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Investigation of rainwater drainage's problems in the coastal cities

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Abstract

The problem of storm-water drainage in urban areas is analyzed, particularly in areas of rapid and recent urban development such as the Spanish Mediterranean coast. The impact on drainage of an urban development process that does not respect the hydrology of pre-existing natural basins is studied. The problems presented by numerical modelling of the different processes involved in urban drainage are also analyzed in a conceptual way, especially the hydraulic behavior of collector networks.

Keywords: Rainfall; Drainage; Coast; Mediterranean area; Storm.

1. Introduction

1.1. Specific problems of urban drainage infrastructures

The tendency of the population to move from rural areas to urban areas is well known. Currently, almost 50% of the world's population lives in urban areas, having increased by more than 80% in the last 20 years. This phenomenon also occurs in Spain, a clear example of which is the increase in population mainly in urban area that has occurred on the Mediterranean coast, where in some areas there has been an annual population increase of more than 5% in the period 1970-1986.

The growth of cities requires significant investments in infrastructure, most of which are used daily by citizens. This is the case of communication routes, green areas, hospitals, networks for the supply of fluids, etc. However, the use of these infrastructures and the

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normal development of citizen activity are, at certain times, conditioned by the correct functioning of another infrastructure: the stormwater drainage network.

The daily use of communication routes makes citizens value the political will and technical capacity that made them possible. This is difficult to happen in a network of collectors that remains "hidden" underground, whose every nature does not contemplate direct contact with the citizen and therefore it is difficult for them to assess its correct functioning. On the other hand, it is normally a deficiency in said functioning that attracts public attention and subsequent administrative awareness in search of solutions.

In addition to the low public echo that they generate, there are other factors that make the actions on the collector networks unique compared to those on other urban infrastructures. A first factor is the sporadic nature of their operation under the conditions (flow) foreseen in the project: a 10% probability that within a given year it will operate at full capacity for a few minutes is a criterion normally used. Conversely, the need for extensive actions (in space and time) on roads in densely populated areas is a determining factor in the high economic and social costs associated with these works.

All of the above justifies the need for a strong political will be resolved the significant drainage problems present in many cities with rapid and recent urban development.

1.2. Impact of urbanization on storm water drainage

Urban development substantially alters the hydrology of the basins where it occurs. In particular, the drainage network and the rainfall-runoff transformation process are modified. As a consequence of urban development activity, the natural channels that formed the original hydrographic network are often profoundly altered, which directly affects their drainage capacity and therefore encourages flooding. The rainfall-runoff transformation is altered as a consequence of the traditional criterion present in many urban development processes: rainwater must be eliminated as quickly and efficiently as possible. This involves avoiding temporary surface retention and infiltration, as well as increasing the speed of water circulation towards the lower parts of the basin.

The final result of this dynamic is that the drainage networks of these lower parts are subjected to hydrographs with greater volume (higher runoff coefficient), higher peak flow and greater abruptness (less time between the start of the rain and the appearance of the maximum flow, decreased concentration time). When urban development is carried out from the old core towards areas located at a higher altitude, the processes mentioned above usually give rise to an increase in flow that cannot be transported by the drainage network existing in the old urban area, giving rise to problems due to flooding. This situation is frequent in cities located next to the coast and that have experienced rapid growth inland. This problem is analyzed in detail by Arandes (2005).

As an example of the above, the results obtained in a small experimental basin (0.97 km^2) in Japan can be presented by Yoshino and Yoshitani (1990). The Minamiosawa basin went from having an urbanized area of 0% to 61.5% of its surface and the consequences on drainage can be summarized as follows:

- The runoff coefficient went from having a value between 0.03 and 0.46 (31 rainy episodes studied) to another between 0.11 and 0.64 (20 rainy episodes studied). It should be noted that the runoff coefficient tends to be higher the greater the intensity of the rain.
- The concentration time went from being between 60 and 100 minutes before urbanization, to 35-50 after it.

All the problems described above are aggravated in certain areas where short-term but extremely intense rainfall occurs with relative frequency. This is the case in many areas of the Mediterranean coast where the intensity of rainfall corresponding to a given duration and probability is approximately double that corresponding to non-Mediterranean European cities. Thus, for a return period of 10 years and 30 minutes in Montpellier and Barcelona the intensity of rainfall is greater than 80 mm/h, Barcelona City Council (1988). It should be remembered that the average annual rainfall in Barcelona is approximately 550 mm. An analysis of the extreme characteristics of rainfall in Mediterranean Spain can be found in Martín Vide (1992). This causes very high specific flows: in the small urban basins around Barcelona, for a return period of 10 years, peak flows of 15 to 25 $m^3/sec/km^2$ are normal in basins smaller than 25 km^2. In the Bogatell basin, which is about 25 km^2 and drains approximately 25% of the surface area of Barcelona, the flow corresponding to its drainage to the sea and for a return period of 10 years is approximately 350 m^3/s. The maximum capacity of this section was 40 m^3/s before the remodeling of the Barcelona drainage network was carried out. This explains the drainage problems and the frequent flooding suffered by the urban areas located in the lower part of the Bogatell basin.

2. Actions to improve urban drainage

In order to solve the flooding problems that exist in a given urban area, actions are normally proposed that tend to artificially restore the natural behavior that existed in the basin before it was occupied by the city. Fundamentally, these actions can be divided into two categories: those that aim to increase the drainage capacity of the collector network (which replaces the natural hydrographic network) and those that tend to reduce runoff (increase surface retention and infiltration). In addition to these actions, it is evident that correct management of the infrastructures and services related to urban services can help to improve their efficiency. In Carriço *et al*. (2022) the current evolution and trend in such management are described.

Apparently, the capacity of a collector is linked to its dimensions and the speed at which the water moves through it. The high urban density especially in older areas, significantly limits the dimensions of a new collector. On the other hand, speed is closely linked to topography, so that in coastal areas the absence of topographical differences is usually a determining factor in the design. Therefore, the difficulty that normally entails increasing the drainage capacity of an urban drainage network is evident. For this reason, pumping is sometimes used, with the risk involved in depending on the correct operation of a large pumping group during the short period of time in which the maximum flows occur in the collector. Obviously, this risk can be minimized if strict maintenance work is ensured, which, in contrast, is not easy due to the highly sporadic nature of its operation. A detailed analysis of the design criteria for pumping stations in collectors can be seen in Cabrera *et al.* (1992).

The natural retention that takes place on the surface of a basin in an urban area can be replaced by retention tanks or ponds that temporarily store part of the runoff. One drawback to the construction of these structures is the difficulty in having the space required for their location in the urban area. A variant of retention tanks consists of using the storage capacity of the collector network itself when it is sufficiently extensive and there is a clear differentiation in the spatial and temporal distribution of rainfall that does not rain identically throughout the basin (Haghroosta and Ismail, 2017). If the network is equipped with the necessary control elements, those collectors with sufficiently low flow rates can be used as reservoirs. This can be achieved by operating the gates in such a way that the water transported by collectors with capacity problems is totally or partially diverted towards them. Obviously, this type of real-time operation requires, in addition to the installation of gates, the existence of a measurement network that allows the situation (flow rates and levels) in the collector system to be known at all times. The instrumentation of collector networks has undergone significant advances, Martín Vide *et al.* (1992) but, in our opinion, as important or more important than the measurement and control systems mentioned above, is having a sufficiently precise degree of knowledge of the hydraulic behavior of the network, such that in a short time the appropriate decisions can be made to operate the gates. It should be noted that extreme flows during a rainy episode, which is typical of Mediterranean urban basins, occur very quickly (in less than half an hour).

A detailed analysis of the design criteria for ponds and lamination tanks can be found in Stahre and Urbonas (1990). Significantly reducing runoff by increasing infiltration is practically impossible in cities as densely populated as those in Spain (almost 18,000 inhabitants/km^2 in the case of Barcelona). It is possible to facilitate infiltration in certain areas such as parks, car parks, squares, etc. However, from a global point of view of the city (or one of its basins) these actions alone will hardly be able to solve the drainage problems caused by an urban development process that did not respect the pre-existing natural hydrography. Therefore, normally the solution to flooding problems in densely populated urban areas involves increasing the drainage capacity of the collector network.

The magnitude of the flows and the construction conditions imposed by the city itself mean that such actions require high investments. Thus, the works on the collector networks carried out in Barcelona during the period 1986-1992 represent a cost of around 27,000 million pesetas and have largely resolved the existing problems: the floodable area, which was initially around 13 km^2 (13% of the municipal area of Barcelona), has been reduced by 44%, according to Malgrat and Vázquez (1992) and De Glasea *et al.* (1992). The great interest in optimizing these important investments is clear and this requires a detailed knowledge of the hydrological and hydraulic phenomena linked to urban drainage. This need for the advancement of knowledge has motivated the appearance, not many years ago, of a new discipline called urban hydrology, which incorporates and adapts the classic knowledge of hydraulics and hydrology to the particular characteristics of the urban environment. Within this discipline, the study of urban drainage attracts considerable attention, as shown by the existence of an international congress on "Urban Storm Drainage" every three years. The first of these was held in 1978 in Southampton and the next one is scheduled to be held in July 1996 in Hannover.

To sum up, normally the only solution to solve drainage problems in densely populated cities is to increase the drainage capacity of the collector network. This requires high investments that justify, and even demand, a detailed knowledge of the different phenomena related to urban drainage.

2.1. Urban Drainage-General outline

The study of urban drainage and the design of actions aimed at improving it requires a detailed analysis of three hydrological-hydraulic phenomena:

Characterization of rainfall in order to establish the project rainfall, transformation of rainfall into surface runoff in order to obtain the inflow hydrographs in the drainage network (collectors) and the propagation of these hydrographs through the network. The three processes mentioned above are basic in surface hydrology, but they have very different characteristics when they refer to the urban environment. In what follows it will be referred to the first two processes. From the following section onwards the hydraulic behavior of collector networks will be analyzed.

The design rainfall can be obtained from rainfall intensity records. These records must be reliable and long-term, requirements that are not normally met. Vázquez *et al*. (1987) present the methodology used to characterize the rainfall intensity in the Barcelona area from the rainfall bands obtained at the Fabra observatory. When there are no intensity record available, different techniques can be used to obtain an approximate design rainfall. Once the rainfall has been determined, the hydrograph corresponding to the surface runoff must be obtained. For this purpose, different methodologies can be used that form the basis of the models normally used, Monte and Marco (1992).

There is a clear need to improve the information currently available, in order to be able to take advantage of the high performance of existing numerical models for the study of rainfall-runoff transformation. In particular, it is necessary to have reliable information regarding rainfall intensities and to carry out field studies that will allow, in the near future, to quantify with precision the retention and infiltration capacity of our urban basins. The results obtained in similar studies carried out in other countries (Ismail and Haghroosta, 2018) are not directly applicable in Spain, particularly on the Mediterranean coast, due to the marked rainfall and urban peculiarities of the cities. The investments required to carry out this improvement of the information are minimal, compared to the savings that could be obtained by improving the knowledge of the phenomena and, therefore, by reducing the degree of uncertainty in the design parameters of urban drainage infrastructures.

In contrast, the limitations to the advancement of knowledge in urban hydrology are not in the capacity of numerical models to reproduce the physical phenomena involved or in the calculation capacity of computers. These limitations, very important in our opinion, are in the available field information: rainfall and flows mainly. Improving this information involves expanding the data collection network of very little importance the one currently existing in urban areas, and modernizing the transmission and storage of information. But this improvement also requires better maintenance of the network.

Finally, it is of great interest to develop global studies referring to a certain geographical area. These studies will allow us to homogenize the different criteria that condition the design of the actions: project rainfall, impermeability, retention, constructive solutions, etc. They will also allow us to analyze the implications that a certain action may have on neighboring basins. All of this will allow us to optimize the high investments to be made. An example of the above can be the Special Sewerage Plan of Barcelona and its Hydrological Area, Barcelona City Council (1988), Malgrat and Vázquez (1992).

2.2. Hydraulic behavior of a collector network

A collector network is made up of a set of conduits interconnected by their unions, which we call nodes. These conduits are normally designed to operate in free-flow mode when the project flow hydrograph that flows through them. Free-flow mode allows the collector to connect to the surface of the city, which facilitates the incorporation of flows. If the collector operates under pressure, flows may pass from the collector to the outside. Obviously, this is more likely the shallower the collector is. It should be noted that there is always the possibility of a flow rate greater than that considered in the project, which causes the collector to come under load.

Since the flow rates entering the network are variable over time, the characteristics of the water movement in the collectors will also be variable over time. The free-form movement can take place in slow, critical and fast regimes, depending on whether the Froude number corresponding to a section is less than, equal to or greater than one. The hydraulic behavior of a free-form conduit is notably different depending on whether one regime or another is present (Williams, 2023). When the movement is variable, the Froude number for a section varies with time. The change from fast to slow regime is produced by a jump, which, given the non-permanent characteristics of the movement, will move along the collector. Normally, collector networks reduce the slopes from the high areas of the basin to the low ones. For this reason, the hydraulic regime is usually fast at the head of the collector network and slow at the end. This requires the presence of a mobile jump that allows the change from one regime to another.

In order for the resulting numerical model to reproduce reality as closely as possible, it must be:

- capable of incorporating all the geometric singularities of the network.
- capable of correctly simulating the different hydraulic phenomena present in the non-permanent movement of water along the collectors and nodes.
- capable of establishing a comfortable and agile dialogue with the computer that allows the characteristics of the network and the calculation hypotheses to be introduced into the model, as well as an easy interpretation of the results.

Compliance with the above requirements presents significant difficulties:

- Difficulty in obtaining information that allows reproducing the geometry of the network; different types of sections, slopes, layout and characteristics of the nodes.
- Difficulty due to the wide range of non-permanent hydraulic phenomena that may occur in a free-flowing conduit and the complexity of its study. All of this requires a significant calculation capacity, which is no longer a problem due to the high performance of the computers currently in existence.
- Current graphic screens and the software available for their use greatly facilitate dialogue with the computer. However, the great variety of geometries and the enormous number of hydraulic situations that may occur in a collector network make it extremely difficult for all of them to be foreseen in software for data entry and analysis of results on a graphic screen.

As these difficulties are overcome, the model will be useful for accurately simulating the hydraulic behavior of the collector network when certain hydrograph flow rates which flow through it. In what follows, we will analyze in detail those characteristics that, in our opinion, should be required of a numerical model that aims to be useful for studying the hydraulic behavior of a collector network.

3. Materials and methods

Unlike other physical processes within the general problem of urban drainage, such as the rainfall-runoff transformation on the surface of the city, the aspects related to the mathematical description of hydraulic behavior are much better known. Since the longitudinal dimension of the collector predominates over the other two, it is assumed that a one-dimensional description is valid. The most general type of movement possible, non-permanent, is described by the equations of Saint-Venant (1871), which for a collector of constant section have the following expression:

The Saint-Venant equations are a system of two partial differential equations that have no analytical solution. For this reason, numerical calculations must be used to solve them. Until the emergence of new computer tools and efficient numerical solution schemes, a series of simplified procedures had been used that were established in practice. For this reason, the following dilemma can be raised: should we use the complete equations or will an approximate method that neglects some terms of the complete equations and allows the problem to be solved sufficiently be sufficient? The answer to this question is obtained by analyzing these simplified processes, their advantages and disadvantages. Among the most common we have:

Hydrological methods, which consider exclusively the continuity equation in their formulation, such as the modified Puls or Muskingum methods. They are the simplest process in relation to the calculation effort they require, and generally involve a transposition of traditional procedures from other fields of Hydraulics and Hydrology. Although they are easy to implement, in their definition they may require a series of parameters that are difficult to estimate. For example:

The fact that the balance of forces and the failure to consider the actions on moving water means that not all hydraulic phenomena occurring in a drainage network can be represented. For all these reasons and given the existence of other more complete alternatives, their use would end up being discouraged.

The kinematic wave approximation, which ignores the inertial and pressure terms in the dynamic equilibrium equation, considers the action of the forces of gravity and friction to be predominant. It can be accepted as a good approximation to reality provided that the drainage network is dominated by steep slopes, greater than 1%, with rapid flows. However, there should not be any reflux effects between the concurrent collectors at a node, since this formulation does not allow the reproduction of such effects. Another limiting point is the impossibility of modelling the lamination of the flow hydrographs (reduction of the maximum flow in its circulation along the collector). Any lamination obtained by this method is exclusively attributable to numerical effects. This situation, in the case of analyzing networks of great length (several kilometers) and with reduced slopes, can lead to overestimating the flow results. The kinematic wave formulation is incorporated into different commercial models, either as the main calculation process or as an alternative calculation to choose from among others, in the case of requiring approximate results of the overall behavior of a network (Singh, 2001).

4. Results

4.1. Calculation in permanent regime

Traditionally, the dimensioning of the collectors has been carried out using Manning-type formulas considering a permanent and uniform regime:

Constant depths and speeds throughout the collector. It is evident that this calculation hypothesis does not take into account the mutual interferences between collectors and therefore its application will only be justified in cases where said interferences do not condition the hydraulic behavior. This circumstance may occur, for example, in the central part of a collector of great length and steep slope.

Another possibility is the study in a gradually varied steady state (backwater curves) considering maximum flow. This allows the incidence of the boundary conditions on the hydraulic behavior of the collector to be taken into account (for example, levels at the downstream end). Given the difficulties in obtaining the correct hydrograph and the complexity of the calculation in a non-steady state, the correct application of backwater curves can in many cases provide an adequate degree of precision for the diagnosis of a network and the design of actions. In our opinion, it is more advisable to reduce the rigor in the type of calculation (for example, use the theory of backwater curves) and require more precision in the information on the geometry of the network than the other way around. In many cases, the drainage capacity of a network is limited by the existence of a small section of poorly designed collector. Quantifying the incidence of this anomaly and establishing criteria to resolve it does not normally require the simulation of the entire network in a variable state, but rather simple calculations in a steady state and the application of engineering common sense.

Obviously, calculation in a steady state is not possible when it is necessary to know the propagation of the hydrograph, as occurs when considering the existence of deposits or lamination ponds. In short, in many cases a simulation in a gradually varied steady state (stagnation curves) is sufficient to analyze the hydraulic behavior of a network and define actions to improve it Dolz (1987) and Gómez *et al*. (1992).

4.2. Data input, output and analysis

The complexity of the geometry of a collector network makes it necessary to facilitate its incorporation into the numerical model as much as possible. Likewise, the volume of results obtained (draft and flow values in numerous sections of the network and over a long period of time) justifies the need for the model to devote special attention to the analysis of results. If these capacities exist to establish a comfortable and agile dialogue with the computer, the usefulness of the model for the analysis of the hydraulic behavior of a network and the study of alternatives to improve said behavior will be greatly enhanced. This is currently possible thanks to the graphic screens and software available for use. However, as has already been previously mentioned, the great variety of geometries and the enormous number of possible hydraulic phenomena in the movement of water in a network make it very difficult to develop software that contemplates this wide range of cases.

Finally, it is important to note that it is of great interest that the selection of the value of the parameters to be introduced into the model and the analysis of the results be carried out by technicians with a clear engineering profile who are familiar with the characteristics of the network and have a good physical knowledge of the hydraulic phenomena present in it. It is important to avoid, as frequently happens, that numerical modelling is entrusted to people who are experts in modelling but who are unaware of the physical reality linked to the network and its hydraulic behavior. This is even more important when the results of the modelling will be used for the design of expensive infrastructure works that require a clear knowledge of Hydraulic Engineering in order to optimize their design.

Conclusions

For the operation of a drainage network to be in accordance with its initial design, it is essential to verify the planned flow rate scheme for the network. The design of collectors has been carried out based on a hydrological study that predicted flow rates or hydrographs for entry at specific points in the network. If these forecasts are not met, for example because we are not able to ensure that the runoff water enters the network at the planned sites, the entire initial flow rate scheme changes and the hydraulic behavior of the network is significantly modified. Insufficient collection works can cause a transfer of flow between urban basins, overloading collectors that would in principle be well designed if the water were introduced into the network at the planned points, and also cause opposite situations such as collectors operating well below their maximum drainage capacity due to the lack of flow input.

Urban development significantly alters the hydrology of the basins where it occurs. In particular, the drainage capacity of the stormwater drainage network is reduced and extreme flows and runoff volumes increase. These phenomena are very common in different areas of Spain and in particular on the Mediterranean coast where, in addition to intensive urban development that does not respect hydrology, there is relatively frequent rainfall of high intensity.

All of the problems described above give rise to serious flooding problems in urban areas. Solving these problems requires a strong political will to promote the presence of Hydrology as a tool for Land Use Planning and to find solutions to existing problems. Normally, the only solution to solve drainage problems in densely populated cities is to increase the drainage capacity of the collector network. This requires high investments, which demand detailed knowledge of the different phenomena associated with the drainage of rainwater in urban areas. In particular, it is of interest to analyze the hydraulic behavior of collector networks.

There are currently no major limitations in the capacity of numerical models to accurately simulate this behavior, nor in the computing capacity of computers. The limitations are in the information available regarding the geometry of the network and in the field data required to determine the flow rates. It should be noted that, sometimes, the quality and quantity of this information does not justify the use of high-performance numerical models, but rather advises the performance of simple calculations by technicians with adequate knowledge of the collector network and the hydraulic phenomena that occur there. We see, therefore, that the improvement of knowledge in the field of urban drainage is largely conditioned by the availability (in quality and quantity) of rainfall data, as well as the degree of knowledge of the basin and the collector network. It is necessary to improve this information if we wish to be able to take advantage of the great possibilities currently offered by numerical modelling to analyze the different phenomena involved in urban drainage and thus be able to optimize the high investments to be made in infrastructure.

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