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MOBESCA v.2.0: a new software to design surface drainage systems in urban catchments

MOBESCA v.2.0 : Un nouveau logiciel pour la conception de systèmes d'avaloirs en milieu urbain

Beniamino Russo*, Angel Villanueva**, Marc Casas**

* Technical School of La Almunia (EUPLA), University of Zaragoza, Mayor St., La Almunia de Doña Godina, 50100, Zaragoza, Spain (brusso@unizar.es)

** Clavegueram de Barcelona S.A. (CLABSA), Acer 16, 08038, Barcelona, Spain (Angel@clabsa.es; Mcasas@clabsa.es)

RÉSUMÉ

Les systèmes d'assainissement pluviaux sont généralement conçus pour faire face aux risques et dommages causés par les orages. Pour cela, une bonne conception des réseaux d'assainissement de surface est essentielle. Les éléments clés à connaître sont la fréquence des tempêtes, l'écoulement au niveau des caniveaux, et, surtout, la capacité d'infiltration des avaloirs. Lorsque le réseau d'assainissement de surface est négligé, l'eau n'entre pas dans le réseau à l'endroit prévu, et la capacité de traitement du système n'est pas satisfaisante malgré des investissements élevés. Pour cette même raison, la modélisation du comportement des systèmes d'assainissement pourrait ne pas être réaliste. En 2006, un logiciel spécifique, MOBESCA v.1.0, a été développé par CLABSA pour servir de support lors de la conception des avaloirs dans les nouvelles zones urbanisées, au moyen de critères de risque variables (selon les choix des différentes communes). Le logiciel est basé sur la méthode rationnelle, et sur des expériences pour estimer l'efficacité hydraulique des avaloirs, réalisées par l'Université Polytechnique de Catalogne. Plus récemment, une deuxième version du logiciel, MOBESCA v.2.0, a été élaborée. Il se base sur l'approche 1D de la vague cinématique et peut être utilisé pour étudier le comportement hydraulique des réseaux d'assainissement de surface existants, pour pouvoir proposer des améliorations en fonction de critères de risque spécifiques. Le logiciel accepte l'entrée de données telles que les hyétogrammes ou les courbes d'intensité, de durée, de fréquence, et peut simuler un débit variable.

ABSTRACT

Stormwater drainage systems are typically designed to prevent the risks and damages due to the floods produced by heavy storm events. Moreover, an efficient surface drainage system is an essential condition to guarantee a safe vehicular and pedestrian circulation. A good design of surface drainage system requires a satisfactory knowledge in terms of storm frequency, gutter flow and, above all, inlet hydraulic capacity. Without an adequate regard for the surface drainage system, modeling of sewer systems behavior could not be realistic and expensive hydraulic structures could not work satisfactorily only because water is not getting inside the network where it was supposed to. In 2006, with the aim of design inlet systems for new urbanized areas, on the base of flood hazard criteria previously established by Public Administrations, a specific software, MOBESCA v.1.0, was developed by the company Clavegueram de Barcelona S.A (CLABSA). The software allowed calculating inlet spacing on the basis of the rational method and some experimental expressions proposed by the Technical University of Catalonia to estimate inlet hydraulic efficiency. Recently a second version of the software, MOBESCA v.2.0, has been developed. It is based on the 1D kinematic wave approach and may be used to study the hydraulic behavior of existing surface drainage systems and to propose new solutions according to specific flood hazard criteria. The software accepts input data like hyetographs or Intensity Duration Frequency curves and carries out simulation considering not steady flow.

KEYWORDS

Flood hazard, hazard criteria, inlet systems, kinematic wave approach, MOBESCA v.2.0 software.

1 INTRODUCTION

1.1 The problem of flooding in urban catchments

Cities and urban communities experience ever growing problems related to urban flooding. As a watershed becomes more populated, natural surfaces that absorbed water and recharged groundwater supplies, are covered with hard and impervious surfaces. An increase of impervious areas determines a growth in terms of surface runoff. Moreover the lower roughness of the urban surfaces produces an increase in terms of water velocities circulating over the catchment (the time of concentration decreases). After heavy storm events, floods often occur faster and with no warning. Such floods can occur in a matter of minutes generating hazard for vehicles and human subjects as well as significant damage to properties. This type of flood can appear very locally and may be rather independent of the flows and levels in natural streams and rivers. In fact it can be only due to the excess of runoff not adequately discharged into the drainage system and concern a limited urban area that, because of its population and properties density, is critically vulnerable.

1.2 Hydraulic performance of surface drainage systems

Sewer systems are typically designed as conveyance system to avoid nuisances and flow damages that could be created during heavy storms (Butler and Davis, 2004). In fact, in case of heavy storm, runoff that is not conveyed into the sewer system by drain elements can increase up to generate dangerous values of flow depth and velocity for the vehicular and pedestrian circulation and nuisances for the urban activities. Water on the pavements can interrupt traffic, reduce skid resistance and increase potential of hydroplaning.

Many urban communities and cities present a great number of surface areas directly connected to the sewer system (roofs, terraces, etc.). In these cases the surface runoff drainage is generally provided and assured. In others areas as roadways, sidewalks, open squares and other impervious areas, stormwater is conveyed into the sewer system through surface drainage structures placed in roadway gutters, parking lots and other locations.

The hydraulic performance of a surface drainage structure regulates the amount of circulating discharge that may be intercepted by the surface drainage structures and is conveyed into the sewer system and the remaining flow rate that is not intercepted and circulates over the land. The hydraulic behavior of this type of elements depends on its geometry as well as the characteristic of the gutter flow and the geometric characteristics of the street. Specifically the hydraulic efficiency can be defined as the ratio of the discharge intercepted by the structure to the total discharge approaching to it:

$$E = \frac{Q_{int}}{Q} \quad [1]$$

where:

E is the hydraulic efficiency

Q_{int} is the discharge intercepted by the surface drainage structure

Q is the circulating discharge approaching to the surface drainage structure.

Flow that is not intercepted by the structure, *carry-over* (Guo, 1997) or *bypass discharge* (Nicklow and Hellman, 2004) is defined as follows:

$$Q_b = Q - Q_{int} \quad [2]$$

where Q_b is the carry-over discharge.

1.3 The state of the art in this field and the need of MOBESCA I

Actually very poor information and techniques are available to estimate the hydraulic performance of the surface drainage structures in urban areas. Many times engineers don't dispose of any hydraulic information about drainage inlets, because of the catalogues published by the foundries and the norms concerning this type of elements (as such as the European Norm EN124) only provide information related to bearing features, whit no regard to the performance of the hydraulic design, that

is the only factor able to improve grate efficiency and, consequently, to reduce runoff circulating on the streets (ECS, 1994). In this framework, in 1997, Clavegueram de Barcelona S.A. (CLABSA), a mixed company for the management of the sewer systems of Barcelona, and the Hydraulic Department of the Technical University of Catalonia (UPC) promoted a new research line in the field of the road grates efficiency. The most common grates used in the city were tested in a laboratory by a platform that can simulate the hydraulic behavior of a lane 3 m wide. On the base of these tests and the studies of the HR Wallingford (Spaliviero *et al.*, 2000) empirical expressions were achieved and a methodology based on the rational method was elaborated (Russo *et al.*, 2007). MOBESCA v.1.0 was developed in 2006, on the basis of this methodology, with the specific objective to calculate inlet spacing according to a scientific approach and to several flood hazard criteria established by a Public Administration. During the last years, MOBESCA v.1.0 represented, for the engineers of Barcelona Municipality, an adequate tool to design inlet systems in a very quick way (Russo *et al.*, 2007).

1.4 Why MOBESCA v.2.0? The general objective of MOBESCA v.2.0

As said in the previous section, MOBESCA v.1.0 can be used to design inlet systems related to new urbanizations and in this case it represents a valid tool. On the other hand, MOBESCA v.1.0 presents several important limitations, such as the following:

- The code is based on the rational method (so on its hypothesis of storm duration equivalent to the time of concentration of the drainage area and uniform rainfall intensity in the whole analyzed domain);
- A necessary hypothesis that must be assumed for the inlet system design is the lack of discharges coming from upstream the system;
- The software considers only one type of inlet for the design of the surface drainage system;
- The software considers a single street with uniform longitudinal slope and symmetric widths of lanes and sidewalks respect to the carriageway axis.

It is clear that MOBESCA v.1.0 cannot be considered as a valid tool for the analysis of the hydraulic behaviour of an existing urban catchment in case of storm events. MOBESCA v.2.0 was born in this framework with the aim to analyze in a very detailed way the hydraulic behaviour of existing urban catchments in case of storms. The general requirements of MOBESCA v.2.0 were the ability to know flow parameters (flow depth and velocity) in any point of the catchments according to the real surface drainage system existing in the analyzed domain and the possibility of proposing new inlet systems to reduce circulating runoff for the specific flood hazard criteria fulfilment (maximum flow depth and velocity) established by the Public Administration.

2 METHODS

2.1 Hydrologic and hydraulic approach used for MOBESCA v.2.0 development

The hydraulic behaviour of an urban catchment formed by a series of streets may be studied through procedures considering 1D flow propagation, while the rainfall runoff transformation may be treated in different ways. If surfaces as terraces and roofs are directly connected to the sewer system, an urban catchment can be represented as a series of sidewalks and roads that compose the hydrological subcatchments. Every subcatchment should be characterized through its own geometrical and physical parameters (longitudinal and transversal slopes, wide, roughness, etc.). Each variation in term of physics or geometric parameters determines a hydrological limit between two adjacent subcatchments. Moreover each inlet represents a hydrological limit too, such as a crossroads where hydrographs proceeding from different streets will be combined (Gómez *et al.*, 2009).

Once an urban catchment has been divided into an adequate number of subcatchments, for each of them it is necessary to define a valid approach to simulate the rainfall runoff transformation and the flow propagation. For MOBESCA v.2.0, 1D kinematic wave approach was chosen, considering that many urban surfaces can be represented as regular planes (i.e. street lanes, sidewalks, terraces, etc.) characterizing them through geometric and physical parameters (defining area, wide, roughness and slope). Normally in these cases surfaces are almost impervious, so it is possible to neglect the infiltration losses (Fig. 1).

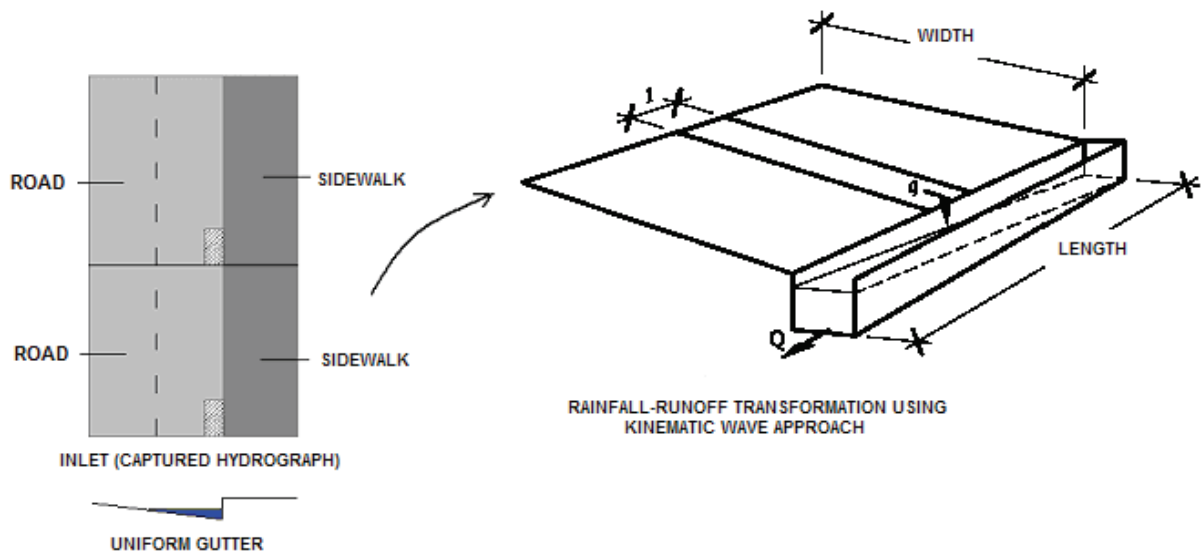


Figure 1: Schematization of an urban street using the kinematic wave approach

Actually one of the most common approach used in urban drainage, is the kinematic wave model. It formulates the hypothesis of a relationship between discharge and flow depth at each point in the plane (Fig. 2). 1D approach can be justified considering the one-dimensional flow pattern in the gutter above all when longitudinal and transversal slopes are pronounced.

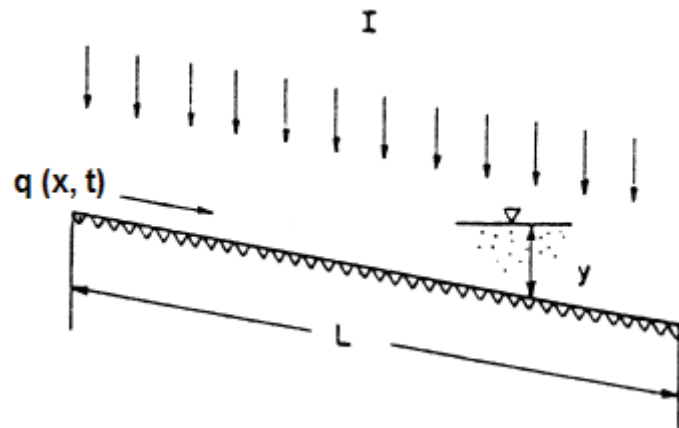


Figure 2: Overland flow on a plane where I is the rainfall intensity, q is the specific circulating flow, y is the hydraulic depth, L is the plane length, x is the longitudinal coordinate and t is the time

The most complete physically based model for the analysis of flow propagation in a one-dimensional channel is represented by the solution of the continuity equation coupled with the momentum equation. The formulation of these equations is due to Adhémar Jean Claude Barré De Saint Venant (1871). According to a 1D approach, Saint Venant expressions can be expressed as:

$$A \frac{\partial v}{\partial x} + v \frac{\partial A}{\partial x} + \frac{\partial A}{\partial t} - q_i = 0 \tag{3}$$

$$\frac{\partial y}{\partial x} + \frac{v}{g} \frac{\partial v}{\partial x} + \frac{1}{g} \frac{\partial v}{\partial t} = S_{ox} - S_{fx} \quad [4]$$

where:

A is the flow section

v is the flow velocity

q_l is the lateral inflow for unit length of channel

x is the coordinate in the flow direction

t is the time

y is the water depth

g is the gravity acceleration

S_{ox} is the channel bed slope in the x direction

S_{fx} is the energy line slope

The couple of equations [3] and [4] constitute a first order partial derivate system that cannot be solved through analytic solutions and requests the adoption of numerical integration methods. For this reason, some simplifications can be used in order to reduce the computational effort maintaining the fundamental characteristic of the flow propagation phenomena. The momentum equation [4], is also called *dynamic equation*, includes a term related to the pressure forces generated by the variation of water depth, the convective acceleration, the local acceleration, a term related to the gravity force and other related to the friction force. Some of these terms may be more significant than others, giving the opportunity for simplifying the momentum equation and generally the couple of Saint Venant equations. In order to reduce computation time, in urban drainage is very common to use a more drastic simplification: *the kinematic wave approach*. According to the kinematic wave approach, the terms related to the pressure forces, and the inertial terms (convective and local accelerations), are neglected and Saint Venant equations are normally expressed, in urban drainage, as:

$$\frac{\partial q_x}{\partial x} + \frac{\partial y}{\partial t} = q_{rain} \quad [5]$$

$$S_{ox} = S_{fx} \quad [6]$$

where:

q_x is the circulating discharge per unit width of the plane in the x direction

q_{rain} is the rainfall ($q_l = q_{rain}$)

Using Manning's equation, it is possible to express S_{fx} as:

$$S_{fx} = S_{ox} = \frac{n^2 q_x^2}{\frac{10}{y^3}} \quad [7]$$

where:

n is the Manning's roughness coefficient.

The equation [7] can be written as:

$$q_x = \frac{S_{ox}^{\frac{1}{2}} h^{\frac{5}{3}}}{n} = \alpha_{kw} \cdot y^{m_{kw}} \quad [8]$$

where:

$\alpha_{kw} = \left(\frac{S_{0x}^{\frac{1}{2}}}{n} \right)$ and $m_{kw} = \left(\frac{5}{3} \right)$ are the kinematic wave parameters.

Combining equations [5] and [8] and using the previous kinematic wave parameters, it is possible to obtain the kinematic wave equation:

$$\frac{\partial y}{\partial t} + \alpha_{kw} m_{kw} \cdot y^{m_{kw}-1} \frac{\partial y}{\partial x} = q_{rain} \quad [9]$$

The kinematic wave does not attenuate, but translates at constant celerity. In every instant and every section the flow is uniform, even if the water depth can vary in each section according to the wave translation. Equation [9] can be solved through an approximation of finite differences once planes parameters have been adequately defined. Ponce *et al.* (1978) quantified the range of application of the simplifications. Particularly for the kinematic wave it was demonstrated that kinematic wave approach is reliable if:

$$D_w \cdot S_{ox} \frac{v_0}{y_0} > 171 \quad [10]$$

where:

D_w is the duration of the flood wave (s)

v_0 is the initial flow velocity (m/s)

y_0 is the initial flow depth (m/s)

The main equations derived above are usually solved using finite difference method, involving dividing distance and time to small discrete steps. Without entering in the details of different numerical solution methods, it is important to underline that these approaches can suffer from various form of inaccuracy, especially when the input data contain rapid changes. The problems are generally overcome by selection of appropriate solution methods and suitable time and distance steps. Explicit schemes usually have to satisfy the Courant condition to maintain stability:

$$\frac{\Delta x}{\Delta t} > c' \quad [11]$$

where c' is the wave celerity.

2.2 Hydrological schematization of the catchment used by MOBESCA v.2.0

As said in the previous section, the most important requirement of MOBESCA v.2.0 was the ability to analyze the hydraulic behaviour of an existing urban catchment formed by a series of streets (normally surfaces as terraces and roofs are directly connected to the underground sewer system). MOBESCA v.2.0 assumes that a hydrological catchment can be divided into several subcatchments whose hydrological limits are characterized by:

- The presence of inlets (at one or both sides of the streets);
- Geometric changes in terms of carriageway (changes of lane or sidewalk widths, change of longitudinal or transversal slopes, etc.);
- Changes in terms of pavement roughness;
- The presence of crossroads.

2.3 Characterization of a subcatchment in MOBESCA v.2.0

MOBESCA v.2.0 considers a subcatchment as the drainage area between two hydrological limits defined by the presence of one of the situation aforesaid. According to the kinematic approach, the

flow propagation model is based on the hypothesis that all the unitary flows related to all the involved planes (normally two sidewalks and two planes corresponding to a half of roadway) discharge into the gutters where propagation is simulated considering previous routing equations (see eq. [7] and [9]) (Fig. 3). When a surface drainage element is reached, an intercepted hyetograph is captured from the gutter according to some empirical expressions achieved by Gómez and Russo (2005) during experimental campaigns carried out in the hydraulic laboratory of the Technical University of Catalonia (following UPC). Specifically these expressions allow to deduce the captured hyetograph on the base of the discharge approaching the inlet, the geometry of the grate and the geometry of the gutter. In this way each surface drainage elements can be hydraulically characterized by a curve approaching flow (Q) vs. intercepted flow (Q_s).



Figure 3: Representation of an urban subcatchment composed by 4 planes discharging to uniform triangular gutters. In this case the subcatchment hydrological limits are represented by the section where inlets are located

3 RESULTS

3.1 General features of MOBESCA v.2.0.

MOBESCA v.2.0 is structured into the following 6 different packages that compose the main software:

- “Inlet package” for the inlet hydraulic characterization;
- “Hydrology package” for the storm event characterization;
- “Catchment package” for the geometric and physical characterization of the subcatchments;
- “Hazard criteria package” for the flood hazard assessment in the whole analyzed domain;
- “Simulation package” for the simulations of the diagnostic phase (analysis of the hydraulic behaviour of the catchment) and the prognostic phase (analysis of the hydraulic behaviour of the catchment considering the proposal of the new surface drainage system for the hazard criteria fulfilment);
- “Results package” for the representation of the results in terms of tables and graphics.

3.1.1 Inlet package

This package allows to define the inlet geometry (grate width and length, total area, void area, number of longitudinal, transversal and diagonal bars, etc.) for the estimation of its hydraulic performance

during the simulations. It is possible to introduce directly some empirical coefficients in case of tested grates according to the UPC methodology (Gómez and Russo, 2005). If inlet images are available in the data base of MOBESCA v.2.0, it is possible to view them in a specific framework of this section (Fig. 4). The software analyzes the hydraulic performance of all existing inlets located in the domain, and of the new inlets proposed by the user for the hydraulic rehabilitation of the catchment necessary for the accomplishment of the hazard criteria in the prognostic phase.

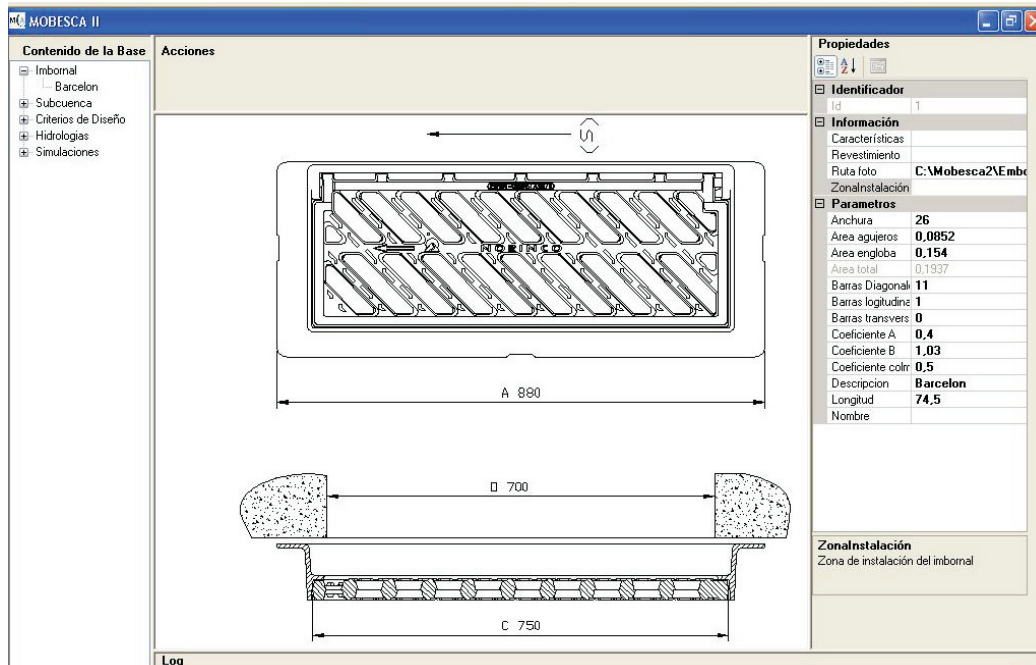


Figure 4: "Inlet package" with a view of "Barcelona" grate

3.1.2 Hydrology package

MOBESCA v.2.0 presents an important improvement respect to the previous version in the field of rainfall data input. In fact the user can introduce a real storm event, or can define a storm event through a specific design hyetograph or an Intensity-Duration-Frequency (IDF) curve (in this case MOBESCA elaborates a project storm through the Chicago discretized method). The user can define the position of the peak hyetograph according to some proposed rainfall patterns. In this section it is possible to introduce a runoff coefficient in order to take into account hydrological losses.

3.1.3 Catchment package

This package allows to elaborate the model defining the different subcatchments in terms of geometry, physical parameters and connectivity among the elements. In this section it is possible to define "Subcatchment element" (defining all the planes that compose it and the geometry of the gutter) and the "Combo element" representing a crossroads where hydrographs coming from different subcatchments are combined.

3.1.4 Hazard criteria package

The flood hazard level is commonly related to flow depth (y) and velocity (v). In the last years several authors have proposed different maximum values of flow depth and velocity in order to express the hazard level in case of flooding (Abt *et al.*, 1989; Kelman, 2002). A specific section of the software is dedicated to the "flood hazard criteria package" where the user can introduce the maximum values of flow depth and velocity that MOBESCA v.2.0 will use for the flood hazard assessment in the diagnostic phase and for the proposal of the new surface drainage system (in this case the maximum circulating flow in the street will be limited through the fulfillment of flood hazard criteria).

3.1.5 Simulation package

The MOBESCA “simulation package” allows to run the simulations concerning the diagnosis phase (hydraulic behaviour of the analyzed catchment according to the existing surface drainage system) and the prognosis phase (hydraulic behaviour of the analyzed catchment according to a new surface drainage system proposed by the software on the base of a specific algorithm for the calculation of the minimum inlets spacing and the accomplishment of the adopted hazard criteria). In the following figure two catchment schematizations are represented in a MOBESCA v.2.0 window. In the Fig. 5 a catchment representation with several subcatchments and two crossroads is represented in the diagnostic phase (on the left). In red it is showed a subcatchment with high flow parameters (hazard criteria are not accomplished). On the right of Fig. 5 the new model proposed by MOBESCA is represented. It is possible to see that the “red subcatchment” of the diagnostic phase has been subdivided into two new “blue subcatchments” in the prognosis. Subdivisions of catchment occur changing the initial hydrological limits through inlets placing.

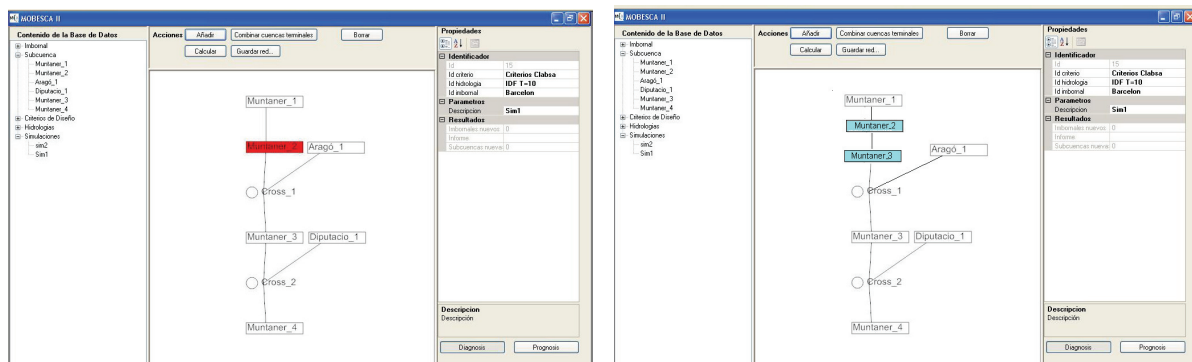


Figure 5: Hydraulic behaviour of a catchment in the diagnosis (on the left) and prognosis (on the right) phases.

3.1.6 Results package

MOBESCA v.2.0 provides a report including the following documents:

- Short summary of the hydrological data (hyetograph, IDF curve, etc.), criteria adopted for the flood hazard assessment, inlet data for the hydraulic rehabilitation of the catchment, etc;
- Table of the maximum flow parameters in each subcatchment (flow discharge, flow depth, velocity, etc.) remarking hazardous conditions if these occur;
- Graph of the model in the initial phase (diagnosis) remarking in red the hazardous conditions;
- Table of the maximum flow parameters in each subcatchment for the proposed model considering the new surface drainage system. In this case the table will present more subcatchments respect to the initial table, in fact other subcatchments will be generated through the definition of new hydrological limits related to the new placed inlets;
- Graph of the model proposed by MOBESCA with new subcatchments proceedings from the subdivision of all subcatchments that presented hazardous flow values in the diagnosis phase.

3.1.7 Uncertainty of the modelling results

The software is based on a robust algorithm for the hydrologic and hydraulic modelling of the involved processes and several empirical equations concerning the hydraulic performance of the inlets. Notwithstanding uncertainty about modelling results could be generated by the following hypothesis on which MOBESCA v.2.0 is based:

- MOBESCA v.2.0 was designed to simulate essentially rainfall-runoff processes of tree-type systems, which is ineffective to simulate looped network. In case of subcatchments with low physical slopes, surface runoff could not present a main direction at the crossroads.
- Kinematic wave approach is not advisable in case of low road gradients
- The software only considers rectilinear streets with uniform (triangular) gutter sections.

4 CONCLUSIONS

Effective drainage of urban streets is essential to guarantee a safe vehicular and pedestrian circulation in case of storm events; in fact stormwater on the pavements can interrupt traffic, reduce skid resistance and increase potential of hydroplaning. Generally surface runoff is not conveyed entirely by storm sewers for the lack of an efficient system of drainage inlets and can increase up to generate dangerous values of hydraulic parameters (flow depth and velocity).

Software MOBESCA v.2.0 has been developed by CLABSA to analyze the hydraulic behavior of urban catchments in case of storm events and to assess the flood hazard related to the circulating runoff. It can be used for the analysis of existing surface drainage systems and for the design of new inlet systems according to several flood hazard criteria and a specific methodology for the estimation of the hydraulic performance of the inlet system.

In case of low gradients and no rectilinear roads, MOBESCA v.2.0 could be ineffective to simulate the hydraulic behavior of the streets in case of flooding. In these cases a two-dimensional analysis is advisable.

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