

Review of the hydraulic capacity of urban grate inlet: a global and Latin American perspective

M. Cárdenas-Quintero and F. Carvajal-Serna

ABSTRACT

The most recent numerical models of urban drainage allow the integration of runoff from roads with the network of sewer pipes, thus evolving towards a holistic version of the system. A fundamental part of this integration is the capture of stormwater in urban drain inlets. These studies have recently increased, resulting in different methodologies to represent the uptake process and making it difficult to apply unified or general formulations. Therefore, this document intends to be a review of the most representative experimental and numerical studies on the capture of rainwater through grates. In addition, the review includes the proposed methodologies for estimating the flow captured by urban storm drains to define a starting point for new and complementary studies to be carried out by researchers, manufacturers, and operators involved in public drainage service systems. Particularly in Latin America, research on the subject is limited even though it is a highly urbanized region. In this context, this document has an additional interest in presenting a particular analysis of the concept of urban drainage in Latin American cities.

Key words | grate inlet, hydraulic efficiency, numerical model, physical model, review, urban drainage

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HIGHLIGHTS

- A review of the literature on the hydraulic capacity of drain grates.
- The review presents the methodologies for the estimation of the captured flow.
- We propose the characteristics of a general hydraulic test.
- The bibliographic review includes studies of 3D numerical modeling of grate inlets.
- A critical analysis is carried out on the current challenges of urban drainage for the globe and especially in Latin American countries.

INTRODUCTION

Urban drainage models were developed to understand and take advantage of water resources in cities. They serve purposes such as reducing and mitigating the economic and social impacts of floods, improving the quality of rainwater that returns to natural channels, reusing rainwater in secondary processes, and seeking to strike a better balance with the natural environment considering the increase in anthropic processes and urbanization.

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The focus of studies on traditional urban drainage systems is on understanding the hydraulic processes in underground sewer pipe networks, and more recently, on the quality and quantity of rainwater discharge into the receiving water bodies (Tshrintzis & Hamid 1997; Lee & Bang 2000; Gilbert & Clausen 2006). However, the processes of transformation of rainfall to runoff in urban settings have been studied to a lesser extent; the classical methodologies applied to rural hydrology have been simply applied to the urban environment (Niemczynowicz 1999; Fletcher *et al.* 2013; Salvadore *et al.* 2015). Furthermore, all the effective precipitation is considered to be transformed

into flow and to enter the underground sewer system (Rossman & Huber 2015), regardless of the hydraulic processes that occur in urban storm drains located above the surface.

The hypotheses of the traditional models of urban drainage are justifiable for the knowledge of their time and the technical and economic resources during their development. However, they have been put to test with changes in the urbanizing dynamics of the cities and the increase in the magnitudes and frequencies of extreme flood events (Gill *et al.* 2007; Praskievicz & Chang 2009; Willems *et al.* 2012).

Against this background and owing to the advances in numerical models and calculation engines, various models of urban drainage were developed. These models complement many of the deficiencies of the traditional models. The surface drainage models (Cea *et al.* 2010a, 2010b) include the hydraulic processes of the roads and green areas and provide knowledge about the direction and magnitude of surface floods. These models are complemented by integration with the hydraulic processes in the underground sewer pipes to realize the so-called dual drainage models (Chang *et al.* 2018; Jang *et al.* 2018, 2019). The hydraulic interaction between the surface and underground processes is generally realized by urban storm drains (grate inlets, curb-opening inlets, combination inlets, transverse grates, inclined grates in Figure 1).

The hydraulic processes occurring in urban storm drains vary depending on the geometry of the grates that compose it and on the type of flow that develops in its proximity (sub-critical and supercritical flows). This increases the research scope and the development of methodologies allowing a wide operating margin of these hydraulic structures. Although research interest about the inlet processes of urban storm drains has increased, the challenge is to define formulations for the inflow to the storm drain under different hydraulic conditions and for a large number of grate geometries available in the market. Then, dual

drainage models can be used and verified, expanding their use in the engineering, academic, and industrial environment.

This paper presents an extensive review of the existing formulations to estimate the flow captured by an urban storm drain in the context of urban drainage hydraulic models, thereby defining a starting point for future studies on the subject. The formulations used to estimate the flow captured by a grate inlet depend on the conditions and capacities of the experimental setup and the drainage model in which they are used. The urban drainage models, their advantages and limitations, and the different formulations developed to represent the catchment process of an urban drain are described. Further, the most representative experimental and numerical studies carried out in North America, Europe, Asia, and Latin America on the hydraulic capacity of grate inlets are presented, and finally, a critical analysis of future perspectives in the research and development is presented, especially in the context of Latin American countries.

HYDRAULIC MODELS OF URBAN DRAINAGE

Traditionally, developments in hydraulics and classical hydrology have been used to analyze urban drainage, from the transformation of rainfall into runoff to the flow of rainwater on roads and highways, as a one-dimensional (1D) hydraulic phenomenon. Uniform flow equations are useful in determining flow depths and velocities (Chow 1959; Marbello & Cárdenas 2012). From these one-dimensional hydraulic characteristics, different formulations can be used to estimate the flow captured by the urban storm drain and to determine the amount of rainwater entering the sewer pipe network (Brown *et al.* 2013). The one-dimensional simplification of flows in urban settings has some physical limitations arising from the inadequate

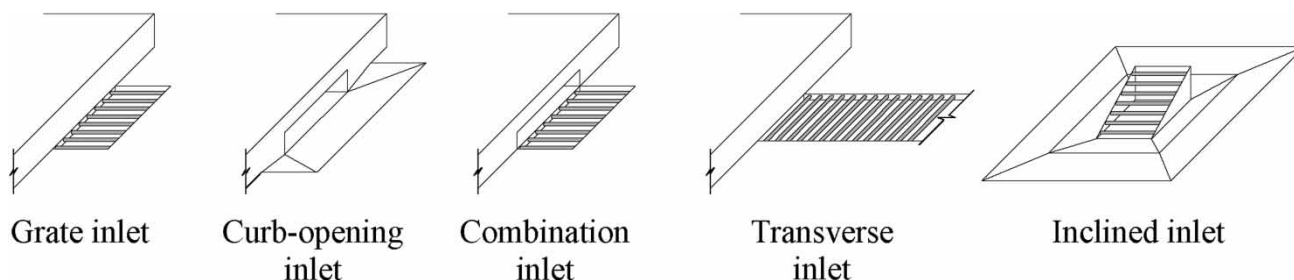


Figure 1 | Types of drain inlets.

representation of some factors; for example, heterogeneous distribution of rain or flow contributions and real irregularities of roads, as indicated by different widths and longitudinal and transverse slopes and irregular crossings of streets not being considered in these simplified flows (Cárdenas-Quintero *et al.* 2019).

The development of two-dimensional (2D) hydraulic models helped overcome some limitations of the 1D models. The 2D models allow analysis of the movement of water in two horizontal directions, thus considering the irregular geometries of roads, road crossings, and different flow contributions. Additionally, the flow captured by the storm drains is included as a particular flow outlet using weir- or orifice-type formulations or by simply defining a rule that relates the hydraulic characteristics of the surface flow with the captured flow. Thus, the physical phenomena on the road surface are included in the models; hence, preferred flow paths can be determined, and better recommendations can be made for the locations of grates (Cárdenas-Quintero *et al.* 2019). Further details on 2D hydraulic models for urban drainage are presented in Bulti & Girma (2020).

Three-dimensional (3D) hydrodynamic models will be useful to represent the flow on road surfaces, but the depths of the runoff are much smaller than the horizontal scale, and hence, the phenomenon is weakly three dimensional (Nanía *et al.* 2010). Additionally, 3D models require long computation times and complex parameterization. Therefore, it is important to consider the type of hydraulic model to be used and the corresponding formulation for the grate inlet.

HYDRAULIC CAPACITY OF URBAN GRATE INLETS

Types of formulations

The formulations to represent the flow captured by an urban grate inlet were developed considering the temporal, technical, and economic capacities necessary for the experimental setup and the specific tested grates. Earliest studies aimed to determine the flow captured by a particular grate from the flow in the road; the relationships of the captured flow and total flow were satisfactory for this purpose. Later, there was a need to compare the flows captured by different types of grates; efficiency ratios (flow captured with respect to the total flow) were found very useful for this purpose. Later, empirical and semiempirical formulations of efficiency were developed – these formulations distinguished

each type of target grating and its geometry. With the development of new computational applications, it was possible to dispense with the total flow to estimate the captured flow and to associate the hydraulic conditions of the flow near the grate using the amount of water entering the sewer network through weir- and orifice-type formulations.

Relations of inlet flow (Q_{in}) or hydraulic efficiency (E)

The inlet flow of a storm grate or its hydraulic efficiency (ratio between the inlet flow and the total flow), has commonly been related to hydraulic characteristics, such as total flow (Q), depth (y), flow velocity (v), or geometric characteristics such as the longitudinal (S_L) and transverse (S_T) slope of the road, for example Equations (1) and (2).

$$Q_{in} = f(Q, y, v, S_L, S_T) \quad (1)$$

$$E = \frac{Q_{in}}{Q} = f(Q, y, v, S_L, S_T) \quad (2)$$

Generally, the graphs to determine the captured flow show an increasing relationship of the captured flow with the total flow and cross slope (Figure 2(a)), and the efficiency of the grate decreases with increase in the total flow, speed, longitudinal slope, and inverse of the depth and cross slope (Figure 2(b)). Although efficiency formulations are useful for determining the flow captured in experimental setups or in 1D hydraulic models, they may not work well for 2D hydraulic models because the spatial distribution of the total flow upstream of the grate varies across the width of the street and is not known in advance. Regarding 3D hydraulic models, they have been dismissed for conventional simulations of urban drainage.

Weir (Q_w) and orifice (Q_o) equations

The flow captured by a grate or combination inlet is described by means of the predominant physical phenomenon: for low total flows, the entry of water into the grate is similar to free discharge (weir-type formulation), and for high total flows, the flow collides or splashes above the bars of the grate, partially or totally covering the area of the grate, and it is similar to an orifice (orifice-type formulation). Traditional weir and orifice equations are commonly implemented in 1D and 2D hydraulic models and will depend on hydraulic variables adjacent to the grate, such as depth and flow velocity, and will not depend solely on total flow upstream. The weir- or orifice-type

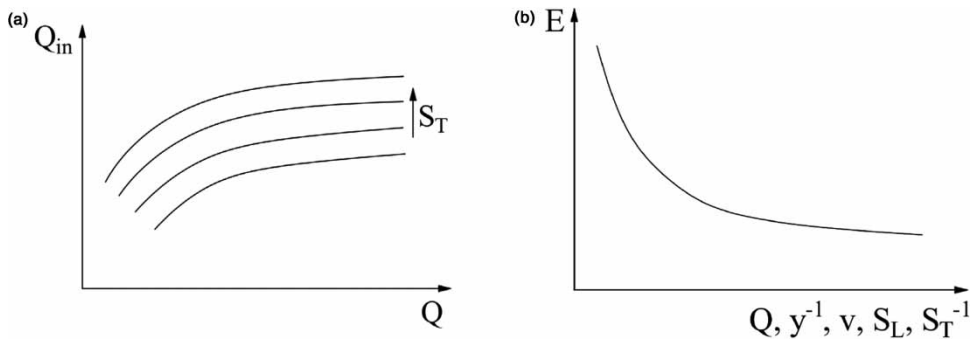


Figure 2 | Examples of graphs that relate (a) the flow captured and total flow and (b) the efficiency of the grate with different hydraulic and geometric variables of the road.

discharge coefficients are adjusted experimentally or numerically for each type of grate.

The general equation of the flow through a weir is presented in Equation (3), where C_{dw} is the weir-type discharge coefficient; g , the acceleration due to gravity; L , the length of the weir; and E_o , the specific head upstream of the grate, consisting of the sum of the depth of the flow and the velocity head ($E_o = y + v^2/2g$). Sometimes, the weir coefficient is represented as $C = (2/3)C_{dw}\sqrt{2g}$, and the head is reduced to the depth of the water when the speed is low, as in Equation (4). The length L in the weir equation will vary according to the type of flow; for supercritical flow it corresponds to the sum of the length and width of the grate ($L_g + B_g$) and for subcritical flows to the sum of the length and twice the width of the grate ($L_g + 2B_g$).

$$Q_w = \frac{2}{3}C_{dw}\sqrt{2gLE_o^{3/2}} \quad (3)$$

$$Q_w = CLy^{3/2} \quad (4)$$

The orifice-type flow is represented by Equation (5), where C_{do} is the discharge coefficient per orifice; A_n , the net or free area of the grate; and E_o , the specific head. As in the case of weirs, here too, the specific head is reduced to only the depth of the water when the speed is low, as in Equation (6).

$$Q_o = C_{do}A_n\sqrt{2gE_o} \quad (5)$$

$$Q_o = C_{do}A_n\sqrt{2gy} \quad (6)$$

These discharge coefficients are usually considered approximately constant, but more recent studies show that

they vary depending on the Froude number or the flow velocity (Cárdenas-Quintero *et al.* 2017; Cosco *et al.* 2020).

Earliest investigations of the hydraulic capacity of grate inlets

The hydraulic behavior of grate inlets has been evaluated experimentally. The geometries of the grate inlets used in the drainage systems of a city or town vary markedly. These variations have hindered the sequential evolution of research on the subject; therefore, little comparative results have been presented for different grate geometries. While these results satisfy the research objectives themselves, there is a lack of effective feedback or lack of complementarity between the results. Therefore, a direct and quantitative comparative analysis of the results of the studies is difficult to achieve, due to the characteristics of the experimental setups and the different types of gratings tested. This review aims to present the main characteristics of the studies, the type of formulations or equations developed, and the most representative conclusions. The details and specific characteristics of each study consulted are presented in Table 1.

One of the first experimental studies on inlet flow of the grate was presented by Black (1967), who tested six configurations of grate and combination inlets and determined the efficiency curves as a function of total flow and longitudinal and transverse slopes.

The Federal Highway Administration (FHWA) conducted extensive hydraulic and safety tests of the typical gratings used in the USA from the perspective of pedestrians and cyclists (Burgi 1977; Burgi & Gober 1977; Brown *et al.* 2013). The initial results related the efficiency of each grate to the total flow circulating through the experimental setup as well as to the longitudinal slope and the maximum spread on the platform, ensuring that the cross section is

Table 1 | Summary of studies on the evaluation of the hydraulic capacity of grate inlets in North America, Europe, and Asia

Reference	Inlet type	Number of grates or configurations	Model features	Formulation type	Equations
Black (1967)	Grate and combination inlets	6	Scale [1:1] Length [9.6 m] Width [1.2 m] S_L [0.4–6%] S_T [2–6%] Flow [6.6–21.8 l/s]	Graphics of: E vs. Q E vs. S_L E vs. S_T	–
Burgi & Gober (1977), Burgi (1977), Brown <i>et al.</i> (2013)	Grate and combination inlets	7	Scale [1:1] Length [18.3 m] Width [2.4 m] S_L [0.5–13%] S_T [1–6.2%] Flow [< 160 l/s]	Graphics of: E vs. Q E vs. T E vs. S_L	Ratio of frontal flow to total discharge (E_{QF}): $E_{QF} = 1 - \left(\frac{B_g}{T}\right)^{2,67}$ Ratio of lateral flow to total discharge (E_{QL}): $E_{QL} = 1 - E_{QF}$ Ratio of frontal flow intercepted (R_F): $R_F = 1$, if $V < V_s$ $R_F = 1 - K_F(V - V_s)$, if $V > V_s$ Ratio of lateral flow intercepted (R_L): $R_L = \left(1 + \frac{K_L V^{1,8}}{S_T L_g^{2,3}}\right)^{-1}$ Efficiency of grate (E): $E = R_F E_{QF} + R_L (1 - E_{QF})$
Davis <i>et al.</i> (1998)	Grate inlet	3	Scale [1:1] Length [7.3 m] Width [2 m] S_L [0.3–3.3%] S_T [1.6–3.3%] Flow [–] ^a	Graphics of: E vs. S_L E vs. T E vs. L_r E vs. B_r E vs. β	–
McEnroe <i>et al.</i> (1999)	Grate, curb opening and combination inlets	4	Scale [1:4] Length [15 m] Width [–] ^a S_L [0.5–5%] S_T [1.6–3.1%] Flow [< 7.8 l/s]	Graphics of: Q_{in} vs. Q $Q_{in} = f(y)$	Extensive equations for each grate
Spaliviero <i>et al.</i> (2000)	Grate and curb opening inlets	24	Scale [1:1.28] Length [4.9 m] Width [1.5 m] S_L [0.5–6.6%] S_T [2–7.6%] Flow [< 150 l/s]	$E = \alpha - G \frac{Q}{y}$ α, G varies for each grate	$E = 102, 7 - G \frac{Q}{y}$ $G = \frac{69}{A_g^{0,75} \sqrt{P}} (n_t + 1)^{0,19} (n_l + 1)^{0,07} (n_d + 1)^{0,15}$

(continued)

Table 1 | continued

Reference	Inlet type	Number of grates or configurations	Model features	Formulation type	Equations
Despotovic <i>et al.</i> (2005)	Grate, combination and transverse grates	3	Scale [1:1] Length [5 m] Width [3 m] S_L [0.5–4%] S_T [0–2] Flow [< 60 l/s]	Graphics of: Q_{in} vs. Q E vs. Q	–
Guo <i>et al.</i> (2009)	Grate, curb opening and combination inlets	6	Scale [1:3] Length [20 m] Width [3.5 m] S_L [1%] S_T [1%] Flow [< 32 l/s]	Weir and orifice equations	For grate inlets: $Q_w = N_w C_w \sqrt{2g} (2B_g + L_g) y^{3/2}$ $Q_o = N_o C_o \sqrt{2g} B_g L_g y^{1/2}$ For curb-opening inlets: $Q_w = C_w \sqrt{2g} L_{co} y^{3/2}$ $Q_o = C_o \sqrt{2g} L_{co} H_{co} y^{1/2}$ For mix flow (transitional flow): $Q_m = C_m \sqrt{Q_w Q_o}$ For inlet flow: $Q_{in} = \min(Q_w, Q_m, Q_o)$ For combination inlets: $Q_{in} = Q_{sf} + Q_{sl} - K \sqrt{Q_{sf} Q_{sl}}$
Gómez & Russo (2011)	Grate inlet	11	Scale [1:1] Length [5.5 m] Width [3 m] S_L [0–10%] S_T [0–4%] Flow [20–200 l/s]	$E = f(Q/y)$	$E = A \left(\frac{Q}{y} \right)^{-B}$ $A = \frac{1,988 A_g^{0.403}}{p^{0.19} (n_t + 1)^{0.088} (n_l + 1)^{0.012} (n_d + 1)^{0.082}}$ $B = 1,346 \frac{L_g^{0.179}}{B_g^{0.394}}$
Comport & Thornton (2012)	Curb opening and combination inlets	3	Scale [1:3] Length [6.3 m] Width [1.6 m] S_L [0.5–4%] S_T [1–2%] Flow [< 180 l/s]	$E = f \left(\frac{Fr}{A}, \frac{L_T T}{A}, \frac{hT}{A}, S_T, S_L \right)$	$E = N Fr^a \left(\frac{L_T}{A} \right)^b \left(\frac{hT}{A} \right)^c S_T^d S_L^e$ N, a, b, c, d, e varies for each inlet
Lee <i>et al.</i> (2012)	Grate inlet	1	Scale [1:10] Length [6 m] Width [0.5 m] S_L [0%] S_T [0%] Flow [0.8–5 l/s]	Weir and orifice equations	$Q_{in} = \frac{2}{3} C_{dw} (L_g + B_g) \sqrt{2g} E_0^{3/2}$ $Q_{in} = C_{do} L_g B_g \sqrt{2g E_0}$ $C_{dw} = 0,378$ y $C_{do} = 0,51$

Sabtu (2015), Sabtu et al. (2016)	Grate inlet	2	Scale [1:1] Length [4.27 m] Width [1.83 m] S_L [0–3.3%] S_T [–] ^a Flow [< 50 l/s]	Graphics of: Q_{in} vs. y Q_{in} vs. Q E vs. Q C_d vs. Q C_d vs. Q_{in}	Fit equations of: C_d vs. $B_g/(E_o/y)$ C_d vs. $(E_o/y)/L_g$ C_d vs. v C_d vs. Fr
Wu et al. (2015)	Grate inlet	4	Scale [1:2] Length [1.4 m] Width [1 m] S_L [5–20%] S_T [2.5%] Flow [3.8–7.6 l/s]	$E = f\left(Fr, \frac{y}{L_r}, \frac{T}{B_r}\right)$	$E = aFr\left(\frac{y}{L_g}\right)^{0.8} \frac{T}{B_g} + b$ a, b varies for each grate
Choi et al. (2016)	Grate inlet	3	Scale [1:3] Length [12.3 m] Width [0.6 m] S_L [0–10%] S_T [0–10%] Flow [< 6.5 l/s] ^a	$Q_{in} = f(y, S_T, S_L)$ $Q_{in} = f(y, \beta)$	$Q_{in} = ay^b S_T^c S_L^d$ $Q_{in} = ey^f$ a, b, c, d vary for flow condition and for each grate e, f varies for β and S_L
Kim et al. (2016)	Grate inlet	3	Scale [1:2] Length [11 m] Width [1.25 m] S_L [2–10%] S_T [2–10%] Flow [0.5–6 l/s]	$Q_{in} = f(Q, S_T, S_L)$	$Q_{in} = aQ^b S_T^c S_L^d$ a, b, c, d varies for each grate
Veerappan & Le (2016)	Combination inlets	3	Scale [1:1] Length [–] ^a Width [3 m] S_L [1–3%] S_T [1–4%] Flow [–] ^a	Graphics of: E vs. S_T E vs. S_L E vs. i	–
Rubinato et al. (2018)	Grate inlet	10	Scale [1:6] Length [8.2 m] Width [4 m] S_L [0.1%] S_T [0%] Flow [4–10 l/s]	Graphics of: Q_{in} vs. y Weir and orifice equations	$Q_{in} = \frac{2}{3} C_{dw} P_{ew} \sqrt{2gy}^{3/2}$ $Q_{in} = C_{do} A_{eo} \sqrt{2gy}^{0.79}$ $C_{dw} = 0, 2853 P_{ew}^{-0.79}$ $C_{do} = 0, 0167 A_{eo}^{-0.785}$
Kemper & Schlenkhoff (2019)	Grate inlet	6	Scale [1:1] Length [10 m] Width [1.5 m] S_L [2.5–10%] S_T [2.5%] Flow [3–21 l/s]	$E_T = f\left(\frac{Fr, y, B_g}{L_g, A_{eo}}\right)$	$E_T = 1 - Fr^{9.5} \left(\frac{y^{1.5} B_g}{\sqrt{L_g A_{eo}}}\right)^S$ S varies according to the distribution of the bars of the grate

(continued)

Table 1 | continued

Reference	Inlet type	Number of grates or configurations	Model features	Formulation type	Equations
Wakif & Sabtu (2019)	Grate inlet	2	Scale [1:1] Length [2.44 m] Width [1.83 m] S_L [0–2%] S_T [0–2.5%] Flow [2–12 l/s]	Graphics of: E vs. Q E vs. S_L E vs. S_T $E = f(q/y)$	$E = -0.5374 \left(\frac{q}{y}\right)^2 + 1.1992 \left(\frac{q}{y}\right) + 0.1622$
Cosco <i>et al.</i> (2020)	Grate inlet	3	Scale [1:1] Length [5.5 m] Width [3 m] S_L [0–10%] S_T [0–4%] Flow [25–200 l/s]	Weir and orifice equations	$Q_w = \frac{2}{3} C_{dw} (L_g + B_g) \sqrt{2gE_0} \frac{3}{2}$ $Q_o = C_{do} \epsilon A_g \sqrt{2gE_0}$ C_{dw} and C_{do} varies with Fr

E : Efficiency of inlet; Q : Total flow; Q_m : Inlet flow; q : Unit flow; Q_w : Weir-type captured flow; Q_o : Orifice-type captured flow; y : Water depth upstream the inlet; v : Water velocity upstream the inlet; E_0 : Specific energy upstream of the inlet ($E_0 = y + v^2/2g$); Fr : Froude number upstream from the inlet; S_L : Longitudinal slope; S_T : Transverse slope; T : Water spread; T' : Maximum water spread; B_g : Width of the grate; L_g : Length of the grate; β : Bar orientation to the curb; L_{co} : Length of the curb opening; H_{co} : Height of the curb opening; A_g : Minimum area of the grate (including inlet void area); p : Percentage ratio of the area of the void to A_g ; n_t , n_l , and n_d : The number of transverse, longitudinal, and diagonal bars, respectively; C_{dw} : Weir-type discharge coefficient; C_{do} : Orifice-type discharge coefficient; i : Rainfall intensity; P_{ew} : Weir effective perimeter; A_{eo} : Effective orifice area; E_T : Efficiency of the inlet flow with respect to frontal flow in a gutter.

^aThe missing data in the physical or numerical model characteristics are not available in the studies or reports consulted.

always triangular. Subsequently, mathematical formulations were derived to separate the total flow of the road over the width of the grate and outside it, and for each of these formulations, an empirical equation was proposed to estimate each, the frontal and lateral efficiency. To estimate the efficiency of the front flow of each grate, the threshold of the splashing velocity was defined; for approach speeds below this threshold, the frontal efficiency is equal to unity, and for approach speeds greater than this threshold the flow collides and splashes over the bars, reducing the frontal efficiency (Brown *et al.* 2013). Subsequently, tests were conducted on the same experimental platform for curb-opening and transverse grates in bridges by Holley *et al.* (1992) and Hammonds & Holley (1995).

Davis *et al.* (1998) tested three grates with different geometries. The results of the experimental tests graphically relate the hydraulic efficiency to the width, length, and depression of the grate as well as to the orientation of the bars of the grate. Furthermore, they present conceptual conclusions on the hydraulic behavior of a grate inlet.

Later, Spaliviero *et al.* (2000) reported about the physical experimentation of numerous grates in the United Kingdom, and related the efficiency to the ratio of the total flow and the depth of flow upstream of the grate along the curb, E vs. Q/y . The efficiency and the Q/y ratio were represented by a linear function whose adjustment coefficients depended on the type of the grate. These coefficients were estimated from the physical characteristics of the grate geometry, such as the net area, number of transversal, longitudinal and diagonal bars. Although the proposed linear relationship only adequately represents the highest efficiencies (it neglects the highest values of the Q/y ratio), it represents the first approximation to estimate the hydraulic capacity of untested grates with different geometric configurations.

Despotovic *et al.* (2005) conducted full-scale physical experimentation for various types of grates – mixed and transverse inlets – and reported that the captured flow and efficiency are functions of the total approaching flow. They also assessed various degrees of obstruction and obtained curves similar to those of the totally free grate, and found that the efficiency of the drain is lower when the obstruction occurs in the width of the grate in proximity to the curb.

Guo *et al.* (2009) adopted a novel approach to establish the processes that occur between a weir type inlet and orifice type inlet, for which a mix or transition flow was proposed. Experimentation of grate and curb-opening inlets allows one to determine the discharge coefficients for the grates tested in that specific study. To determine

the flow captured by a combination inlet, they propose the sum of the flow captured by both sumps minus the flow indicated by a reduction factor.

Recent research on the hydraulic capacity of grate inlets

Using a full-scale model, Gómez & Russo (2011) performed physical tests for numerous grate inlets, and related the efficiency of the grate to the ratio Q/y for a wide range of this parameter. The established relationship was a potential type of the form $E = A(Q/y)^{-B}$, where the parameters A and B can be estimated for any grate from its geometry, net area, and number of longitudinal, transversal and diagonal bars, similar to the proposal by Spaliviero *et al.* (2000). The authors of this review consider that this methodology is one of the best approaches to define the hydraulic capacity of grate inlets due to the wide range of variables evaluated in the grates and the experimental platform, even when experimentation has not been conducted for each individual type of geometry.

Comport & Thornton (2012) performed physical experimentation on a reduced-scale model for combination and curb-opening inlets, and the results were compared with those of similar inlets presented in Urban Design Manual HEC 22, Brown *et al.* (2013) by FHWA. They obtained an improved version of the HEC 22 equations for the tested inlets. Additionally, Comport & Thornton (2012) obtained new empirical relationships for the efficiency of the inlets through dimensional analysis.

Experimental studies have also been conducted in Asia. For example, Lee *et al.* (2012) tested physical models with and without grate inlets and obtained weir- and orifice-type discharge coefficients for both grates. The experimental results were successfully compared with the results of 2D numerical simulations, with differences in the discharge coefficient between 1.5 and 14%.

Sabtu (2015) and Sabtu *et al.* (2016) tested several grate inlets in a full-scale model considering three types of flow conditions: intermediate capture, where the flow enters partially through the upstream flow of the platform; terminal or total capture, where the flow enters entirely from both extremes of the platform; and surcharge flow, where water is conducted from the bottom pipe to the platform and the grate works as a source. For all the flow conditions, curves relating the captured flow and grate efficiency with the flow depth were obtained, and weir discharge coefficients were adjusted according to different hydraulic relationships.

Wu *et al.* (2015) performed tests in a reduced-scale model, varying the flow and longitudinal slope for various types of grate inlets. The results associate the efficiency (E) with dimensionless numbers associated with the flow in the road, such as the Froude number (Fr), ratio of the depth of the flow and length of the grate (y/L_g), and ratio of the spread of the flow and width of the grate (T/B_g).

Choi *et al.* (2016) compiled reports on several studies carried out in South Korea, and complemented the investigation with grating experiments in which the angle of orientation of the bars was varied. The captured flow was represented using empirical equations depending on the flow type (free or submerged), the angle of orientation of the bars, the depth of flow upstream of the grate, and the longitudinal and transverse slopes of the road. Similar experiments were carried out by Kim *et al.* (2016), who represented the flow captured by various bars by an empirical equation based on the total flow and the longitudinal and transverse slopes of the road.

Veerappan & Le (2016) carried out full-scale physical experimentation using sprinklers with intensities between 133 and 250 mm/h with variations in the longitudinal and transverse slopes of the road. The tests examined bars without obstructions and bars with obstructions such as fallen leaves and other residue litter on the roads that reduced the percentage of the area of the grate. The comparative results of the tests were represented using graphs of grate efficiency as a function of the intensity of rain and the longitudinal and transverse slopes of the road.

Rubinato *et al.* (2018) conducted physical experiments with numerous circular grates on a platform with low longitudinal slope. The results were represented as curves of the captured flow and water depth upstream of the grate. Weir- and orifice-type flows were also evaluated, and discharge coefficients between 0.115–0.372 and 0.349–2.038, respectively, were obtained. Additionally, there was a good fitting of the discharge coefficients to a function of the perimeter and effective area of the grate grooves.

Kemper & Schlenkhoff (2019) derived a novel empirical equation for determining the efficiency of the grate as a function of the width and length of the grate and the depth, speed, and Froude number of the flow upstream the grate. The proposed formula was compared with the methodologies presented in Brown *et al.* (2013), Spaliviero *et al.* (2000) and Gómez & Russo (2005), obtaining a good adjustment with the equations of the efficiency of the grate proposed by Brown *et al.* (2013).

Wakif & Sabtu (2019) tested grates with and without vertical depression in a physical model, the latter representing

grates at the road level, and evaluated the intermediate or partial uptake system and terminal system with full uptake, similar to the experimental setup considered by Sabtu (2015). The results show that the efficiency of a grate with vertical depression is less than that of a grate at the road level for intermediate configurations, but the relation is reversed for terminal conditions or low points for which the depression of the grate improves rainwater harvesting. The results were represented using curves of efficiency and total approach flow. The relationship of efficiency with unit flow and water depth was shown using a polynomial curve.

Cosco *et al.* (2020) carried out experimental studies of three grates on a platform and with test protocols similar to those used by Gómez & Russo (2011). The captured flow was represented by weir- and orifice-type equations and the discharge coefficients vary between 0.01–0.28 and 0.10–0.40, respectively. The strong influence of the Froude number upstream of the grate on the variation of the discharge coefficient through a potential adjustment is also presented.

Investigations on the hydraulic capacity of transverse grates, inclined grates, and the phenomenon of obstruction

In addition to the aforementioned research, the hydraulic capacity of transverse grates has been examined in detail in studies such as those of Gómez & Russo (2009) and Russo *et al.* (2013). The latter proposed methodologies for estimating the hydraulic efficiency of transverse gratings of any geometry, similar to the methodologies reported by Gómez & Russo (2011). Besides, Holley *et al.* (1992), Hammonds & Holley (1995), Sipahi (2006), and Özbey (2015) conducted physical experiments on transverse grates.

It is common practice to use sump grates inclined such that they protrude from the surface in medians or dividers of multi-lane highways. Such grates are known as inclined grates. Since they are not installed on roads, they do not interfere with vehicular traffic. Further, their inclination provides greater effective free area and less area covered by obstructions as compared to grates without any inclination. Comport *et al.* (2012) and Guo *et al.* (2016) have reported some results on physical experiments on inclined grates.

Obstruction by obstacles is inevitable and refers to the accumulation of plant litter such as tree leaves, garbage, sedimented materials, and any other residue that may be removed from the pavement surface during a storm. Although tests have been conducted with various degrees

of obstruction, there is a lack of a detailed analysis of the quantitative representation of reduced flow rate or efficiency of the grates. Guo (2000) modeled obstructions using a factor that reduced the flow captured in grate inlets (single) and an exponential decay factor to represent the reduction in flow in series of grates (multiple). Their analyses also considered the length of the curb-opening inlets. Similarly, flow reduction factors related to the presence of obstructions in single grates and decay factors in multiple grates were experimentally evaluated by Guo & MacKenzie (2012) for various types of grate inlets, curb-opening, and combination inlets.

Gómez et al. (2013, 2018) conducted field campaigns to visually determine the most recurring patterns of real obstructions in the grates of two urban basins. The field campaigns were carried out after heavy rains and after a dry season, and hence, information on the patterns of obstructions generated by the material carried in the first wash and the material accumulated by residues and debris in the dry season could be obtained. The obstructed parts in the grates of each pattern were casted with plaster and physically modelled following the test protocol of Gómez & Russo (2011). The results of the hydraulic efficiencies were compared with those of clean grates, and a clogging coefficient was defined as the ratio of the difference in efficiencies of the two evaluated conditions and the efficiency of the clean grate. Clogging coefficients were determined between 0.26 and 0.50 for inspections after rain and 0.66 in dry weather.

Experimental studies of lateral drains are beyond the scope of this review owing to the large amount of studies on this subject. Further, these drains have lower hydraulic capacity than grates and transverse inlets. Experimental studies of curb-opening inlets were reported by Izzard (1949), Holley et al. (1992), Hammonds & Holley (1995), Guo et al. (2009), Guo & Mackenzie (2012), Comport & Thornton (2012), Brown et al. (2013), Schalla et al. (2017), Hodges et al. (2018), and Li et al. (2019).

Studies using 3D numerical models

3D numerical simulation is a powerful tool to represent hydraulic phenomena by using a computational engine. It is being increasingly applied and complements laboratory or field measurements. After validation of the captured flow, 3D models have been used for laboratory verification of difficult-to-observe processes, such as streamlines or flow patterns. Further, they complement tests beyond the

measured ranges, improve scientific understanding of case studies, and have many other potential uses.

Numerous 3D numerical simulation studies have been conducted in the field of hydraulics of urban storm drains. Fang et al. (2010) used a numerical computational model to represent the catchment of curb-opening inlets, and validated and complemented the test results reported by Hammonds & Holley (1995), especially for low cross slopes. Fang et al. (2010) used a rectangular mesh of size between 15 and 76 mm and an absolute roughness of 7.6 mm and with a renormalization group (RNG) turbulence model. The maximum differences in the captured flow and the efficiency of the grate were 5.3% and 2.4%, respectively.

Begum et al. (2011) performed a 3D numerical study of the hydraulic capacity of the inlet through a grate and curb-opening inlets from the perspective of designing a device to improve the quality of rainwater on the road. The numerical modelling results were in good agreement with experimental data for the same device with differences between 1 and 16%, using an unstructured mesh of size between 2 and 13 mm and with the κ - ϵ turbulence model.

Galambos (2012) performed 3D numerical simulations of grate inlets using unstructured meshes with tetrahedral elements of sizes between 2 and 70 mm and using a κ - ω turbulence model. The numerical simulation was validated with the experiments carried out by Sabtu (2015), considering the water depth on the platform and grate efficiencies.

Sezenöz (2014) simulated transverse grates in a 3D hydrodynamic model with structured mesh sizes between 10 and 20 mm; the results were compared with the experimental results of Sipahi (2006) and Gómez & Russo (2009).

Kemper & Schlenkhoff (2016) performed 3D numerical simulations of grate inlets from the preliminary experiments that were subsequently reported in Kemper & Schlenkhoff (2019), used a structured mesh size of 3–4 mm near the bars and 3–12 mm in the approach channel, and used the RNG κ - ϵ turbulence model. The magnitudes of the absolute roughness used for the channel and grate were 1.5 and 0.3 mm, respectively. The numerical results were compared with the experimental results, performing differences less than 10 and 4% for the water depth and the captured flow, respectively.

Gómez et al. (2016) simulated the entire test platform used by Gómez & Russo (2011). In the simulation, a structured mesh of size 10 mm in the grating and 20 mm in the rest of the approach channel was used. The absolute roughness of the channel was 0.9 mm, and that of the grate was 0.5 mm. The RNG turbulence model provided a better fit to the experimental data. The water depth in the platform

and total flow captured by the grate were numerically calculated, with mean relative errors of 10 and 4%, respectively. Furthermore, the flow captured by the frontal and lateral mechanisms of the grate was numerically determined, with percentage of distribution between frontal and lateral flows varying between 60–40% and 80–20%.

Lopes *et al.* (2016) performed 3D simulation of the hydrodynamic phenomenon at the inlet of a transverse grate using a reduced calculation domain limited to the width of the slot between the bars and an unstructured mesh of size between 3 mm and less than 1 mm. The numerical results were based on the efficiency of the transverse grate in comparison with the measurements reported by Gómez & Russo (2009), with relative deviations for the captured flow of less than 28%.

Recently, Kemper & Schlenkhoff (2018) performed a 3D numerical modelling and an experimental study of grate inlets using structured meshes of sizes 1.5–6 mm for the modeling, setting the absolute roughness as 1.5 mm, and adopting an RNG κ - ϵ turbulence model. The simulation and experimental results were compared in terms of the water depth and flow velocities, and the rate of the flow captured by the grate.

The results of these studies imply that 3D numerical models are an acceptable alternative when no physical experimentation is possible; thus, numerical models are a virtual laboratory in themselves. The numerical studies must be accompanied by validations with previous and similar studies and must be rigorously evaluated.

Investigations on the hydraulic capacity of grate inlets in Latin America

In Latin America, there has been comparatively less research on the hydraulic capacities of the grate inlets because of budget limitations for research, in general, and other factors such as the lack of attention of grate manufacturers and operators of public storm sewer systems. The reduced interest in these practical applications possibly lies in the limited vision of a holistic urban drainage system, absence of laboratories equipped for this type of installation, lack of knowledge of the new integrated models of urban drainage and the need to satisfy the supply of water in rural populated centers, where most of the studies in developing countries are concentrated. Some advances are reflected in the general rules of aqueducts and sewers in each country or town (for example, in Colombia MinViv 2017 and EPM E.S.P. 2013); however, in these cases, literature mainly comprises formulations with few

technical details of methodologies from other countries whose grate geometries could differ from those employed in the Latin American countries.

Some studies conducted in this region focused on physical experimentation on the hydraulic capacity of sump grates focusing on using reduced scale models, where the flow ranges and longitudinal and transverse slopes are limited. The results were not compared with more general formulations, such as those presented in Gómez & Russo (2011). In one of the most extensive studies conducted in Chile (Kaliski & Cortéz 2004, 2005), the efficiency was determined as a function of the inlet flow and longitudinal and transverse slopes of the full-scale experimental assembly. Subsequently, Cortéz & Kaliski (2006) continued the investigations using eccentric grates or outside the curb of the road, with unevenness or depressions with respect to the road and approximation of depression around the grate. The hydraulic capacity of the grate inlet was represented by curves that relate the efficiency and total flow. It was concluded that an uneven configuration with a zone of influence has higher efficiency than does a configuration with the grate at track level.

In a similar study, Kaliski & Cortéz (2008) examined rainwater drains considering a partial eccentricity with respect to the road curb and variations in the unevenness and areas of influence. The inlet of the grates was represented by curves relating the efficiency and total flow. For most of the tested cases, efficiency increased with unevenness and areas of influence, thereby improving the conduction of water to the grate. In all the previous studies, it was evident that the side window that accompanies the bottom grating in combination inlets does not result in a significant increase in the captured flow rate and therefore an increase in efficiency. The studies carried out by the National Hydraulic Institute of Chile were compiled and reanalyzed by Morales (2016); the results of these studies were compared with the potential relationship between the efficiency of the sump and the Q/y relationship proposed by Gómez & Russo (2011), which were adjusted satisfactorily for some bars. Morales (2016) also modified the efficiency and flow rate captured with polynomial functions of the water depth.

In Brazil, Cardoso *et al.* (2004) used a physical model of curb-opening inlets with deflectors or grooves at the bottom. These deflectors increase the capture capacity with respect to the standard depressions and reduce the interference arising from the passage of vehicles and pedestrians. Cardoso *et al.* (2004) obtained the curves and equations relating the flow captured per unit length of the curb-opening inlet and the depth of

the flow upstream of the sump for different transverse slopes. They found that the effects of surface tension distort the final results, making necessary a correction of discharge coefficients. Lara & Araújo (2011) performed experiments with a reduced scale model with a gutter next to the curb for different grate configurations, curb openings, and combination inlets with and without depressions. Cardoso *et al.* (2004) found the relationships between the flow captured per unit length as a function of the depth of the upstream flow for each configuration and various longitudinal slopes.

In Argentina, Chirichigno *et al.* (2011) conducted experimental studies using a reduced-scale model for curb-opening and combination inlets and evaluated their hydraulic capacity with clean bars, and then included wastes such as leaves and bags and plastic containers at the entrance. The flow results were represented using curves relating the efficiency and total flow to the model. Plastic waste did not influence the capacity of the grate inlet due to their buoyancy, locating on the bars without obstructing the captured flow that circulates under them. In contrast, leaves adhered to the bars of the grates, thereby reducing the effective capture area.

In Ecuador, Pasmíño *et al.* (2017) experimented with single and serial grate inlets in a reduced-scale model and obtained potential equations between the efficiency and the total flow for different longitudinal and cross slopes.

In Colombia, Barragán (2010) conducted a small-scale experimental study with different configurations of curb-opening inlets with and without depression. The curb-opening inlets with depression had 2 and 8% higher hydraulic capacity compared to that of the sinks without depression. Sabogal & Hernández (2011) experimentally studied six types of grate inlets using a reduced model and obtained the efficiency curves as a function of the longitudinal slope for various flow rates and cross slopes.

Cárdenas *et al.* (2017) performed 3D hydrodynamic simulations of the grate inlet, partially following the testing protocol defined by Gómez & Russo (2011). The numerical simulations were adjusted by the conclusions of the 3D model used by Gómez *et al.* (2016) and indirectly calibrated by applying the methodology of Gómez & Russo (2011). Potential relationships between the efficiency and the Q/y ratio were obtained; relationships of the inlet flow-type; that is, weir and orifice types, and a unit power threshold to distinguish these intake types were obtained. Cárdenas *et al.* (2017) found that the weir- and orifice-type discharge coefficients are related to the Froude number of the flow upstream of the sump, similar to the results obtained by Cosco *et al.* (2020).

Most of the Latin America studies have limitations in terms of experimental setups, sometimes with very low economic budgets, and their possibilities for advances are reduced because of the limited depth of their scope and the limited scientific dissemination. More details of the studies carried out in Latin America are presented in Table 2.

Temporal evolution of hydraulic studies of urban storm drains

Based on the extensive bibliographic review, the accumulated number of experimental studies from North America, Europe, and Asia, as well as the numerical and experimental studies from Latin America are shown in Figure 3. There is an enormous gap between the date of the first publications in Latin America and the date of the first studies in the rest of the world, suggesting the need for a more work to be done in these topics. The last decade has stimulated the use of numerical computational models, which allow the simulation of the inlet processes in urban storm drains, driven by the increasingly powerful and fast calculation engines.

Furthermore, there has been a huge increase in research on storm drains in the last 15 years, corresponding to the increasing use of hydraulic surface models and dual models of urban drainage. This is also in line with the current challenges in urban hydraulics, such as measures to be taken to cope with more intense and frequent storms (climate change), reduction and mitigation of flood risks, needs arising from the accelerated growth of cities, effects of increased impervious surfaces in cities, treatment of rain-water quality, and steps to be taken in keeping with a great interest in the welfare of the population.

IDEAL TEST SETUP

Based on the literature review, some characteristics of the ideal configuration for determining the hydraulic capacity of an urban storm drain can be recommended:

- The configuration should be physical and in full-scale models to avoid distortions in the results due to the scaling effects of surface tension in the small slots of the grates (Russo & Gómez 2014; Russo *et al.* 2015). A reduced-scale model can be used as long as the independence of the scale is demonstrated; that is, the evaluation of the experiment for several scales independent of the results obtained. Numerical models may be an option

Table 2 | Summary of studies on the evaluation of the hydraulic capacity of grate inlets in Latin America

Reference	Inlet type	Number of grates or configurations	Model features	Formulation type	Equations
Kaliski & Cortéz (2004, 2005)	Grate, curb opening and combination inlet	5	Scale [1:1] Length [14 m] Width [3.5 m] S_L [$< 3\%$] S_T [$< 5\%$] Flow [< 120 l/s]	Graphics of: E vs. S_L E vs. S_T	-
Cortéz & Kaliski (2006)	Combination inlet	1	Scale [1:1] Length [14 m] Width [3.5 m] S_L [$< 3\%$] S_T [$< 5\%$] Flow [< 180 l/s]	Graphics of E vs. Q	-
Kaliski & Cortéz (2008)	Grate, curb opening and combination inlet	1	Scale [1:1] Length [14 m] Width [3.5 m] S_L [$< 3\%$] S_T [$< 3\%$] Flow [< 180 l/s]	Graphics of: E vs. S_L E vs. S_T	-
Morales (2016)	Grate, curb opening and combination inlet	7	Scale [1:1] Length [14 m] Width [3.5 m] S_L [$< 3\%$] S_T [$< 5\%$] Flow [< 180 l/s]	$E = f(Q/y)$ $E = f(y)$ $Q_{in} = f(y)$	$E = A(Q/y)^{-B}$ $E = Cy^2 + Dy$ $y = EQ_{cap}^3 + FQ_{cap}^2 + GQ_{cap}$ $E = H(y/B_T)^{-1}$ $A, B, C, D, E, F, G, H, I$ varies for each grate, Q, S_T
Cardoso <i>et al.</i> (2004)	Curb opening inlet	1	Scale [1:3] Length [4 m] Width [0.75 m] [0 – 20%] [5 – 20%] Flow [< 8 l/s]	$Q_{in}/L_{co} = f(y, S_T)$ $E = f(S_L, f, L_{co})$	$Q_{in}/L_{co} = 2.05y^3$ $E = 0.68 \frac{L_{co}}{yS_T\sqrt{S_L/f}}$
Lara & Araújo (2011)	Grate, curb opening and combination inlet	5	Scale [1:3] Length [6 m] Width [0.75 m] S_L [0.5–14%] S_T [3%] Flow [< 12 l/s]	$Q_{in}/L_{co} = f(y)$	$Q_{in}/L_{co} = ky^3$ $Q_{in}/L_{co} = k_1y^{3/2} - k_2$ k, k_1, k_2 varies for each grate and S_L

Chirichigno <i>et al.</i> (2011)	Curb opening and combination inlet	4	Scale [1:2] Length [11 m] Width [1.75 m] S_L [0.24%] S_T [2%] Flow [< 53 l/s]	Graphics of: E vs. Q	-
Pazmiño <i>et al.</i> (2017)	Grate inlet	2	Scale [1:4] Length [-] ^a Width [0.95 m] S_L [0.5–12%] S_T [2–4%] Flow [< 7.19 l/s]	Graphics of: E vs. Q $E = f(S_T, S_L, Q)$	$E = \beta Q^{-\alpha}$ α, β varies for S_T and S_L
Barragán (2010)	Curb opening inlet	8	Scale [1:6,67] Length [-] ^a Width [0.60 m] S_L [0.5–8%] S_T [0–4%] Flow [< 3.52 l/s]	Graphics of: E vs. S_L for different Q	-
Sabogal & Hernández (2011)	Grate inlet	6	Scale [1:5] Length [-] ^a Width [0.60 m] S_L [0–10%] S_T [0–4%] Flow [< 1.97 l/s]	Graphics of: E vs. S_L for different Q and S_T	-
Cárdenas <i>et al.</i> (2017)	Grate inlet	1	Scale [1:1] Length [5.3] Width [3 m] S_L [0.1–10%] S_T [0–5%] Flow [50–250 l/s]	$E = f(Q/y)$ Weir and orifice equations	$E = A(Q/y)^{-B}$ $Q_w = \frac{2}{3} C_{dw} (L_g + B_g) \sqrt{2gE_0^3}$ $Q_o = C_{do} \epsilon L_g B_g \sqrt{2gE_0}$ C_{dw} and C_{do} varies with Fr

E : Efficiency of inlet; Q : Total flow; Q_{in} : Inlet flow; Q_w : Weir-type captured flow; Q_o : Orifice-type captured flow; y : Water depth upstream the inlet; v : Water velocity upstream the inlet; L_{co} : Length of the curb opening; E_0 : Specific energy upstream of the inlet ($E_0 = y + v^2/2g$); Fr : Froude number upstream from the inlet; S_L : Longitudinal slope; S_T : Transverse slope; B_g : Width of the grate; L_g : Length of the grate; C_{dw} : Weir-type discharge coefficient; and C_{do} : Orifice-type discharge coefficient.

^aThe missing data in the physical or numerical model characteristics are not available in the studies or reports consulted.

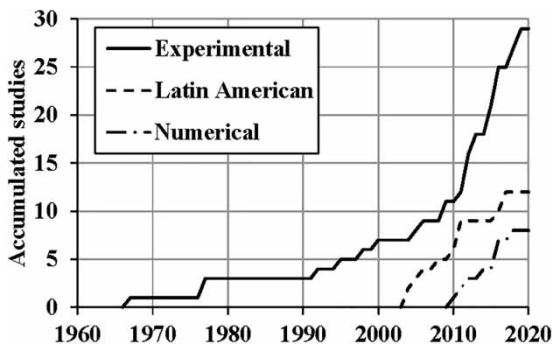


Figure 3 | Historical evolution of the experimental and numerical studies worldwide and the total of such studies conducted in Latin America.

when the resources necessary for a physical assembly are not available, but these models should be tested and appropriately validated using either other experimental data or recommendations from similar studies.

- The experimental set-up should consist of a platform that represents the road surface, with the minimum dimensions of one lane of the road, greater than 3 m (minimum one road lane). The length of the platform will allow the approximate development of a uniform flow upstream of the grate, for supercritical flows, and downstream of it, for subcritical flows. This length depends on the development of the flow based on the magnitude of the flow and the available slopes. However, the platform length should be at least two times the platform width, with similar length upstream and downstream from the grate.
- The cross slope may be varied from 0% to 5% (with variations of 1%), which is the maximum cross slope allowed by some geometric design manuals for urban roads. Likewise, the longitudinal slope may be varied from 0% to 10% (with variations of 2%), representing the high-slope roads in mountainous regions.
- The tests should be performed with a variable flow rate of at least 100 l/s, which will allow the evaluation of discharges that immerse the entire grate. Higher flows will allow the evaluation ranges to be higher, especially for the extreme storms that generate large floods. The tests can have flow intervals between 25 and 50 l/s. The flow of 100 l/s presents approximately a critical depth of 0.05 m in a 3.0 m wide road and a 0% cross slope.
- Much of the research consulted has focused on supercritical flows for surfaces with a high longitudinal slope. However, the evaluation of subcritical conditions is also necessary to analyze the hydraulic behavior of grates at low points or with hydraulic control, which are possibly the most recurrent conditions in flood zones.

- The grate geometry varies with the city or country, and the investigations should consider the needs of the particular region to which the study pertains. Therefore, an objective and quantitative comparison of the results and advances is difficult. Hence, the unification of the experiments is proposed through a typical universal grate, which will allow us to expand, share, and compare the physical understanding of the collection processes around an urban grate and allow connectivity with scientific developments worldwide. This universal grate is not intended to replace previous studies or grate used in different cities.
- Experiments should consider grates of various geometries, such as those with general lengths and widths; with longitudinal, diagonal, and transversal bars; with different slot widths and effective areas. The experiments should be complemented with a variety of inlet configurations commonly used for urban roads, such as simple, series, and parallel configurations, configurations with vertical depression and different approximation depression, and configurations wherein the grate is located beyond the curb of the platform.
- The test results may be presented as graphs of the efficiency or the inlet flow for different physical and hydraulic variables of the flow to analyze its variation. It is also necessary to define a common set of variables and parameters for the equations that allow comparison of the results obtained with the existing formulations, thereby allowing validation and complementation of previous studies. Thus, general or universally accepted formulations can be formed and included in the computational models of surface or dual drainage.

CHALLENGES IN LATIN AMERICA

Scientific studies on the hydraulic behavior of urban storm drains in Latin America have a smaller scope and extent compared to those conducted in North America, Europe, and Asia because of technical and economic limitations in developing countries and possibly because of the limitations in the traditional paradigms present in engineering and scientific projects in Latin America. In the following section, a critical and reflexive analysis of the necessary changes in the traditional paradigms in Latin America is presented.

Paradigm change

Because of the continuous boom and growth of Latin American cities, the efforts of the operators and administrators of

the drainage and sewerage systems have been focused on increasing the coverage of the underground infrastructure of urban drainage and attending to the critical concerns of frequent flooding. In Latin America, owing to limited economic resources for research, the surface infrastructure of the drainage is given secondary importance. Hence, the traditional and biased concept of urban drainage has not been modified, and research interest is limited only to the sewer pipe network and more recently to the quality of the water in the receiving water bodies.

Urban drainage should be conceptualized holistically, so that the integration of the hydrological and climatic processes of the cities interacts with the existing infrastructure in a rational and quantifiable way. This will significantly reduce the uncertainty and risks associated with urban floods, causing smaller economic and social impacts in the cities and allowing greater control and benefit from the water resource.

To improve the traditional paradigms, different techniques and tools available in the academic and engineering environment are examined and explored extensively to conceptualize and understand urban drainage. Computational models of surface or dual drainage can be used for various scenarios in different cities after obtaining the necessary inputs for these models. This change in the paradigm can be effected only when various actors participate: grate manufacturers must be aware of the hydraulic characteristics of the products they offer, and meritorious competition and not merely low cost must be encouraged; operators and administrators of drainage services and systems are responsible for defining and receiving the hydraulic works for the public service of the communities; researchers and academics should employ scientific and technical developments from the perspective of the needs of communities; design engineers should update their knowledge and techniques and put into practice previous research contributions for realizing rational, reliable, and economic works.

Computer tools are an available and necessary means for analyzing critical flood points in cities, optimizing the existing infrastructure, and reducing construction, operation, and maintenance costs.

Research lines on hydraulic capacity of grates

The review of the aforementioned studies shows that the hydraulic processes in an urban drain grate are complex and vary with the geometric configuration of the grate. Usually, the typical geometries or specifications of the

grates of the drains vary with the city, thus expanding the scope of the studies needed. Below are some lines of research to develop drainage-related projects in Latin America:

- Physical experimentation of grate inlets under supercritical conditions for a wide range of flows and transverse and longitudinal slopes based on the test protocol of [Gómez & Russo \(2011\)](#). This is necessary for mountainous areas with high road slopes (where low flows are observed, but since inlet efficiency is very low, the flow that is not captured will continue downstream, leading to possible floods).
- Physical experimentation of grate inlets under subcritical conditions for a wide range of flows and downstream controls such as those proposed by [Nanía *et al.* \(2011\)](#) to consolidate a new testing protocol that is complementary to the testing protocol for the supercritical regime. These flow conditions are frequent in roads with very low longitudinal slope, depressed roads, and areas subjected to frequent flooding by particular hydraulic controls. The physically tested grate must be one that is the most commonly used in the cities, and any new grate to be installed must meet the minimum hydraulic specifications.
- Less frequently, there are particular configurations of grate inlets that require physical experimentation, such as: serial or parallel grates, outside the curb, with depression or with areas of influence. These drainage configurations must be defined and regulated by the drainage service operators based on extensive technical support.
- Limitations imposed by high costs of physical experimentation in full-scale models. In view of the high cost of full-scale model studies, the study of the problems associated with surface tension in reduced-scale models will be decisive in expanding the scope of physical tests.
- 3D numerical simulation as an alternative to physical experimentation to satisfactorily represent the hydraulic processes at grate inlets. Although 3D numerical models require long calculation times, they may be a starting point for achieving the formulations required by dual drainage models.
- Garbage and plant litter present on the road reaching the grates during rainfall events and reducing their hydraulic capacity. It is necessary to carry out field campaigns to define frequent obstruction patterns in each city. These patterns may be then included in the grates and must be physically or numerically tested to complement the design criteria. The location of the sites with the greatest obstructions will allow correlation of the magnitude of

the rain events with the priority places so that the cleaning and maintenance works reduce the impacts of the floods in advance.

- Compatibility of the formulations to represent the inlet of an urban storm drain. These formulations should be compatible with urban dual drainage models to obtain the necessary inputs for the analysis of these models, such as the inventory of the urban drainage infrastructure (surface and underground), topography of roads, roofs and green areas, and high-resolution precipitation records, continuous measurements of the surface water level at critical flood points, and measurements of the flow in pipes in strategic locations in the city.
- For the use of dual drainage models, it is necessary to study the surcharge conditions in the gully boxes. This phenomenon occurs when the sewer pipes do not have the hydraulic capacity to transport the flow, entering a surcharge condition and expelling part of the flow towards the surface. It is possible to study the interaction of the grates under surcharge conditions such as those carried out by Lopes *et al.* (2013), Martins *et al.* (2017), Beg *et al.* (2018) and Gómez *et al.* (2019).
- Emphasis on the subjects of hydraulics or urban hydrology in undergraduate and postgraduate courses of civil, sanitary, and environmental engineering. This will ensure the increase and continuity of knowledge and research on the subject. Drainage service operators and grate manufacturers will be able to actively engage with academic centers by providing information and financial funding to contribute to increased understanding of urban drainage.
- Further Latin American research on urban drainage. Further research in Latin America will help create a greater impact via the increased accumulation and extent of knowledge, dissemination of the accumulated knowledge, creation of cooperation and sequence among studies, and the possibility of continuous training to achieve objectives of great interest to the communities.

CONCLUSIONS

A general context of the interaction between surface runoff and the network of storm sewer pipes through urban drains is presented in this paper. Adequate representation of the inlet process in the grates will determine the flow rate to the entrance to the underground system and will reduce the risk to pedestrians, vehicles, and surface infrastructure. This is possible through the use of modern dual drainage

models, which can incorporate general methodologies to quantify the captured flow.

The review of the methodologies to estimate the flow captured by urban grate inlets opens up an extensive and complex panorama. Future studies may be aimed at unifying the results and establishing universal, replicable, and complementary methodologies based on physical principles and on easy practical application in hydrodynamic drainage models. Weir- and orifice-type equations may be initial valid options to achieve this objective. The discharge coefficients can be calculated automatically based on the hydraulic parameters at the surface, such as the water depth, speed, or the Froude number.

The use of models based on computational fluid mechanics allows us to combine and complement the physical and numerical studies when the studied phenomenon allows it. Thus, it becomes possible to optimize the available resources and prioritize the lines of research. These tools will make it possible to overcome some challenges and problems faced in the field of modern urban hydraulics.

Knowledge about the interaction between the surface and underground domains will be the basis for the real management of rainwater in cities, especially in Latin America. This knowledge will help quantify with greater certainty the magnitude of the uses and exploitation, and aid in the control and reduction of flood risks and in understanding the interaction of cities in their continuous adaptation to the natural environment.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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