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The Relevance of Grated Inlets within Surface Drainage Systems in the Field of Urban Flood Resilience. A Review of Several Experimental and Numerical Simulation Approaches

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Abstract: Urban drainage networks should be designed and operated preferably under open channel flow conditions without flux return, backwater, or overflows. In the case of extreme storm events, urban pluvial flooding is generated by the excess of surface runoff that could not be conveyed by pressurized sewer pipes, due to its limited capacity or, many times, due to the poor efficiency of surface drainage systems to collect uncontrolled overland flow. Generally, the hydraulic design of sewer systems is addressed more for underground networks, neglecting the surface drainage system, although inadequate inlet spacings and locations can cause dangerous flooding with relevant socio-economic impacts and the interruption of critical services and urban activities. Several experimental and numerical studies carried out at the Technical University of Catalonia (UPC) and other research institutions demonstrated that the hydraulic efficiency of inlets can be very low under critical conditions (e.g., high circulating overland flow on steep areas). In these cases, the hydraulic efficiency of conventional grated inlets and continuous transverse elements can be around 10–20%. Their hydraulic capacity, expressed in terms of discharge coefficients, shows the same criticism with values quite far from those that are usually used in several project practice phases. The grate clogging phenomenon and more intense storm events produced by climate change could further reduce the inlets' performance. In this context, in order to improve the flood urban resilience of our cities, the relevance of the hydraulic behavior of surface drainage systems is clear.

Keywords: pluvial floods; urban resilience; inlet systems; hydraulic efficiency; discharge coefficient; experimental campaigns; numerical studies

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1. Introduction

The term resilience is frequently used in various fields, including engineering and water resources management. In the context of flood risk management, resilience can be defined as the capacity of a system, community, or society, potentially exposed to flood hazards, to adapt by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure [1].

According to Directive 2007/60/EC, a flood is defined as the "temporary flooding of land that is not normally covered by water" [2]. Within the context of urban flood management, urban flooding can include pluvial, fluvial, and coastal flooding.

Pluvial flooding occurs when stormwater saturates the capacity of the land or the sewer drainage network in the case of urban areas, and the runoff volumes accumulate in sag points or circulate in an uncontrolled manner along the surface's areas. Urban drainage networks should be designed and operated preferably under open channel flow conditions without flux return, backwater, or overflows [3]. Notwithstanding, in the case of extreme storm events, the high amount of generated runoff could exceed the maximum capacity of the sewer system, producing pressured pipe conditions.

Two main trends suggest that the problem of urban pluvial flooding is likely to increase [4]. The first of these is the growing number of people that live in cities due to the fact that the world's population is becoming increasingly urban, while the second trend arises from the possibility for climate change to lead to more extreme rainfall [5,6].

In this context, pluvial flood urban resilience should currently be the main concern of our city planners, which needs to be carefully evaluated in order to guarantee the normal development of urban activities [7,8], to ensure people are safe [9,10], and to reduce economic losses [11].

Urban pluvial flooding may occur due to two reasons that can be concomitants: surface drainage deficiency and underground sewer system failure [12].

The first phenomenon occurs when extreme rainfall events produce high surface runoff rates flowing along preferential pathways, typically roads, footpaths, natural ground depressions, small water courses, etc., that cannot be efficiently conveyed into the underground storm water drainage system.

In other cases, the underground stormwater drainage system itself overflows due to its poor capacity to convey the runoff produced on peri-urban catchments and the discharges captured by the surface drainage system.

Until recently, storm sewer systems were typically designed on the assumption of near full-flowing pipes, often with little regard for how surface runoff is delivered to it [13,14].

Indeed, runoff is almost never fully conveyed by storm sewers in the case of extreme storm events when the capacity of the surface drainage system is poor. Even if the sewer systems are designed by the best hydrological and hydraulic methods, they will not be able to work adequately if due attention is not given to the design of surface drainage systems [15,16].

The surface drainage system in our city is generally composed of a series of curb-opening inlets, grated inlets, and continuous transverse grates combined with drainage channels (Figure 1). The last two types of elements are the subjects of two specific European Norms (EN) in the context of the European legislative framework [17,18]: the EN-124 (*Gully tops and manhole tops for vehicular and pedestrian area. Design requirements, type testing, marking, quality control*) and the EN-1433 (*Drainage channels for vehicular and pedestrian areas. Classification, design and testing requirements, marking and evaluation of conformity*). Both norms regulate possible locations of these types of structures, materials, design requirements, and testing concerning bearing capacity, but they do not provide anything about procedures or methods to achieve a correct inlet spacing or any other hydraulic aspects related to inlet design.

Furthermore, during recent decades, several studies have been carried out about the effectiveness of structural and nonstructural measures, including nature-based Solutions, to cope with climate change impacts [19–22], but the hydraulic behavior of the surface drainage system in a complex hydrologic context often exacerbated by uncontrolled urban growth and climate change and the way in which it is affected by clogging is often overlooked, thus leading to the misrepresentation of system performance and, in particular, of flooding occurrence [23].

Within this context, what is clear is the relevance of surface drainage systems in urban flood risk management and, in general, as a basic piece of the pluvial flood urban resilience in our cities.

This paper presents the recent advances in the experimental and numerical campaigns carried out during recent decades at the Technical University of Catalonia (UPC) to improve the knowledge about the hydraulic behavior of some inlet elements that are typically included in the surface drainage systems (conventional grated inlets and continuous transverse grates) during extreme storm events and the effects of the clogging phenomenon on their hydraulic performance.

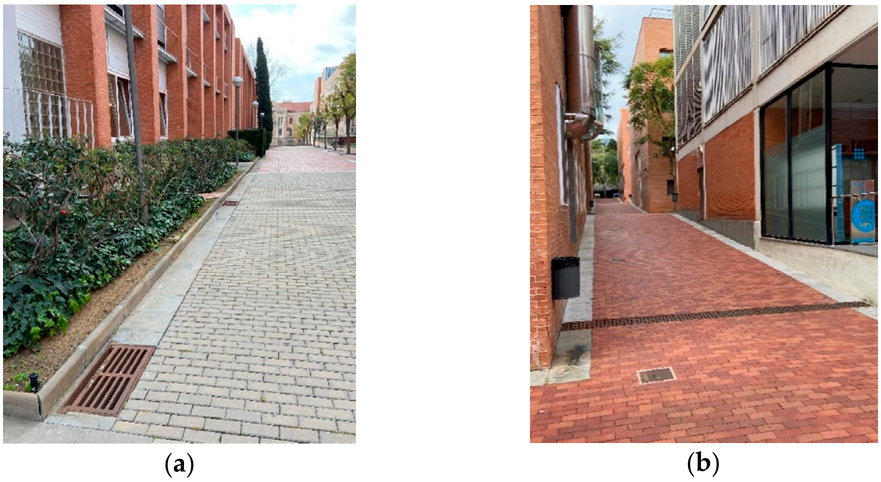
(**a**) (**b**)

Figure 1. (**a**) Grated inlets and (**b**) continuous transverse grates in the Campus Nord of the Technical University of Catalonia (UPC).

Finally, some inlet system models implemented in real cases are described in order to show that cutting edge techniques concerning the estimation of the hydraulic efficiency of these kinds of elements can be applied at the city scale.

2. Hydraulic Performance of Urban Drainage Systems

2.1. Surface Drainage Systems in Urban Areas

The hydraulic performance of urban drainage systems depends on the single performance of its main components and their operational condition [23]. One of the main components of urban drainage systems are the inlet structures (conventional and macro grated inlets, continuous transverse grates, grated manholes, slotted inlets, etc.) through which surface storm-water runoff enters the sewer system and occasionally exits when sewers surcharge [24].

During the design phase, engineers generally hypothesize that stormwater enters into the sewer systems exactly in the same hydrological catchment where it left. According to this hypothesis, they define the limits of the hydrological catchments and sub-catchments by the inlet position (or the position of any surface drainage structure). However, surface runoff is often not diverted entirely by these structures, and significant amounts of runoff can bypass the assumed hydrological limits if the surface drainage system capacity is not appropriated. In fact, the inlet system capacity governs both the rate of water removal from the surface and, as a consequence, the amount of water entering into the storm drainage system. If this hypothesis does not prove to be true, hydrological and hydraulic supposed schemes will be different to those assumed during the design process and, in case of extreme rainfall events, this can suppose serious flooding problems with significant social and economic impacts [25,26]. Thus, there is a clear need to have rigorous and validated experimental and numerical procedures for a correct estimation of the hydraulic performance of these types of elements; a correct inlet spacing is one of the key steps in urban drainage design to guarantee the normal development of urban activities and to avoid or limit economic damage, nuisances, and the risk to people [12,15,16,24,27,28].

Furthermore, surface drainage system design should not neglect other important aspects such as the potential effects of climate change on the maximum rainfall intensity at the local scale [6,29] that can make obsolete inlet spacing criteria adopted in the past, and the sewer inlet clogging phenomenon that can have a large impact on the occurrence of urban pluvial flooding and that is essential to account for variations in sewer inlet capacity in urban drainage models [23,30,31].

Finally, detailed studies about the real performance of surface drainage systems should always be required when important underground drainage structures are planned (storm storage tanks, main sewer pipes, etc.) in order to avoid expensive hydraulic structures not working in the way they were planned, only because water does not enter inside the sewerage system where it was supposed to.

2.2. Inlet Hydraulic Performance

The hydraulic performance of a surface drainage structure depends on its geometry, as well as the characteristic of the approaching flow and the geometric characteristics of the street or place where it is located. Grated inlets are the most common elements to intercept stormwater and introduce it into the underground sewer systems.

In the literature, the flow intercepted by a grated inlet can be calculated by two different approaches. The first one is based on the concept of hydraulic efficiency [32,33] and has also been used for other types of surface drainage elements such as transverse grates [34,35].

The hydraulic efficiency of a grated inlet (and, in general, of a surface drainage structure) can be defined as the ratio of the intercepted flow taken by the inlet to the total approaching flow, which can be described as the sum of the intercepted flow and the carry-over (or bypass) flow passing through the grates. Thus, the efficiency (E) can be calculated by the following equation:

$$E = \frac{Q_{int}}{Q} \tag{1}$$

where E is the hydraulic efficiency of the grated inlet, Q_{int} is the flow intercepted by the inlet, and Q is the flow approaching the inlet.

As mentioned, a flow that is not intercepted by the structure (Q_{bypass}) is defined as follows:

$$Q_{bypass} = Q - Q_{int} \tag{2}$$

The second approach considers the concept of the discharge coefficient through weir and orifice equations. In the literature, several experimental and numerical studies were carried out to estimate discharge coefficients of grated manholes and inlets through orifice [36] or weir [37] equations. Some authors developed their studies considering both formulations, achieving specific discharge coefficients for grated manholes [38] and inlets [39].

In the case of considering a grated inlet as an orifice, the intercepted discharge (Q_{int}) can be expressed by Equation (3):

$$Q_{int}= \mu_o \cdot \varphi \cdot A_T \cdot \sqrt{2 \cdot g \cdot \mathrm{H}} \tag{3}$$

where μ_o is the discharge coefficient of the inlet considered as an orifice, φ is the percentage of void area of the inlet, H is the water energy upstream of the grate (sum of the depth and velocity head), A_T is the total area of the grate, and g stands for the gravity acceleration.

In the case of considering a grated inlet as a weir, the intercepted discharge (Q_{int}) can be expressed by Equation (4):

$$Q_{int} = \frac{2}{3} \cdot \mu_w \cdot \sqrt{2 \cdot g} \cdot \mathrm{L} \cdot \mathrm{H}^{3/2} \tag{4}$$

where μ_w is the discharge coefficient of the inlet considered as a weir, H is the water energy upstream of the grate, L is the effective length of the weir equal to the length plus the width of the inlet, and g stands for gravity acceleration. It may be argued that the effective length depends on the flow pattern around the grate [39].

2.3. Experimental Campaigns to Estimate Hydraulic Efficiency of Grated Inlets and UPC Method

The first methodology carried out for determining the correct spacing among drainage inlets was proposed in 1956 by Li at Johns Hopkins University in the USA [40] and adopted during some decades as the standard code of practice. In March 1984, the U.S. Department of Transportation published the Hydraulic Engineering Circular No. 12 (HEC-12), entitled

"Drainage of Highway Pavements," that is widely known as HEC-12 and describes a semi-theoretical method for estimating inlet hydraulic capacities of specific standardized U.S. grate models. The more recent HEC-22 included an updated HEC-12 version and is, to date, the reference procedure for inlet design in the USA [32]. HEC-12 and HEC-22 introduced the concept of splash-over velocity (the minimum velocity at which some frontal flow passes over the top of the grate without being intercepted), relating it to each grate model previously tested in the laboratory.

In the United Kingdom, until about the year 1969, inlets were spaced at a standard spacing of about 50 m or by the use of a specific design formula [41], whereas, from this year, more robust methods based on the concept of hydraulic efficiency achieved by experimental tests were used [42,43] until the procedure proposed by Spaliviero et al. in 2000 [44].

In Serbia, a full-scale physical experiment for various types of grated inlets and transverse grates was conducted, and the hydraulic efficiency was related to the total approaching flow [45].

In Australia, one of the most important experimental campaign about the estimation of the inlet hydraulic efficiency and the procedure of inlet design was conducted by Argue [46].

Experimental studies were also conducted in Asia. For example, in Malaysia, several full-scale grate inlets were tested, and curves relating the captured flow, the flow depth, and the hydraulic efficiency were achieved [47]. Other experimental studies were conducted in Hong Kong [48], South Korea [49], and Singapore [50].

More recently, Kemper and Schlenkhoff derived a new empirical equation based on an experimental campaign carried out on a full-scale platform for determining the grated inlet efficiency as a function of the grate geometry and upstream flow variables [37], while Wakif and Sabtu studied the effects of vertical depressions on the hydraulic efficiency of some grated inlets [51].

The brief state of the art on this matter presented in this paper aims to demonstrate the relevance of surface drainage systems in the field of urban drainage and, in a broader perspective, in the field of flood risk management and urban resilience.

Among all the experiments mentioned in this section and others that have probably not been cited in this analysis, it is important to remark that only some of them have been conducted on a real scale, avoiding the possible effects of scale, which are a usual problem in the field of physical models. Within the experiences carried out on 1:1 real scale model, very few considered in their experimental tests and protocols significant flow rates similar to those that can be produced during extreme rainfall events in flooded urban streets with a significant limitation of the validity range of the proposed formulas for the estimation of grated inlet hydraulic efficiency. Furthermore, even fewer studies have proposed replicable methodologies for other grated inlets different from the tested ones, which, many times, were only a few types.

For all these reasons, a 1:1 scale hydraulic structure was used to perform a series of experimental tests on several grated inlets (Figure 2) considering high flow amounts (up to 200 L/s) circulating on a platform simulating a road lane with longitudinal slopes up to 10% and transversal slopes up to 4% [33].

In the context of these experimental activities, the following potential inlet efficiency formula was achieved:

$$E = A\left(k\frac{Q_{\mathrm{roadway}}}{y}\right)^{-B} \tag{5}$$

where E is the hydraulic efficiency of the inlet (expressed as a decimal between 0 and 1), y is the flow depth immediately upstream, Q_{roadway} is the approaching flow (m^3/s), k is a coefficient related to the street gutter section and the flow depth, and A and B are empirical coefficients specific to the grate whose values are presented in Figure 2. The validity hydraulic range of the previous equation should be limited to a maximum approaching flow for a lane of 200 L/s and a maximum flow depth of 0.12 m (approximately the height of the curb).

A and B parameters can also be estimated from the grated inlet geometry, so the procedure can be applied to any nontested grate similar to those tested at the UPC and whose dimensions fit in the validity range of the proposed formulas (inlet length from 0.6 to 1.0 m and inlet width from 0.3 to 0.5 m approximately). The procedure was also generalized for each geometric condition of streets with a uniform triangular gutter section, including the coefficient k.

Finally, the UPC method was compared with other existing procedures, demonstrating a great flexibility to be used for other grated inlets not previously tested [52,53].

Grate 1a. A = 0.47; B = 0.74 Grate 2a. A = 0.39; B = 0.87 Grate 3a. A = 0.40; B = 0.83 Grate 4a. A = 0.43; B = 0.81

Grate 5a. A = 0.54; B = 0.79 Grate 6a. A = 0.37; B = 0.86 Grate 7a. A = 0.39; B = 0.79 Grate 8a. A = 0.36; B = 0.85

Grate 9a. A = 0.56; B = 0.71 Grate 10a. A = 0.35; B = 0.72 Grate 11a. A = 0.51; B = 0.69

Figure 2. Grates tested at UPC hydraulic laboratory and experimental coefficients A and B achieved for the proposed potential hydraulic efficiency formula expressed by Equation (5).

2.4. UPC Experimental Campaigns to Estimate Hydraulic Efficiency of Continuous Transverse Grates

Conventional grated inlets are normally located next to the curb to intercept the gutter flow approaching the inlets, but they are not recommended in areas where the transversal profile does not allow the directing of the flow to road sides and where the disposal of isolated grates is ineffective (squares, parks, airport aprons, pedestrian areas, etc.).

Continuous transverse grates and their related drainage channels constitute a set of elements whose hydraulic capacity is limited by the less efficient.

Notwithstanding the broad use of these kinds of surface drainage elements, in the literature, only a few references about the experimental characterization of continuous transverse grate hydraulic performance seem to exist.

In 1992 and 1995, the Center for Transportation Research of the University of Texas at Austin (USA) analyzed some bridge deck drains and provided, for each tested drainage structure, a specific empirical design equation depending on the roadway geometry and approach flow conditions [54,55]. More recently, in 2006 and 2015, two MSc theses developed at the Middle East Technical University of Ankara (Turkey) provided interesting results related to the hydraulic performance of grated inlets placed transversally to the circulating flow in a laboratory channel 1 m wide. These results showed that the grate efficiency could be related to the longitudinal slope, the upstream Froude number [56], and the void ratio of its geometric configuration [57].

At the UPC Hydraulic laboratory, several continuous transverse grates (Figure 3) were tested in the 1:1 physical model previously described, and the results were expressed in terms of the unit efficiency (efficiency per meter of grate). The maximum flow rate per unit width approaching the inlet was 100 L/s/m. Tests were conducted with a fixed transverse slope of 0% and a longitudinal slope up to 10%.

The test results showed that the continuous transverse grate efficiency decreases for high longitudinal slopes and high flow rates. In fact, while, for low flow rates, the hydraulic efficiency of this type of structure was close to 100%, for the maximum circulating flows (from 66.7 up to 100 L/s/m) and high longitudinal slopes (close to 10%), the hydraulic efficiency was between 15 and 50%, depending on the grate type. These results demonstrated that the hydraulic performance of these kinds of surface drainage structures is higher than the hydraulic performance of inlets placed in the gutter at the road sides [33–35,52].

As the main result of this second experimental campaign, a dimensionless equation was proposed to estimate the hydraulic efficiency E on the basis of upstream flow parameters and grate geometry:

$$E = \alpha \cdot \mathrm{Fr}\left(\frac{y}{L}\right)^{0.812} + \beta \tag{6}$$

where α and β depend on the geometric characteristics of the grate, L is the effective length (length of the grate opening in the flow direction), and Fr and y/L are the Froude number and the normalized flow depth related to L, respectively, both calculated immediately upstream of the grate.

In order to apply the previous equation to other grates not previously tested, α and β were also related to some geometric parameters [35].

Grate 1b. $\alpha = -0.882$; $\beta = 1.209$ Grate 2b. $\alpha = -0.799$; $\beta = 1.215$ Grate 3b. $\alpha = -0.544$; $\beta = 0.861$ Grate 4b. $\alpha = -0.774$; $\beta = 1.030$

Grate 5b. $\alpha = -1.292$; $\beta = 1.187$ Grate 6b. $\alpha = -1.289$; $\beta = 1.279$ Grate 7b. $\alpha = -1.209$; $\beta = 1.201$

Figure 3. Continuous transverse grates tested at the hydraulic laboratory of the UPC to achieve experimental coefficients α and β.

2.5. UPC Experimental Campaigns to Estimate Discharge Coefficients of Grated Inlets

The flow captured by an inlet can be described by means of the predominant physical phenomenon [58]. For low overland flow, the entry of water into the inlet presents free discharge conditions and can be approached by the weir-type formulation, while, for high overland flows, the discharge bumps up against or splashes above the grate bars, partially or totally covering the area of the grate, and the process can be described by an orifice-type formulation. Traditional weir and orifice equations are generally used in urban stormwater 1D-2D coupled models [7] and depend on flow conditions in the nearness of the grate [58]. In a recent study, Rubinato et al. [38] focused on circular inlets with different grate designs under subcritical flow conditions, in order to obtain discharge coefficients adopting both orifice and weir approaches.

In this context, real-scale experimental campaigns were carried out at the UPC hydraulic laboratory to estimate discharge coefficients for these kinds of applications and to provide useful information for practitioners and inlet manufacturers [39]. Tested discharge values were between 25 and 200 L/s, whereas transversal and longitudinal slopes were from 0to 4% and from 0 to 10%, respectively. Three grated inlets were analyzed by obtaining values of discharge coefficients in situations for which the flow completely covers the grates and supercritical flow conditions. Discharge coefficients were obtained as such of the strong relationships between their values and upstream Froude number. Considering the orifice approach, the discharge values found for the three grates varied approximately from 0.4 to 0.1 or less (Figure 4). These values are lower than the default ones used in commercial software and in the literature. Conversely, for the weir assumption, discharge coefficient values found for the three grates were always less than 0.3 and could reach the limit of 0.003. Again, these values of discharge coefficients are drastically low if compared to the default ones used in commercial software and in the literature (Figure 5).

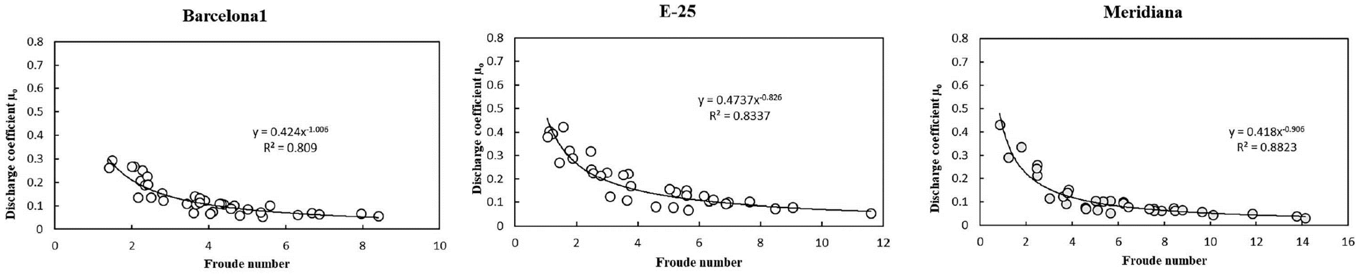

Figure 4. Graphs of discharge coefficients vs. upstream Froude number for the three analyzed grates considering orifice approach.

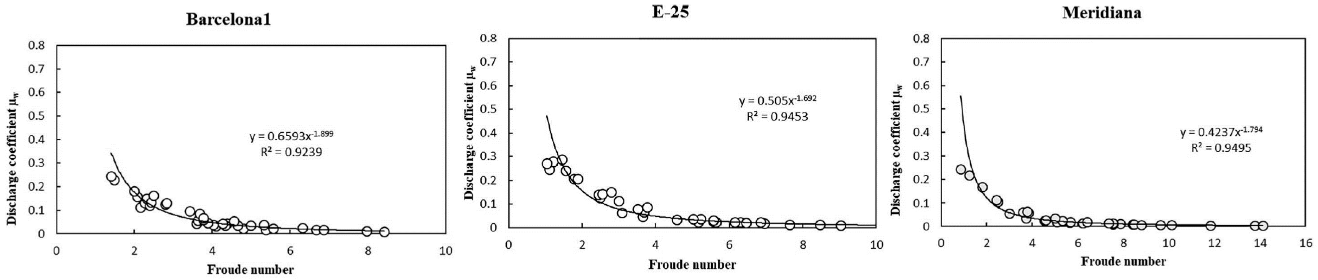

Figure 5. Graphs of discharge coefficients vs. upstream Froude number for the three analyzed grates considering weir approach.

2.6. UPC Experimental Campaigns to Achieve Grated Inlets Clogging Factors

During the experimental studies presented in the previous sections, laboratory tests were carried out under optimal conditions (clean water and inlets with no clogged area), so, the obtained results, expressed in terms of the inlet hydraulic efficiency of intercepted discharges, represented an upper limit that can be unrealistic in the case of inlet clogging. In fact, under real conditions, dust, dirt, leaves, or debris can reduce the area of grated inlet holes, thereby reducing the amount of water to be captured [31].

In order to take into account the clogging phenomenon, Guo [59] proposed the concept of clogging coefficient, which reduces the hydraulic efficiency with a factor between 0 and 1. Gómez et al. [31] defined the clogging coefficient C_0 as follows, where E_{clogged} is the efficiency of the clogged inlet, and E_{clean} is the efficiency of the clean inlet:

$$C_0 = \frac{\Delta E}{E} = \frac{E_{\text{clean}} - E_{\text{clogged}}}{E_{\text{clean}}} \tag{7}$$

The clogging phenomenon depends on several factors such as inlet design, type and density of vegetation, rainfall patterns, street slope, and cleaning frequency of inlet and urban surfaces [31]. Although the reproduction of the effects of this phenomenon is quite complex, laboratory and field studies could allow a reasonable estimation of the potential reduction in terms of hydraulic efficiency due to clogging.

With this aim, two experimental studies based on several field visits were carried out at UPC.

More than 12,000 grate inlets located in two different basins (with different morphologies) of the city of Barcelona were monitored during dry and wet periods. A database with detailed information on the inlets' location and typology was used to classify all the grates in the main categories. The aim of field campaigns was to achieve three representative clogging patterns depending on the inlet type and previous wet period. Thus, clogging patterns ranged from C1 to C2 and C3 based on the progressive increase in the clogging phenomenon for each analyzed inlet.

The clogging patterns of four grate inlets were reproduced and laboratory tests with the same protocol used for clean inlets were carried out (Figure 6). The tests results confirmed the reduction in inlet efficiency. Moreover, it was demonstrated that the hydraulic characterization of a clogged inlet can be undertaken by employing the same potential law proposed for clean inlets. The achieved clogging factors ranged between 0.23 and 0.68 (Table 1).

Table 1. Clogging coefficients for specific clogging factors of 4 common grate inlets in Barcelona.

$C_0 = \Delta E/E$	Pattern C1	Pattern C2	Pattern C3
Grate 1c	0.451	0.502	0.674
Grate 2c	0.265	0.400	0.677
Grate 3c	0.234	0.360	-
Grate 4c	-	-	0.545

Figure 6. Clogging patterns C1, C2, and C3 for Grate 1c (above) and Grate 2c inlets reproduced at UPC hydraulic laboratory.

3. Numerical Modeling Applied to the Field of Surface Drainage Hydraulic Performance

Three-dimensional numerical models can be used to represent the behavior of complex hydraulic phenomena [58]. In the last two decades, this kind of computational engine has been increasingly used to validate and complement laboratory and field experiences in the field of urban drainage and, in particular, to characterize the hydraulic behavior of surface drainage systems [60–62]. A comprehensive collection of these studies has been recently proposed by Cardenas et al. [58].

A reproduction of the hydraulic tests concerning grated inlets developed at UPC hydraulic laboratory was carried out through a numerical three-dimensional code (Flow-3D). The models aimed to reproduce the hydraulics of the physical models and the behavior of one grate inlet by solving the Reynolds-averaged Navier–Stokes (RANS) equations [63]. Thus, Flow-3D was used as a virtual laboratory to reproduce the hydraulic performance of a previously tested grated inlet under several flow and geometric conditions. These kinds of approaches, once validated, can be used to the obtain inlet hydraulic efficiency without previous experimental tests. Moreover, the 3D model allows a better understanding of the hydraulics of the flow interception and the flow patterns approaching the inlet.

More recently, a 3D/2D hybrid model was developed to reduce the computation time of these kinds of simulations. Specifically, the platform was simulated considering a 2D mesh, but in the nearness of the grated inlet, a 3D domain was nested. The advantage of this model was the provision of reasonable results, drastically reducing the computational time, allowing the simulation of more combinations of approaching flow and geometric configurations [64].

Three-dimensional models are quite useful to represent local complex hydraulics phenomena such as the interception mechanisms of capturing flow via grate and transverse inlets, but, of course, their use is ineffective for a large implementation of hundreds and thousands of inlets at a large scale (for example, when the scope of the analysis is a district or a city). In these cases, the use of 1D/2D coupled models is advisable and the hydraulic characterization of the inlet systems (representing the interface between surface and underground flows) can be achieved through experimental expressions used to estimate the effective runoff flows into the sewers in the case of storms [65]. Recently, the hydraulics of grate inlets under pressurized pipe conditions have been also analyzed, and discharge coefficients for these cases have been proposed [66].

4. Conclusions

The growth of the impervious areas in our cities and the increase in extreme rainfall intensities due to the local effects of climate change can drastically exacerbate the impacts of pluvial flooding in urban areas. In a recent report, the European Environment Agency warned of an increase in damages resulting from shorter and more localized flash floods. However, several national authorities did not quantify the impact of climate change on the probability of pluvial and fluvial floods.

In this context, efficient and safe drainage in a flooding situation caused by extreme rainfall events is one of the most challenging concerns for technicians and policy-makers to guarantee urban flood resilience of our cities.

Within this framework, this paper focuses on a series of laboratorial and numerical experiences carried out at the Hydraulic Laboratory of the Technical University of Catalonia (UPC) (Spain) that allowed the achieving of formulas and methodologies to estimate the hydraulic efficiency of grated and continuous inlets without the need for additional laboratory or field tests, also in the case of the potential clogging phenomenon.

This means that the obtained results can also be adopted for other types of inlets, always ensuring that their grate geometry fits with the validation range proposed by UPC methods and formulas.

Finally, it is important to remark that the proposed approaches have been scaled up to complex numerical calibrated models, from detailed 3D numerical models to large-scale 1D/2D-coupled models, ensuring a wide range of applicability of the achieved results. These last kinds of models can be used to assess urban flood resilience through the joint analysis of the hydraulic behavior of surface urban areas and the sewer system in the case of extreme flooding events.

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