolated to other initial pollutant loads. Discharge remains constant in all cases because hydraulic experiment conditions do not vary throughout the configurations tested in this work.

In these experiments, 93% ± 1% of sediment mass was washed off by rain or remained over the road surface. About 58% ± 2% of mass was recorded at the sewer outlet and about 35% ± 2% was collected over the surface after the end of each experiment. A non-negligible sediment mass was also deposited in the gully pots and pipes (7% ± 1% in mass). These sediment percentages were kept almost constant for all test conditions, therefore the percentage of sediment washoff was unaffected by the initial sediment load over the roadway surface. Mass balance error (ϵ_M) was found below 7% for all experiments, which is reasonably low considering the scale of the system and the studied phenomenon. In the test with the highest TSS peak value, sediment mass at the system outlet was integrated from manual samples curve because the turbidity probe was out of range in these measurement conditions (roughly 800 mg/L, Figure 5(a)).

Sediment distribution method tests

Figure 6 shows the pollutographs and mass balances of the experiments with the same initial load (16 g/m²) and different surface distribution method. TSS peak concentrations are very similar in all these tests, with a slightly higher peak for the 0.25 m grid. Therefore, spreading sediment homogeneously does not introduce qualitative differences either in TSS pollutographs or in the mass distribution. This allowed the development of more realistic experiments

with a homogenous distribution of the sediment load over the surface. The amount of mass collected in the runoff, surface, gully pots and pipes shows small variations between experiments, but the final distribution is similar to the previous tests. Consequently, mass balance is independent from the distribution method too. Again, small relative errors in the mass balances were determined in the tests (below 4% in these cases).

Distance from the curb tests

Results from the third set of experiments are shown in Figure 7. TSS concentration peaks at the sewer outlet were delayed and dumped as surface sediment transport path length was increased from the curb. When the surface load was placed near the curb, TSS peak was recorded after ~100 s from the beginning of the rainfall, meanwhile TSS peaks for tests with sediment area separated 1 and 2 m were collected at ~110 and ~120 s, respectively. Furthermore, smaller TSS concentrations were recorded for longer surface transport and, consequently, more sediments remained over the surface.

For instance, in the test with sediment distributed 2 m from the curb, TSS peak concentrations at the sewer outlet were less than half compared with other experiments. For this test, we have to notice the combined effect of the sediment transport path length with the spatial rainfall distribution. Thus, in the area situated between 1.6–2.0 m away from the curb the rain nozzles overlap each other and create a higher intensity rainfall zone (Figure 2(a)). High rain intensity areas hindered sediment transport from the pavement situated at a further distance from the curb and most of the sediment remain over the pavement. Previous

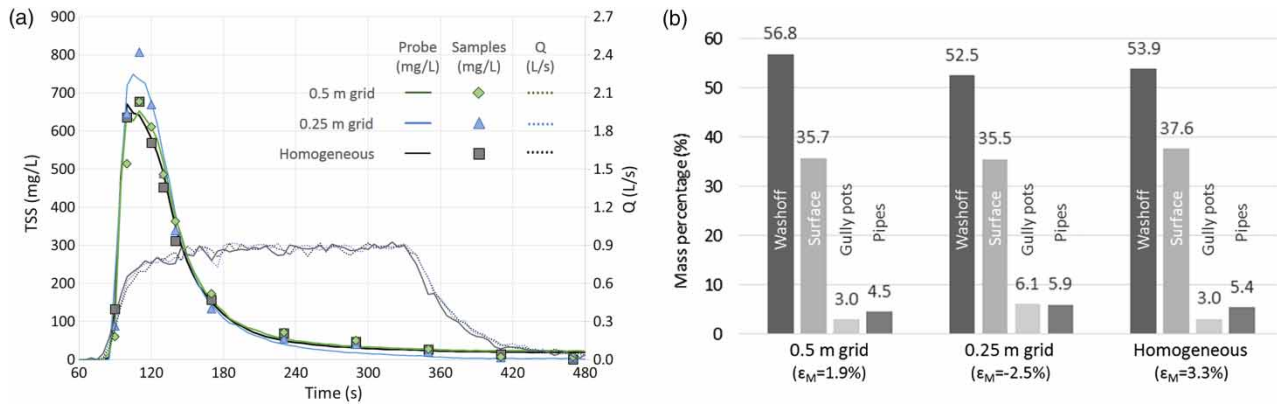


Figure 6 | Samples and turbidity signal derived TSS pollutographs and discharges (a) and mass percentage final distributions (b) placing a sediment load of 16 g/m² over a 4 m² surface on a 0.5 m grid, a 0.25 m grid or spreading homogeneously. Values in parentheses indicate the mass errors balance (ϵ_M).

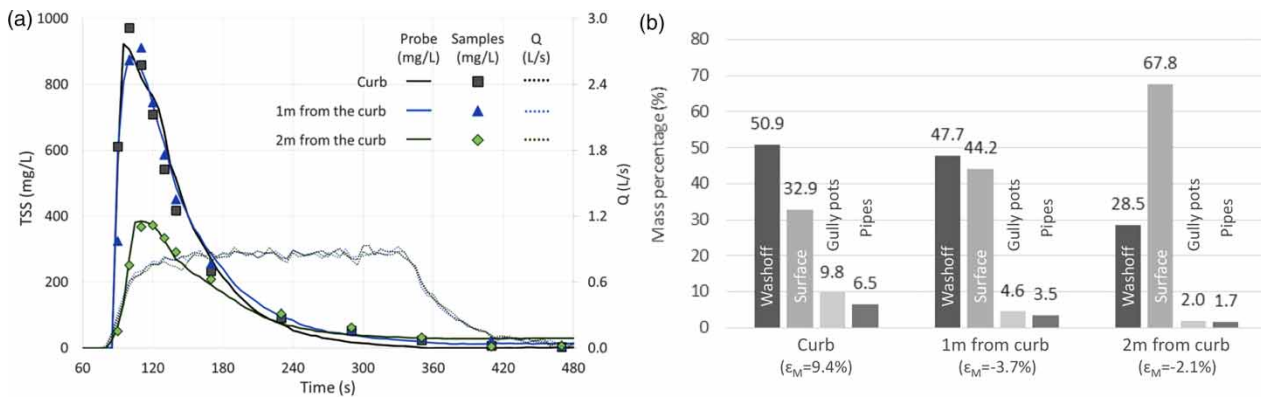


Figure 7 | Samples and turbidity signal derived TSS pollutographs and discharges (a) and mass percentage final distributions (b) for a sediment load of 20 g/m, spread homogeneously over a 5-meter-long and 1-meter-wide surface, attached or 1 or 2 m separated from the curb. Values in parentheses indicate the mass error balance (ϵ_M).

experiments were not affected by this phenomenon because sediments were not placed upstream this high intensity area.

As stated previously, the sediment mass distribution over the surface, in gully pots and pipes is also affected by the position of the sediment strip in the street. When pollutants are far away from the curb, the amounts of sediments collected over the surface increases significantly (from ~30% to ~70% roughly); meanwhile, the mass recovered from gully pots, pipes and, especially, washoff decreases. The maximum mass error balance was slightly increased in these tests ($\epsilon_M = 9.4\%$) probably due to the fact that the sediments were distributed over a larger area.

Curb accumulation tests

Finally, a more realistic sediment distribution was analysed in the curb accumulation tests. Figure 8(a) reveals that higher maximum TSS concentrations were recorded at the

sewer outlet when the same amount of dust load of 20 g/m was distributed over a narrower wide strip. Thus, for a $5 \times 0.5 \text{ m}^2$, the TSS peak is 1,052 mg/L and, for a $5 \times 3 \text{ m}^2$, the peak is 824 mg/L. The recorded time to peak in these three tests is almost constant (about ~100 s from the beginning of the rainfall). Like, in the distance from the curb tests, as the amount of mass washed by the runoff decreases, more sediments remain over the surface and into gully pots and pipes (Figure 8(b)).

The recorded pollutograph and mass balance for the Sartor & Boyd (1972) surface load distribution differ from the previous homogeneous strip load tests. Thus, the outlet pollutograph presents a smaller TSS peak (877 mg/L) and is recorded later (~110 s). In this case, a large percentage of the sediment load was distributed on a small area (0.15 m attached to the curb) where the highest water depths (~0.005 m) were recorded. These depths cause a decrease on sediment erodibility associated with the rain

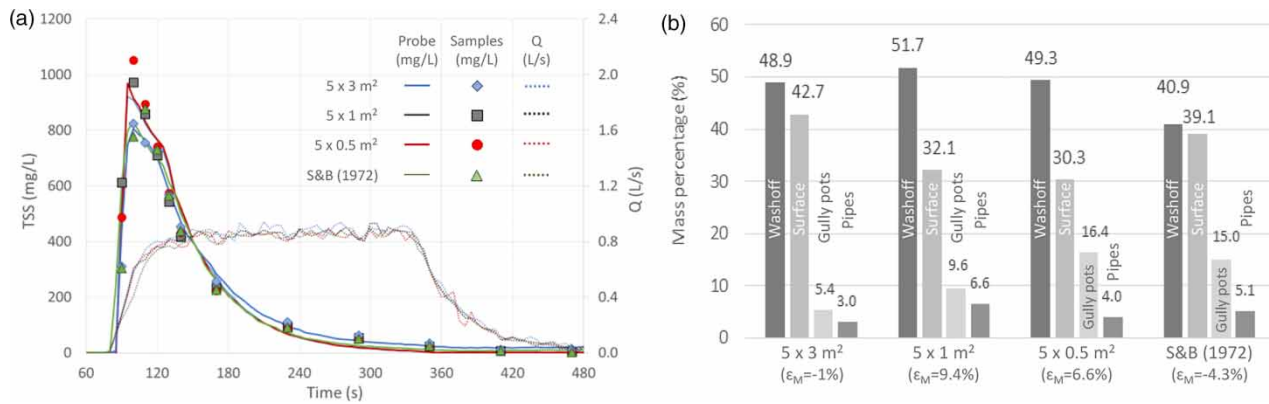


Figure 8 | Samples and turbidity signal derived TSS pollutographs and discharges (left) and mass percentage final distributions (right) for a sediment load of 20 g/m, spreaded homogeneously over a 5-m-long and 3, 1 or 0.5-m-wide surface and placed with a stepped distribution. Values in parentheses indicate the mass error balance (ϵ_M).

drops' kinematic energy, so a high sediment load is deposited near the curb at the end of the test. As the sediment is concentrated in a thinner strip, the washoff efficiency of the curb over land flow may be reduced and more sediments could remain over the surface at the end of the experiment. From the mass balance point of view, the amount sediment collected from gully pots increased as more sediments were placed close to the curb. The effect of non-uniform rain explained in the previous section was also observed in the 5 x 3 m² test, where one-third of the initial load was placed upstream of the high rain intensity area. The maximum error in the mass balance remained around 9.4%.

CONCLUSIONS

In this work, an experimental campaign was performed in a full-street physical model to assess some relevant aspects related with the washoff and pipeline sediment transport processes in impervious urban areas. In the tests, the influence of the initial sediment load and its distribution over the street surface were analysed with a constant 5-minute rainfall. TSS pollutographs and flow discharges were recorded at the sewer outlet. After the rainfall, the sediment deposited over the street surface, gully pots and pipelines was measured in order to determine the mass distribution in different components of the system. Mass balances were performed to estimate the global test accuracy.

The first tests reveal that TSS peak value on pollutographs has an approximately linear relationship with initial sediment load over roadway surface, so results can be extrapolated to other surface load concentrations. In addition, it has been proven that the different methods of distributing the same amount of mass over the same total area do not produce

qualitative differences either in the resulting pollutographs or in the mass distribution on the model. In the third and fourth sets of experiments, we observed that the maximum TSS values decrease as the surface sediment transport path length increases. Consequently, more sediments are deposited over the street surface. Nevertheless, these two parameters (surface sediment load and distribution) cannot explain completely pollutant washoff processes because the spatial rainfall distribution or the runoff depth also affects the outlet pollutographs and system mass balances.

Finally, the obtained outcomes are part of a systematic database which is being developed at our laboratory facility. New tests considering different sediment grain sizes or rainfall intensities will be developed in future. The results obtained will allow the validation and calibration of sediment transport equations for surface washoff, gully pot build-up and pipeline sediment transport in dual drainage models.

ACKNOWLEDGEMENTS

This project was supported by Program for Consolidation of Competitive Research Units GRC2014/041 (Xunta de Galicia). The first author was in receipt of an FPU grant from the Spanish Government (FPU14/01778). This work was also partially funded by the project CGL2015-69094-R (MINECO/FEDER, UE).

REFERENCES

- Anta, J., Peña, E., Suárez, J. & Cagiao, J. 2006 A BMP selection process based on the granulometry of runoff solids in a separate urban catchment. *Water SA* **32** (3), 419–428.

- APHA 1995 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association, Washington, DC, USA.
- Bertrand-Krajewski, J. L. 2006 Modelling of sewer solids production and transport. Cours de DEA 'Hydrologie Urbaine'.
- Butler, D. & Davies, J. 2010 *Urban Drainage*, 3rd edn. Spon Press, Abingdon, UK.
- Charters, F. J., Cochrane, T. A. & O'Sullivan, A. D. 2015 Particle size distribution variance in untreated urban runoff and its implication on treatment selection. *Water Research* **85**, 337–345.
- Chebbo, G. & Gromaire, M. C. 2004 The experimental urban catchment 'Le Marais' in Paris: what lessons can be learned from it? *Journal of Hydrology* **299** (3), 312–323.
- Chow, M. F., Yusop, Z. & Abustan, I. 2015 Relationship between sediment build-up characteristics and antecedent dry days on different urban road surfaces in Malaysia. *Urban Water Journal* **12** (3), 240–247.
- Deletic, A. & Orr, D. W. 2005 Pollution buildup on road surfaces. *Journal of Environmental Engineering* **131** (1), 49–59.
- Deletic, A., Maksimovic, C. & Ivetic, M. 1997 Modelling of storm wash-off of suspended solids from impervious surfaces. *Journal of Hydraulic Research* **35** (1), 99–118.
- Egodawatta, P., Thomas, E. & Goonetilleke, A. 2007 Mathematical interpretation of pollutant wash-off from urban road surfaces using simulated rainfall. *Water Research* **41** (13), 3025–3031.
- Fraga, I., Cea, L., Puertas, J. & Anta, J. 2015a Nonintrusive method to compute water discharge in pipes with a low depth-to-diameter ratio using ultrasonic Doppler velocimetry. *Journal of Hydraulic Engineering* **141** (3), 06014024.
- Fraga, I., Cea, L. & Puertas, J. 2015b Validation of a 1D-2D dual drainage model under unsteady part-full and surcharged sewer conditions. *Urban Water Journal* **14** (1), 74–84.
- Gastaldini, M. D. C., Silva, A. R. V., Cauduro, C., Roberta, A. & Silva, V. 2013 Pollutant distribution on urban surfaces: case study in Southern Brazil. *Journal of Environmental Engineering* **139** (2), 269–276.
- Grottker, M. 1987 Runoff quality from a street with medium traffic loading. *Science of the Total Environment* **59**, 457–466.
- Herngren, L. F. 2005 *Build-up and Wash-off Process Kinetics of PAHs and Heavy Metals on Paved Surfaces Using Simulated Rainfall*. Doctoral dissertation, Queensland University of Technology, Brisbane, Queensland, Australia.
- Hudson, N. W. 1963 Raindrop size distribution in high intensity storms. *Rhodesian Journal of Agricultural Research* **1** (1), 6–11.
- Miguntanna, N. P., Goonetilleke, A., Egodawatta, P. & Kokot, S. 2010 Understanding nutrient build-up on urban road surfaces. *Journal of Environmental Sciences* **22** (6), 806–812.
- Morgan, D., Johnston, P., Osei, K. & Gill, L. 2016 Sediment build-up on roads and footpaths of a residential area. *Urban Water Journal* **14** (4), 378–385.
- Rossman, L. A. 2015 Storm Water Management Model, User's Manual, Version 5.1 (No. EPA/600/R-05/040). US Environmental Protection Agency, Cincinnati, OH, USA.
- Sartor, J. D. & Boyd, G. B. 1972 *Water Pollution Aspects of Street Surface Contaminants*. EPA-R2-72-081. United States Environmental Protection Agency, Washington, DC, USA.
- Tomanovic, C. & Maksimovic, C. 1996 Improved modelling of suspended solids discharge from asphalt surface during storm event. *Water Science and Technology* **33** (45), 365–369.
- Torres, A. & Bertrand-Krajewski, J. L. 2008 Partial least squares local calibration of a UV-visible spectrometer used for in situ measurements of COD and TSS concentrations in urban drainage systems. *Water Science and Technology* **57** (4), 581–588.
- Vaze, J. & Chiew, F. H. 2002 Experimental study of pollutant accumulation on an urban road surface. *Urban Water* **4** (4), 379–389.
- Wang, L., Wei, J., Huang, Y., Wang, G. & Maqsood, I. 2011 Urban nonpoint source pollution buildup and washoff models for simulating storm runoff quality in the Los Angeles County. *Environmental Pollution* **159** (7), 1932–1940.
- Wijesiri, B., Egodawatta, P., McGree, J. & Goonetilleke, A. 2015 Incorporating process variability into stormwater quality modelling. *Science of the Total Environment* **533**, 454–461.
- Zafra, C. A., Temprano, J. & Tejero, I. 2008 Particle size distribution of accumulated sediments on an urban road in rainy weather. *Environmental Technology* **29** (5), 571–582.

First received 14 September 2016; accepted in revised form 30 May 2017. Available online 11 August 2017