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Surface runoff in urban catchments: morphological identification of unit hydrographs from urban databanks

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Abstract

In this study, Urban Unit Hydrographs (URBS-UHs), are derived from the analysis of an urban databank for three urban catchments with surface areas ranging from 18 to 180 ha. The geometry of property lots, streets and sewer networks allows for an explicit description of the runoff production areas and their downstream flow channels. The Manning's equation is used to compute the flow velocity along the identified channels under rainfall intensities that we related, for purposes of convenience, to return periods. The shape and the scale of the URBS-UH are primarily influenced by catchment morphology, channel roughness and rainfall return period. As a consequence, the transfer function is not unique but rather depends on rainfall characteristics. The URBS-UHs identified without any parameter calibration are encouragingly similar in shape and scale to the unit hydrographs derived from rainfall-runoff measurements over the three studied urban catchments.

Keywords: Storm drainage; Urban databank; Unit hydrograph; Travel time; Geographical information system

1. Introduction

The ongoing expansion of urbanized areas has placed increasing emphasis on related water management problems such as flooding and pollution control. Population densities and the size of these areas have led to considering the detailed behavior of water drainage systems at various scales. Changes in both land use and water policy have made it necessary to take into account the rapidly-evolving morphology of urban catchments. Addressing urban water management issues in an efficient manner thus requires special adaptation of hydrological modeling practices.

The widespread development of multi-purpose Urban DataBanks (UDB) has opened up new avenues to the field of urban hydrology, by introducing a meter-scale morphological description of the city. UDB first appeared in many European cities with the modernization of urban cadastre records through Geographical Information System (GIS). The urban cadastre[1] is a public map of the extent and ownership of land serving as a basis of taxation. The unit element

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[1] From the Late Greek *katastikhon* meaning register—The American Heritage® Dictionary.

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is the property lot or cadastral parcel (see Fig. 1). The public domain, encompassing streets, places and parks is also represented. Recent UDBs include a greater number of layers superimposed on this initial information. Private buildings and gardens are also detailed within the cadastral parcels, with in some instances the height and type of building even being available. The street network is regarded both as a plane (street and pavement) data of a known altitude and as a line object in relation to the main undergrounded utility networks: energy, communication, storm and waste waters. The altitude levels of these networks are available in some databanks. Green surfaces constitute a specific data layer. Part of the natural hydrographic network is represented (i.e. the rivers and lakes located in the urban area). To an increasing extent, related raster images from aerial photography or satellite remote sensing have become available. UDBs and GISs are of considerable use in almost all the aspects of urban development (Sui, 1998; Laurini, 2001). City planners consider cadastral parcels and street networks as reference elements in analyzing the urban structure (Lynch, 1960). From a hydrological standpoint, UDBs are attractive tools for at least two reasons: they readily provide information on the morphology of catchments at a level of detail seldom accessible in hydrological studies, and they maintain a record of the evolution in basin morphology by virtue of being regularly updated and documented. They also facilitate the description of

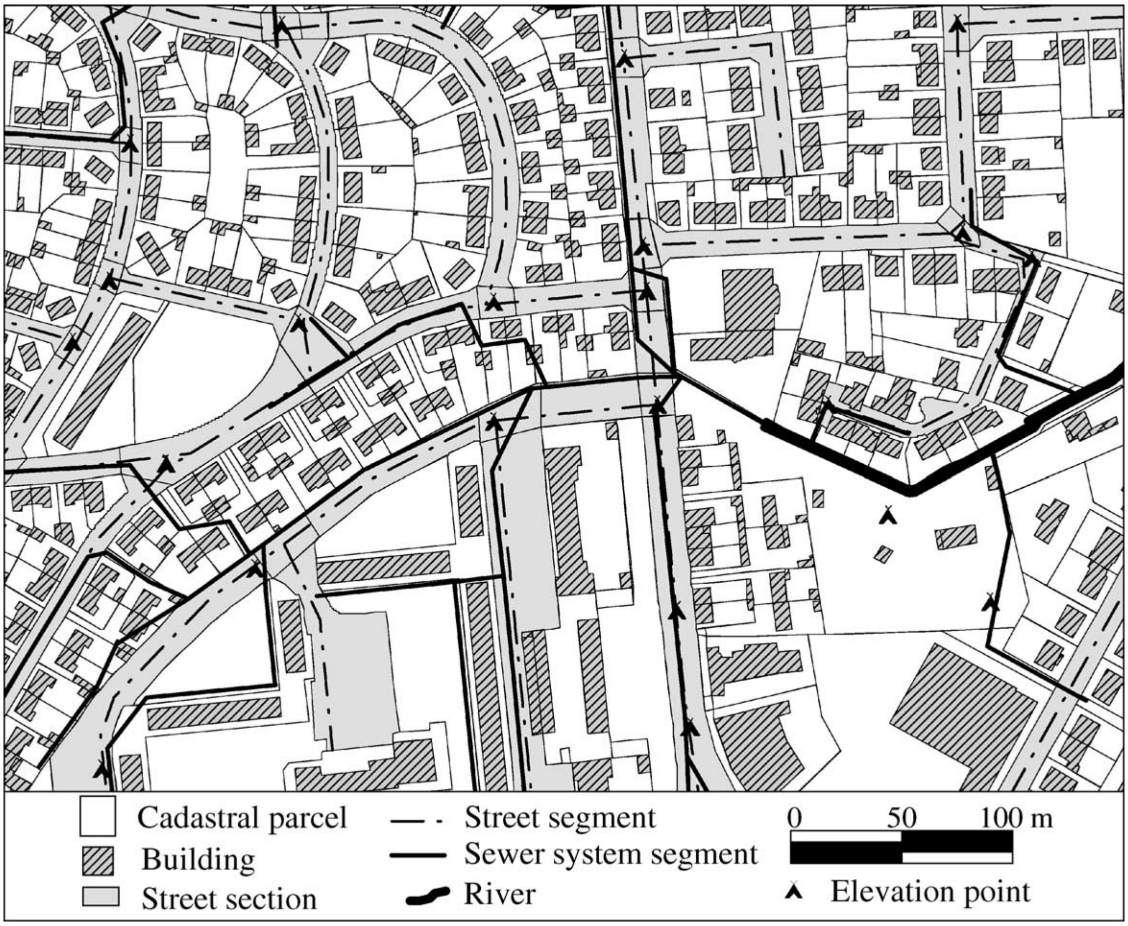

Fig. 1. Map representing the different layers of an urban databank (UDB) used in the present study. The represented catchment is located in the west side of the Nantes metropolitan area in France.

local-scale water behavior in the urban area and its evolution over time.

The aim of this study is to investigate the extent to which UDB information may be of help in reconstructing the rapid hydrological response of urban catchments, represented by their unit hydrographs. In natural settings, the notion of linking the hydrological response of a catchment to its geomorphology has given rise to a complete body of studies over the last two decades. The Geomorphologic Instantaneous Unit Hydrograph (GIUH) was first introduced using probabilistic concepts (Rodriguez-Iturbe and Valdes, 1979; Gupta et al., 1980). The proposed theory assumes that both the structure of the river drainage network and the travel time of water particles adhere to probabilistic distributions. The same theoretical elements subsequently led to considerable advances in our understanding of runoff–terrain interaction (Rodriguez-Iturbe and Rinaldo, 1997) and of runoff regionalization (Gupta and Waymire, 1998). More recently, similar studies of GIUH have relied on the explicit description of the stream network derived from digital elevation models (see for instance Olivera and Maidment (1999)). In urban settings, the use of GIS-related information for rainfall-runoff modeling is yet not usual; the areas drained by a sewer system were defined and estimated by property blocks connected to the sewer inlets (Grayman et al., 1982; Djokic and Maidment, 1991; Greene and Cruise, 1995). The water flow paths at the surface were identified from high-resolution digital elevation models (Smith and Brilly, 1992), and the drainage pipes were conceptualized as 'open thalwegs' (Zech et al., 1994; Rodriguez et al., 2000). The most widely used models: SWMM (Huber and Dickinson, 1988) or MOUSE (Danish Hydraulic Institute, 1998) combine an hydrological stage which simulates the hydrographs from small urban catchments with the propagation of these hydrographs in the main pipe network usually based on St-Venant equations. The modeling of the rainfall-flow transformation is less detailed and often calls synthetic hydrographs, such as the widely used linear reservoirs (Rao et al., 1972; Chocat, 1997, p. 867) whose representativeness is questionable.

This paper is organized as follows. In Section 2 we describe the guidelines of the study and Section 3 displays how these guidelines are followed in practical terms in order to derive the geometry of the water flow paths from an urban databank. Section 4 presents the modeling of Unit Hydrographs (URBSH-UHs) over an urban catchment from urban data banks. Section 5 is devoted to presenting the case study. The sites we selected for illustration are urban catchments located in Nantes, France. In Section 6, we analyze the sensitivity of URBS-UH so as to identify the most influential modeling factors. Section 7 compares URBS-UHs to unit hydrographs derived from rainfall and discharge data series.

2. Modeling principles

In order to derive an Urban Unit Hydrograph (URBS-UH) from the information available in an urban databank, we have followed three basic guidelines.

2.1. Water flows over impervious surfaces and in sewer networks dominate the rapid response

In urbanized areas, the main contribution to the catchment response stems from water flows over impervious surfaces and in undergrounded storm drains. This hypothesis is assumed valid for intense rain events, insofar the imperviousness coefficient of a catchment usually serves as runoff coefficient in design studies. In the presence of saturated soil, excess rainfall from natural surfaces can combine with adjacent impervious surface flows and contribute to runoff. The groundwater drained by the system of undergrounded pipe networks and their intrusion in collectors via water-tightness defaults also participates to urban water transfers (Belhadj et al., 1995). In this study, we assume that the rapid response of urban catchments essentially results from direct runoff on impervious areas. This hypothesis proves to be even more plausible since natural soils are seldom encountered (Berthier et al., 2003) and rain events display a moderate to high range of rainfall intensities. The term 'surface runoff' will be used herein to designate these flows.

2.2. UDBs indicate the geometry of flow paths

Considered in a detailed way, surface runoff first develops on rainfall collecting surfaces (e.g. building roofs and paved surfaces belonging to the private and public domain, such as courtyards, parking lots or streets). It encompasses laminar or multi-channeled flows over impervious surfaces, as well as concentrated flows in gutters and undergrounded pipes draining roofs and other paved surfaces toward the street. Runoff on the street concentrates in gutters along the sidewalks under normal flow conditions. This concentrated flow is limited downstream by the inlets of the underground sewer system, in which the water flows until the cachment outflow or a natural channel.

The aforementioned flow paths always follow well-defined geometrical features like surfaces, gutters or pipes. In this study, we explicitly use the geometric information available from UDBs in order to model the propagation of surface runoff. The word *explicit* herein means that the geometrical support for water movement is known in detail, as opposed to the case where an *implicit* description is provided by some theoretical construction law (for instance, Horton's morphological laws). A compromise is obviously required regarding the level of detail with which the geometrical support is described. This compromise depends on the UDB content.

2.3. The runoff flow velocity is variable in space

The assumption of constant flow velocity through the river system has proved to be efficient in reproducing GIUH (Rodriguez-Iturbe and Valdes, 1979; Gupta et al., 1980). In natural settings, considerations on the equilibrium between slope and flow regime help explain why constant velocity is a fairly good approximation: it would result from a compromise between the increase in water depth and the decrease in the upstream–downstream slope (Kirkby, 1993; Rodriguez-Iturbe and Rinaldo, 1997). This assumption is probably invalid for urban settings where the slope, size and roughness of the drainage system do not result from equilibrium considerations but rather from engineering design practice. The difference is probably not so distinct since drainage networks depend, to some extent, on both the upstream drainage area and the natural topography. Nevertheless, in this study, we consider the flow velocity field as a spatial variable depending on the considered flow conditions and available UDB information. Street runoff propagation as well as sewer inlet facilities are seldom studied, although their hydraulic behavior is far from being simple to represent numerically. Meshed collector networks are modeled with complete open channel hydrodynamics equations that describe unsteady flow conditions. These models extend Barré de Saint Venant equations to compressed flow and use parameterizations for special devices (e.g. siphons or thresholds). Their main advantage definitely pertains to rapidly-varying flow in the presence of a complex downstream influence. As regards our problem (i) flow can be considered as the monotonous response to a rain impulse and (ii) the downstream segments can reasonably be considered to accept the outflow of upstream segments. We have thus assumed that simpler constant flow equations applied to both streets and collectors provide equivalent solutions.

3. Geometry of water flow paths in an urban catchment

The second modeling principle stated in Section 2 concerns the compromise between UDB content and the level of detail in the geometrical description of water flow paths. This section provides a closer examination of this description, which is subsequently used to identify the unit hydrograph of an urban catchment. In the UDB used herein, the relevant layers are the cadastral parcels with their buildings and the networks of streets and sewers (Fig. 1). The street and sewer networks yield the geometry of the flow paths downstream from the property blocks. Along these paths, water flow can be represented explicitly. The detail of the pipes and gutters draining the private impermeable surfaces is lacking, thus the flow within property blocks will be parameterized.

Our analysis of the UDB consists of two main stages:

(i) A two-dimensional plane map is drawn-up in Hydrological Elements (HEs) composed of a cadastral parcel and its corresponding portion of street (see Fig. 2).
(ii) A vector map of water flow paths along the street gutters and inside the sewer network is set up

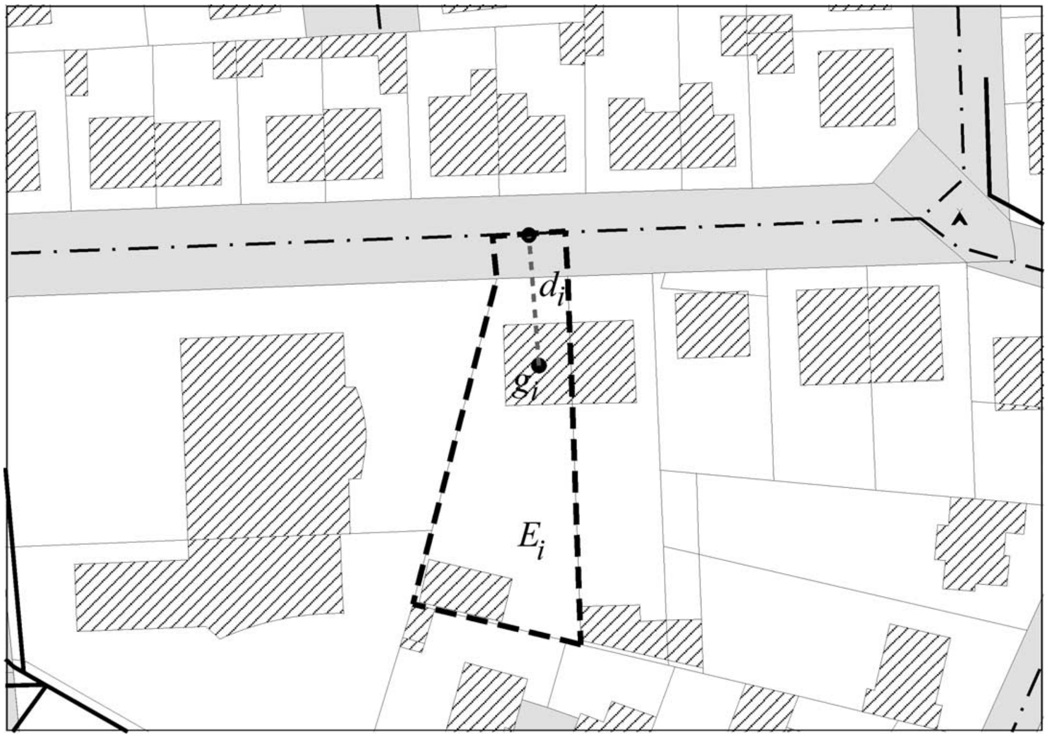

Fig. 2. Detail of the map presented in Fig. 1, providing an example of a Hydrologic Element composed of a cadastral parcel and its adjacent street surface. This cadastral parcel corresponds to a conventional single-family housing plot (830 m^2). The water flow distance d_i, the center of gravity g_i of the HE, and the connection to the adjacent street segment are all represented.

(hereafter referred to as the Runoff Branching Structure (RBS))

Defining the HEs and downstream flow paths constitute the basis of the proposed hydrological modeling approach.

3.1. Hydrological Elements as runoff-concentrating surfaces

Cadastral parcels and street surfaces cover the entire represented space, with the sole exception of natural water surfaces such as rivers. An urban catchment can thus be entirely represented by a set of HEs connected to the RBS. The distribution of street surfaces on cadastral parcels has several advantages: (i) it enables covering the total drained catchment area, (ii) it is physically sound enough to concentrate the diffuse runoff from contiguous street portions and cadastral parcels towards the same RBS inlet; (iii) it prevents the creation of new UDB elements. HEs can be characterized by a set of geometrical parameters.

The *area* of an HE called E_i is expressed as the sum of the area of the cadastral parcel P_i plus the area of its adjacent street portions:

$$a_i = \mathrm{sa}(P_i) + \sum_{l=1}^{n_r} \frac{1}{2}\mathrm{sa}(\mathrm{ST}_i^l)\frac{\mathrm{sa}(P_i)}{\sum_{m=1}^{n_p}\mathrm{sa}(P_m^l)} \tag{1}$$

where a_i is the area of E_i, sa( ) represents the 'surface area' function, ST_i^l is one of the n_r street sections adjacent to parcel P_i, and P_m^l one of the n_p cadastral parcels adjacent to street sections ST_i^l. When a parcel is not adjacent to any street section, the area of adjacent street section is set to zero.

The *impervious fraction* of a HE E_i is denoted c_i and estimated from the building and street areas. The *center of gravity* g_i of the impervious part of the HE is taken either as the center of gravity of the largest house located on the cadastral parcel (if the parcel is built), or as the center of gravity of the parcel itself (if the parcel is empty). The average distance traveled by the runoff flow, called the *flow distance* and denoted d_i, is estimated from the orthogonal projection of the HE center of gravity onto the axis of the adjacent street segment. The *slope* s_i along this flow distance is derived from a triangle-based linear interpolation of the UDB elevation points.

As long as they are associated with their contiguous portion of street, cadastral parcels encompass the main elements acting on the water cycle (buildings, paved surfaces, soil and perhaps vegetation). Each of these elements is thus supposed to collect rainfall and transform it into diffused and then concentrated runoff throughout the catchment. As indicated earlier, information on the geometry of these elements that transform rain into concentrated runoff is lacking; hence, a simple parametric model has been used. First, the mass of rainfall water contributing to runoff is directly estimated from the *impervious fraction*, considered as an initial approximation of the HE runoff coefficient. Next, the diffuse runoff transfer over the impervious surfaces and the concentrated runoff through the private gutters and pipes are represented by a lag-time (denoted $t_{i,0}$). The value assigned to this lag-time is presented in Section 4.2.

3.2. Runoff along streets and sewers

In this study, we identify the linear geometry of the water flow paths along streets and sewer lines, or the RBS, under normal flow conditions. Neither street flooding nor sewage system overflow is allowed, and the following simplifications have been admitted. The water flow exiting the HE only makes a contribution to the street flow. This assumption is compulsory given the absence of precise information on the direct connections of buildings or private paved areas into the sewer network. The street gutter flow is supposed to reach a priori the sewer system at each the street network intersection. This simplification is also necessary because the inlet positions as well as its type are not specified in the UDB used. The hydraulic behavior of inlets has been neglected herein. If more information were available (such as in Greene and Cruise (1995)), the above simplifications could be avoided, and the number of inlets would probably be higher. The hydraulic aspects of the house-street and the gutter-sewer connections could be modeled with greater detail.

The GIS description of the RBS relies on two relationship tables. The first establishes the connection between each Hydrological Element and a street segment by projecting the center of gravity of the parcel onto the closest adjacent street. The second defines the connection between each street or sewer segment and its corresponding downstream segment according to an exhaustive test on the coordinates of the segment ends. Depending on the proximity of the sewer system, the downstream segment of a street segment may be either a sewer or a street segment (see Fig. 3): if a sewer segment exists at one street network intersection, the downstream segment of a street segment is a sewer segment, but if not, it is a street segment. RBS segments are characterized by their length and slope and by a pipe size. In this way, the exact profile of each flow path is known. Street gutters are considered as small-sized pipes (250 mm diameter), assuming that street runoff, for the studied range of rainfall events, is mainly concentrated along the gutters.

In reference to Gupta et al. (1980), each flow path from an HE E_i can be defined by a set of n_i points of coordinates $\{x_{i,j}, j \in [0, n_i]\}$, where $x_{i,j}$ stands both for the jth point of the flow path associated with the HE E_i (Fig. 4) and for the upstream segment draining into this point. The case of the first point $x_{i,0}$ of a flow path is somewhat peculiar. It represents the connection point of E_i to the street as well as an upstream segment draining the HE for which we have no explicit description. According to these notations, a point of the considered catchment will receive as many designations as flow paths containing this point. For instance the outlet of a catchment containing n_e HEs will receive n_e different designations $\{x_{i,n_i}, i \in [1, n_e]\}$ and the total number of designated points for this basin is $n_p = \sum_{i=1}^{n_e} n_i$.

If $M(x_{i,j}) = \{m | x_{m,l} = x_{i,j}, \forall l\}$ denotes the set of indices m of the different paths passing by $x_{i,j}$, it is possible to directly derive the characteristics of the sub-catchment controlled by the segment $x_{i,j}$; its

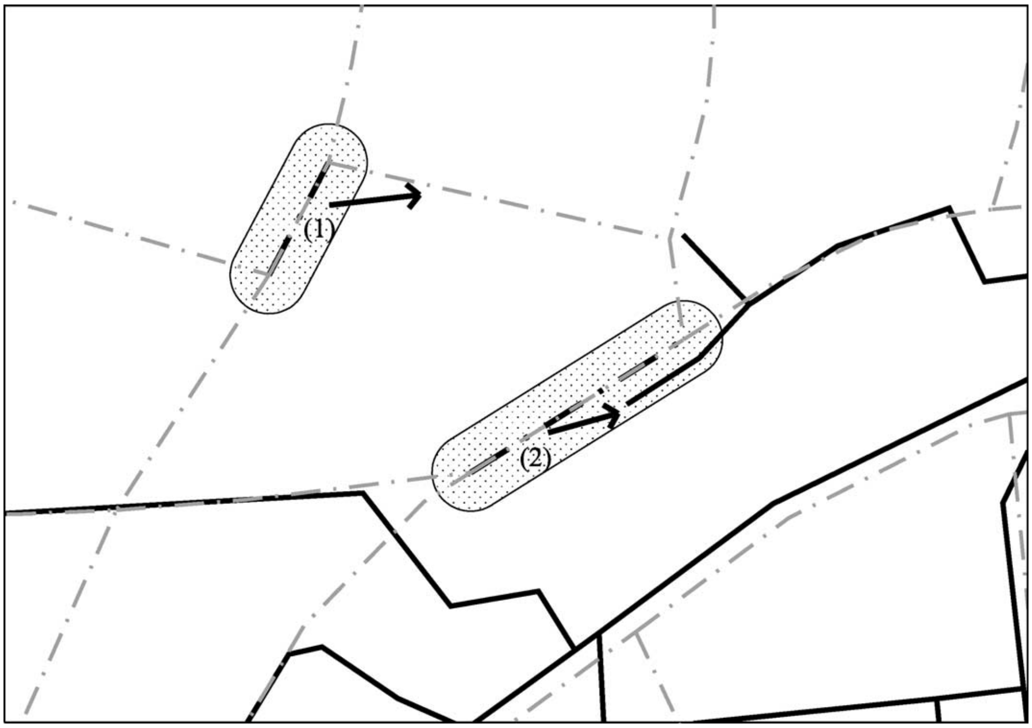

Fig. 3. Examples of street segments connections. A buffer zone of 10 m around the street segment is defined (dotted area). The street segment is connected to the downstream street segment if no sewer segment is included in this buffer (case 1). The street segment is connected to a sewer segment in the opposite case (case 2). The connection is made between the downstream end of the upstream segment and the upstream end of the downstream segment.

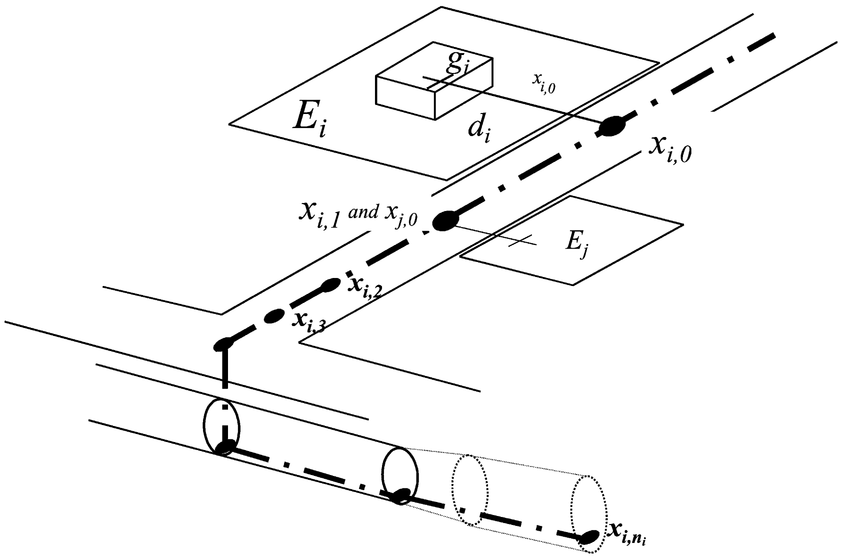

Fig. 4. Schematic representation of both the connection of two Hydrological Elements E_i and E_j to a street segment and the complete downstream flow path.

surface area is expressed as:

$$A_{i,j} = \sum_{m \in M(x_{i,j})} a_m \tag{2}$$

where a_m is the surface area of the HE E_m, given in Eq. (1). Similarly, the impervious fraction $C_{i,j}$ of the sub-catchment controlled by the segment $x_{i,j}$ can be estimated by:

$$C_{i,j} = \frac{1}{A_{i,j}} \sum_{m \in M(x_{i,j})} a_m c_m \tag{3}$$

The surface area of the entire basin is: $A_{i,n_i} = \sum_{m=1,n_e} a_m$ since the set $M(x_{i,n_i})$ combines the first n_e integers; A_{i,n_i} is hereafter denoted A for purpose of convenience.

The characteristics of a segment $x_{i,j}$ of the RBS are: the *length* $L_{i,j}$, the *slope* $S_{i,j}$ (derived from the levels of the ends of the segments), the pipe *diameter* $D_{i,j}$ and the pipe *roughness* $K_{i,j}$. The roughness coefficients are assumed to be dependent solely on segment type. We distinguish the roughness coefficient of the sewer system K_{sewer}, and the roughness coefficient of the street gutters K_{street}.

4. Runoff dynamics and unit hydrograph formulation

4.1. URBS-UH formulation

By spatially distributing the classical formulation of the unit hydrograph, as in Maidment et al. (1996), the discharge at the catchment outlet can be expressed as the sum of the contributions of the n_e HEs:

$$Q(t) = \sum_{i=1}^{n_e} a_i \int_0^t I_i(\tau) h_i(t-\tau)\mathrm{d}\tau \tag{4}$$

where Q is the outlet discharge, $I_i(t)$ is the effective precipitation intensity on the HE E_i and $h_i(t)$ the response function at the outlet of this HE. The formulation of the Unit Hydrograph has been derived from this expression. The main objective of the study being to assess the interest of UDB for a hydrological purpose, it has been decided to derive unit hydrographs by a simple method, which has lead to introduce the three following assumptions:

Assumption 1. The Unit Hydrograph is defined as the hydrograph resulting from one unit of uniform effective rainfall constant during a unit period of time which stands for the discretization time step Δt. This is the classical assumption of computation of a Unit Hydrograph. The effective rainfall can be written:

$$I_i(\tau) = I(\tau) = \frac{1}{\Delta t} \text{ if } \tau \in [0, \Delta t] \text{ and } I_i(t) = 0 \text{ if } \tau > \Delta t \tag{5}$$

which leads to reduce the integral between 0 and t to the integral between 0 and Δt in Eq. (4).

Assumption 2. The rapid response of an urban catchment is dominated by water flow over impervious surfaces (see Section 2.1). This statement allows modifying the surface area that contributes to the discharge at the catchment outlet. The surface of the HEs a_i is then replaced by their impervious surface $c_i\, a_i$ in Eq. (4).

Assumption 3. The response function h_i of the HE number i can be represented by a characteristic function f_{I} depending on t_i, the travel time of the water along the flowpath connecting the HE number i to the catchment outlet. It means that the hydraulic dispersion along the flowpath can be neglected. This hypothesis is equivalent to the pure translation flow model as presented in Maidment et al. (1996). It is justified by the fact that the surface area of HEs is negligible compared to the catchment surface area. The response function reads:

$$h_i(t) = f_{\mathrm{I}}(t - t_i) \tag{6}$$

or in a discrete form $h_i^k = 1$ if $t_i \in [(k-1)\Delta t, k\Delta t]$ and $h_i^k = 0$ if not.
The integration of the response function h_i in Eq. (4) may be written in a discrete form as:

$$\frac{1}{\Delta t}\int_0^{\Delta t} h_i(k\Delta t - \tau)\mathrm{d}\tau = \frac{1}{\Delta t}\int_{(k-1)\Delta t}^{k\Delta t} h_i(\tau')\mathrm{d}\tau' = h_i^k \tag{7}$$

Introducing Assumptions 1, 2 and 3 in Eq. (4) leads to the final expression of the unit hydrograph:

$$Q_k = \sum_{i=1}^{n_e} c_i a_i h_l^k \tag{8}$$

where Q_k is the discrete value of the unit hydrograph during the kth time step.

It is convenient to normalize each component of this hydrograph by the total flow volume at the catchment outlet, which is equal to $\sum_{i=1}^{n_e} c_i a_i 1$ in the present case. Finally, the transfer function of the catchment, called URBS-UH, such as Urban Runoff Branching Structure-Unit Hydrograph is expressed as:

$$H^k = \frac{1}{\sum_{i=1}^{n_e} c_i a_i} \sum_{i=1}^{n_e} c_i a_i h_i^k \tag{9}$$

where k is the time step index and H^k the value of the URBS-UH at this step. The obtained expression indicates that the UH as calculated is equivalent to the distribution of HEs travel times weighted by their impervious area. Note that this URBS-UH may be seen as a spatially distributed UH, insofar it could be estimated with Eq. (9) at the catchment outlet, and at any point of the RBS.

4.2. Travel time estimation

Since runoff geometry is defined according to available urban data information within the RBS, the second modeling stage of the Unit Hydrograph focuses on determining the travel time through the catchment. The travel time is defined as the time difference between the occurrence of an element of the efficient rainfall at one HE and the realization of the effect of this element at the outlet (Singh, 1992, p. 561). Along any flow path, the travel time t_i of the ith flow path is defined as the sum of travel times along each segment:

$$t_i = t_{i,0} + \sum_{j=1}^{n_i} t_{i,j} \tag{10}$$

where $t_{i,0}$ is the travel time inside the HE E_i that constitutes the upstream point of the ith flow path and $t_{i,j}$ is the travel time along the jth segment $x_{i,j}$.

The travel time along the jth segment $x_{i,j}$ is defined by:

$$t_{i,j} = \frac{L_{i,j}}{V_{i,j}} \tag{11}$$

where $L_{i,j}$ and $V_{i,j}$ are the length and the runoff velocity of the jth segment of the ith flow path. In accordance with the arguments put forth in Section 2, the mean flow velocity is computed using the Manning's equation as in Zech et al. (1994) and Maidment et al. (1996), with dispersion around this mean value being considered negligible. A more elaborated hydrodynamics modeling could be set up without changing the general orientation of this study if more complex flow behavior was considered likely (e.g. presence of sewer overflow). The flow velocity along a given segment of the RBS is estimated from the Manning's equation and expressed as:

$$V_{i,j} = K_{i,j}\, R_{i,j}^{2/3}\, S_{i,j}^{1/2} \tag{12}$$

where $V_{i,j}$, $K_{i,j}$, $R_{i,j}$ and $S_{i,j}$ are, respectively, the velocity (in m s^{-1}), the roughness coefficient (m$^{1/3}$ s^{-1}), hydraulic radius (m), and slope (m m^{-1}) of the considered segment. The hydraulic radius $R_{i,j}$ is dependent on the filling rate of the segment pipe (assumed to be circular). As shown in Fig. 5, the filling rate of the pipe is defined by an angle θ varying

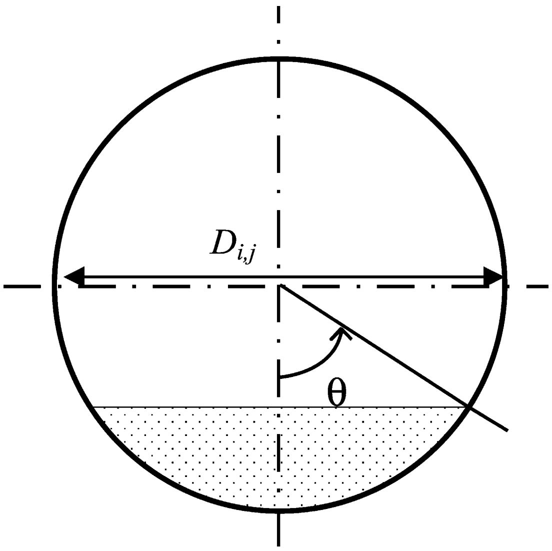

Fig. 5. Filling rate of a cicular pipe of diameter $D_{i,j}$. $\theta = 0$ represents an empty pipe, and $\theta = 180°$ or π rad represents a full pipe.

from $\theta = 0$ rad (empty pipe) to $\theta = \Pi$ (full pipe); the hydraulic radius is related to the filling rate $\theta_{i,j}$ by the following expression:

$$R_{i,j} = \frac{D_{i,j}}{4}\left(1 - \frac{\sin\,\theta_{i,j}\,\cos\,\theta_{i,j}}{\theta_{i,j}}\right) \tag{13}$$

where $D_{i,j}$ is the pipe diameter. Using Eqs. (12) and (13), the flow velocity $V_{i,j}$ and the discharge $Q_{i,j}$, which is equal to the product of velocity by flow cross-section in segment $x_{i,j}$, are given by:

$$V_{i,j} = K_{i,j} S_{i,j}^{1/2}\left(\frac{D_{i,j}}{4}\right)^{2/3}\left(1 - \frac{\sin\,\theta_{i,j}\cos\,\theta_{i,j}}{\theta_{i,j}}\right)^{2/3} \tag{14}$$

$$Q_{i,j} = V_{i,j}\left(\frac{D_{i,j}}{2}\right)^{2}(\theta_{i,j} - \sin\,\theta_{i,j}\cos\,\theta_{i,j}) \tag{15}$$

where $\theta_{i,j}$, $K_{i,j}$, $S_{i,j}$ and $D_{i,j}$ are the characteristics of segment $x_{i,j}$. The determination of the filling rate, assumed to be constant for a given segment, will be discussed in detail in Section 4.3.

The lag time representing water transfer on the HE ($t_{i,0}$ in Eq. (10)) cannot be computed on the basis of the same hydrodynamics considerations cited previously for the RBS segments. We simply consider that the diffuse runoff over the built areas is channeled at a constant velocity towards the street via other impervious areas, gutters and pipes. The typical flow distance is given by the house-to-street distance d_i. In Section 5.1, this distance is shown to fluctuate from one basin to the next, depending on land use. The velocity has been determined from the available literature and in recognition that typical HE slopes are around 1%. For plane surfaces sloping between 0.5 and 5%, Urbonas and Roesner (1993), p. 28.17) mentions average runoff velocities between 0.3 and 2 m s^{-1} for different land uses. We retained a constant velocity of 0.5 m s^{-1}. According to these assumptions, the resulting lag times at the HE level are small compared to total travel time along the downstream flow path.

4.3. Determination of the filling rate of a segment of the RBS

Calculating the URBS-UH components requires determination of the flow travel times in the segments constituting the RBS. These travel times are a function of the flow velocity. For a given pipe, the flow velocity depends on pipe characteristics (i.e. diameter, slope, and roughness) as well as on the flow rate. The flow rate is controlled by two important factors, (i) the contributive surface area drained by the pipe, (ii) the likely rainfall intensity over this surface area. Consequently, the URBS-UH depends on the magnitude of rainfall accumulation over the catchment. In order to explicitly take into account this link between the URBS-UH and rainfall magnitude, we determined the URBS-UH for rainfall accumulation over the time of concentration of the catchment with a given return period. Considering time of concentration as the reference time period presents several advantages: (i) in urban drainage practice, time of concentration remains a key parameter for the design and the study of storm sewer systems (Pilgrim and Cordery, 1993); and (ii) time of concentration allows the RBS to reach a steady-state, which is not satisfied for shorter time periods. The use of return periods is intended to position the rain event with respect to local climatic conditions and the associated hydrological design of the drainage network. The only difficulty lies in the fact that the time of concentration of the catchment also depends on the rainfall intensity. We adopted a simple iterative approach to determine both the catchment time of concentration and the corresponding rainfall accumulation, by virtue of the following steps.

1. An initial guess of the catchment time of concentration t_c is estimated from:

   $$t_c = \text{Max}\{t_i, i = 1, n_e\} \tag{16}$$

   where travel times t_i are given by Eq. (10) according to a very crude hypothesis. For instance, the filling rate is constant in all segments and equal to 50% ($\theta = \pi/2$ rad), as assumed in Zech et al. (1994).
2. Rainfall accumulation over this time of concentration is estimated for the selected return period from local rainfall statistics or by using classical intensity–duration–frequency relationships (Stedinger et al., 1993, p. 18.50). Montana-type formulas are taken as a reference in France (Chocat, 1997, p. 568):

   $$I(T, t_c) = \alpha(T) t_c^{\beta(T)} \tag{17}$$

where I is the rainfall intensity, T stands for the return period, t_c represents the time of concentration of the entire catchment, α and β are the parameters of the Montana formula (which depend on the return period).

3. The flow rate in each segment is computed with the rational formula assuming that: (i) steady-state conditions are reached, and (ii) the impervious fraction is representative of the runoff coefficient. This latter hypothesis is valid for high-intensity rainfall rates; for more typical rain events, the runoff coefficient can be taken as less than the impervious fraction, as proposed by Mosini et al. (2000). The flow rate in $x_{i,j}$ is thereby expressed as follows:

$$Q_{i,j} = F\, I(T, tc) C_{i,j}\, A_{i,j} \tag{18}$$

where F is a unit conversion factor and $C_{i,j}\, A_{i,j}$ represents the total upstream impervious surface area, given by Eqs. (2) and (3).

4. The corresponding filling rate $\theta_{i,j}$ of the segment $x_{i,j}$ is obtained by numerically solving the following equation, deduced from Eqs. (14), (15) and (18):

$$F\, I(T, tc) C_{i,j}\, A_{i,j} = K_{i,j}\, S_{i,j}^{1/2} \frac{D_{i,j}^{8/3}}{2^{10/3}} \frac{[\theta_{i,j} - \sin\theta_{i,j} \cos\theta_{i,j}]^{5/3}}{\theta_{i,j}^{2/3}} \tag{19}$$

Lastly, the travel time in each segment $x_{i,j}$ can be computed using these filling rates, and the procedure is then iterated from step 1.

This numerical procedure converged towards a unique solution within a few iterations when applied to the catchments of the case study presented in Section 5.

4.4. URBS-UH parameters

In sum, the URBS-UH defined in Eq. (9) basically depends on two types of parameters. On the one hand, the geometrical parameters consist of maps of the RBS and the contributive areas, along with the slope and size of the various channels from the upstream house-to-street connection to the sewer outlet. These parameters are certainly subject to many errors relative, among other things, to the level of detail and accuracy of the UDB as well as to the assumptions made regarding the flow paths. Nevertheless, in the remainder of this study, they will be considered as fixed data. On the other hand, the hydraulics parameters comprise the roughness coefficients and the channel filling rate. Roughness coefficients are not readily available from UDB information. Further field investigations should be conducted to identify a relationship between surface roughness and, for instance, the type or age of the streets and sewer systems. In this study, roughness coefficients have simply been extracted from the technical literature, which indicates that concrete roughness varies between 50 and 95 $m^{1/3}\, s^{-1}$ (Graf, 1993, p. 79), with typical values of 66 for concrete pipes (Linsley et al., 1975, p. 468) and 62 for streets (Guo, 1997, p. 29). The filling rate of the segments has been characterized with respect to rainfall return periods by the procedure described earlier.

5. Case study

5.1. Catchments and data sets

The case study presented has relied on the UDB of the Nantes metropolitan area (France). The data layers used are represented in Fig. 1 and the geometrical objects inputted for the hydrology application are listed in Table 1. The GIS software Mapinfo©, which is used throughout the city's Public Works Office, was run for the purpose of our case study. The specific

Table 1
Geographical data

Layer	Geographical data
Property boundary	Polygon
House	Polygon
Street section	Polygon
Street segment	Line
Rain sewer system	Line
River	Line
Elevation point	Point

hydrological analysis was implemented on Mapbasic©, the associated development software.

Three experimental catchments within the Nantes metropolitan area were considered. The *Rezé* and *Les Renards* basins primarily consist of single-family housing while *Les Gohards* also includes multi-family housing, commercial areas and industrial plants. As indicated in Table 2, the surface areas of these basins span one order of magnitude. Differences in land use result in a doubling of the average HE surface area from *Rezé* and *Les Renards* to *Les Gohards*. This difference is also apparent in Fig. 6, where *Les Gohards* exhibits a distinct histogram shape with a substantial proportion of parcels exceeding 0.2 ha. The histograms of *Rezé* and *Les Renards* reveal a more homogenous type of housing. The impervious fractions indicated in Table 2 were determined on *Rezé* catchment through an exhaustive quantitative survey of each parcel. Cadastral information was used for the two other basins. The drainage network of all three basins is composed of separate sewers, thereby allowing better control of the storm response. Fig. 7 displays the network slope distribution over these catchments; it indicates similar ground conditions even if *Les Renards* catchment slopes are higher than the other two. Fig. 8 gives the magnitudes of the contributive surfaces as a function of pipe cross-section for the *Les Gohards* catchment. Contributive areas may vary from 1 to 4 for 1200 mm diameter pipes. This dispersion, despite its apparent significance, may be considered as fairly common in network design due to the influence of other considerations.

The hydrological experimental setup consists of recording rainfall and flow rates. The *Rezé* catchment has been instrumented since 1991 (Berthier et al., 1999); the *Les Renards* and *Les Gohards* catchments have been instrumented for the purposes of this study over a shorter time period (1 year). The rainfall rate was measured by two tipping-bucket rain gauges mounted on each catchment. Flow rates at the catchment outlets were derived from the water level in a calibrated gauging weir in *Rezé*, and from the water level and Doppler velocity in circular sewer pipes in *Les Renards* and *Les Gohards*. In order to ensure a high-quality data, the data validation procedure described in (Berthier et al., 1999) for the *Rezé* catchment has also been applied to the other two; it calls for: control of the total catch from each rain gauge, comparison of time series, and regular calibration of the Doppler sensors. A time step of 1 min was adopted for all rainfall rate and flow rate measurement. Moreover, the time steps of 1 min for *Les Renards*, 2 min for *Rezé* and 5 min for *Les Gohards* adopted to analyze the URBS-UH were based on the respective response times of these catchments. These values allow describing the peak time in 3–5 time steps, according to the classical rules discussed by Obled (1991).

5.2. Runoff branching system and URBAN-UH

The RBS was identified according to the rules laid out in Section 2. Figs. 9 and 10 show the two main stages in the analysis performed by the model over the UDB. The *Les Gohards* catchment was selected for this illustration since it exhibits a wider diversity of land uses. The two-dimensional map of HEs (Fig. 9) is colored as a function of travel time to the catchment outlet, by assuming a rainfall return period of 1 year and roughness coefficients of $K_{\text{street}} = 62\ \text{m}^{1/3}\ \text{s}^{-1}$ and $K_{\text{sewer}} = 66\ \text{m}^{1/3}\ \text{s}^{-1}$. The size dispersion of the HEs

Table 2
Statistics concerning the morphology of the three studied catchments

Catchment	*Rezé*	*Les Renards*	*Les Gohards*
Surface area—land survey (ha)	18	60	180
Surface area—automatic delineation (ha)	21.6	67.9	178.6
Global impervious fraction (%)	38 (measured)	49 (estimated)	38 (estimated)
Number n_e of HEs	256	860	927
Mean area a_i and standard deviation (m^2)	846–1216	790–1200	1927–4459
Mean estimated impervious fraction c_i and standard deviation	0.51–0.12	0.54–0.19	0.44–0.22

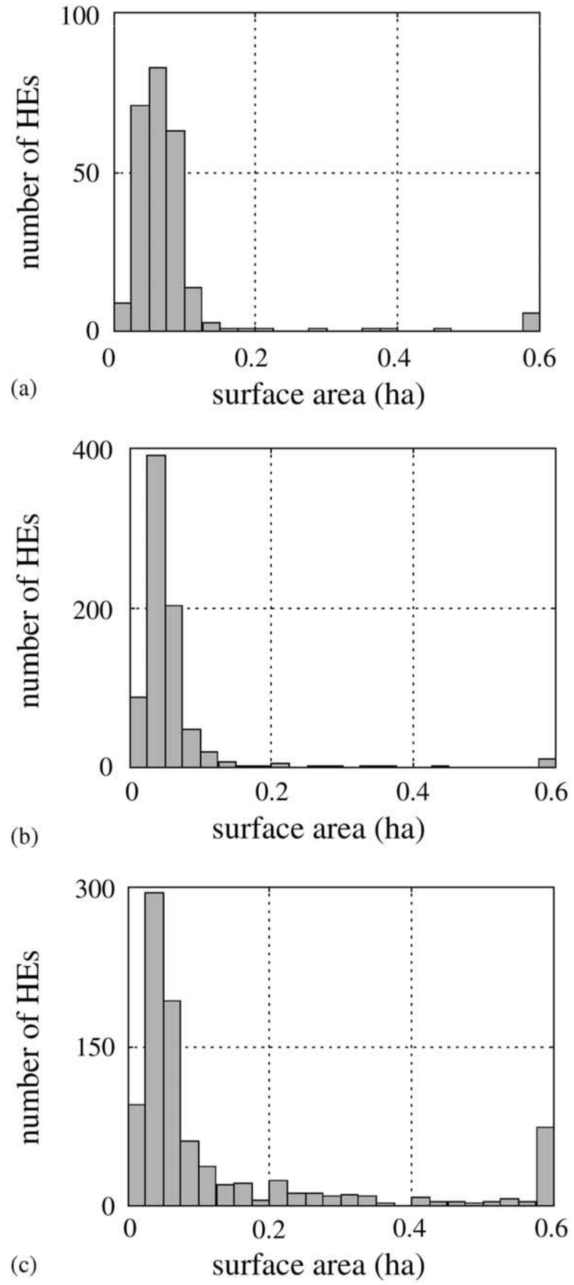

Fig. 6. Histogram of surface areas of the HEs for the three studied catchments: (a) *Rezé*, (b) *Les Renards* and (c) *Les Gohards*.

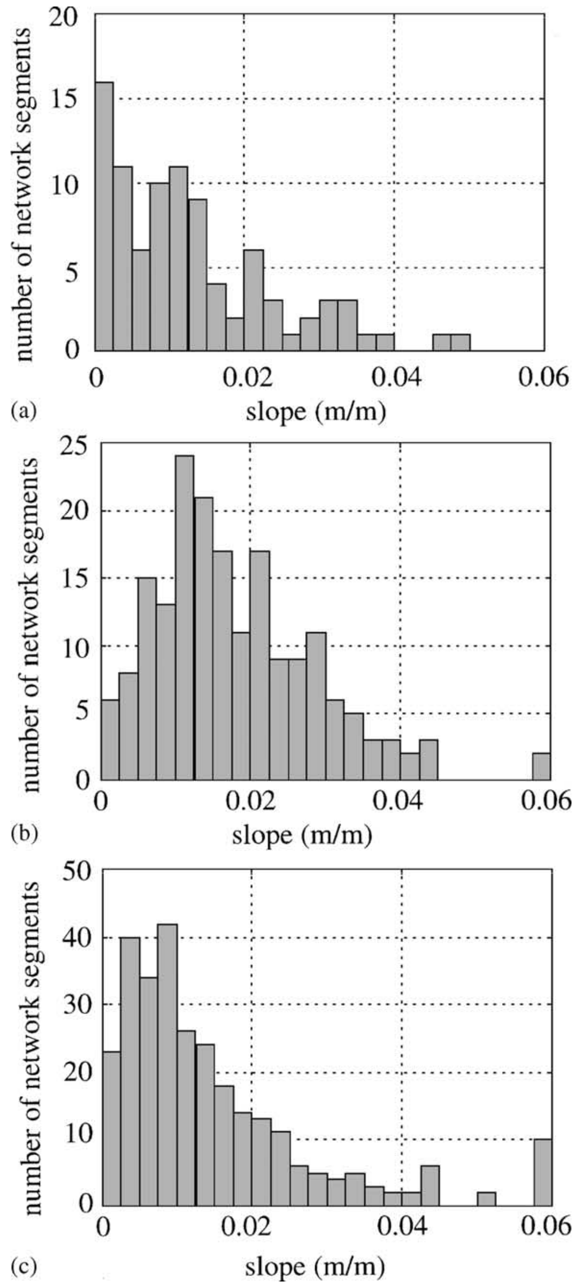

Fig. 7. Histogram of the segment slopes for the three studied catchments: (a) *Rezé*, (b) *Les Renards* and (c) *Les Gohards*.

given in Fig. 6 would appear to be spatially organized. The largest HEs of the industrialized sector are located in the western part of the basin, while the smaller HEs of the residential sector are at the catchment outlet. The steepness of the gradients reveals that travel times to the outlet can double from one parcel to the next, a finding that reflects the complexity of the RBS displayed in Fig. 10.

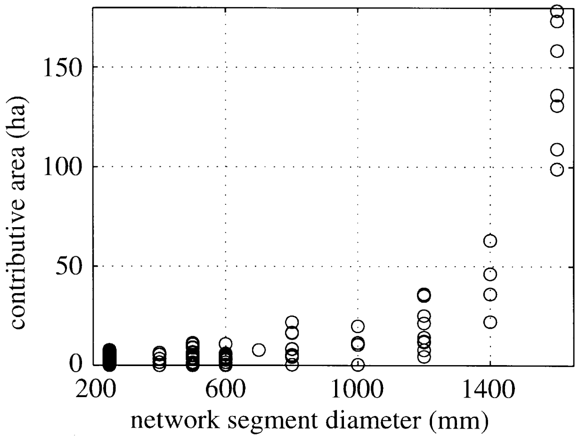

Fig. 8. Contributive areas as a function of the diameter of draining pipes for the *Les Gohards* catchment.

In Fig. 10(a) we have represented the complete RBS, showing how the street network connects to the sewer network. The combined location of the two networks is clearly apparent even if the streets remain the primary drains of significant land areas. The street network presents a grid-like structure in places, meaning that the water flow could potentially make loops, but the slope distribution interrupts these loops. The apparent grid structure of the sewage network is a mere artifact of the graphical representation. In Fig. 10(b), the flow velocity corresponding to an assumed rainfall return period of 1 year is indicated on each segment of the street and the sewer networks, respectively. The segments directed towards the outlet have higher flow velocities, thereby reflecting the general topography of the basin with a general downward slope oriented southeasterly. It can also be noted that the sewer velocities are significantly higher than the street velocities. A by-product of this UDB analysis is the automatic delineation of the catchment. Fig. 9 reports the catchment area as determined from classical field survey. The automatic delineation underestimates the field survey surface by less than 5% and fluctuations in shape are minor (see Table 2).

Fig. 11 displays the URBS-UHs computed according to the method described in Section 4. For the three studied catchments with return periods of 1 month, 1 year and 10 years, the unit hydrographs appear very sensitive to: the size and slope of the basin, the magnitude of the rainfall, and the time step used. The size of the basin obviously governs the temporal scale of the hydrograph with, for instance a time-to-peak varying from 8 to 30 min for the *Rezé* (18 ha) and *Les Gohards* (180 ha) catchments, respectively. The larger surface area and milder slope of the watershed *Les Gohards* induces a smooth URBS-UH, very different from the other two. The difference in slope explains the short time-to-peak of the *Les Renards* catchment (60 ha), which is very close to *Rezé*'s one (the slope of the longest flow path is 1.9% on *Les Renards* and 1.1% on *Rezé*). The increase of the magnitude of rainfall accumulation consistently reduces the response time of the catchments. This effect is more pronounced when moving from a return period of 1 month to that of 1 year than from 1 to 10 years. This example does not highlight the dependence on catchment morphology, as the surfaces and slopes are not comparable.

6. Sensitivity analysis

The URBS-UH relies on several assumptions concerning the RBS and runoff dynamics. A sensitivity analysis conducted in the *Les Gohards* catchment illustrates the influence of these assumptions on the shape and size of the determined URBS-UH. The URBS-UH corresponding to a 1-year rainfall return period and derived from the set of parameters defined in the previous sections serves as the reference URBS-UH. A modification to model parameters yields a modified URBS-UH, which can then be compared with the reference via the Nash criterion *C*Nash (Nash and Sutcliffe, 1970), expressed as follows:

$$C_{\mathrm{Nash}} = 1 - \frac{\sum_{k=1}^{p} (H^k - H^k_{\mathrm{ref}})^2}{\sum_{k=1}^{p} (H^k_{\mathrm{ref}} - \bar{H}_{\mathrm{ref}})^2} \quad (20)$$

where H^k_{ref} and H^k are the current values of the reference and modified unit hydrographs, respectively, for the kth time step over p (the total number of simulation steps), and $\bar{H}_{\mathrm{ref}}$ is the mean value of the reference unit hydrograph. The value of C_{Nash} is known to be sensitive to both the bias and the co-fluctuation between the compared series, with 1 indicating a perfect match.

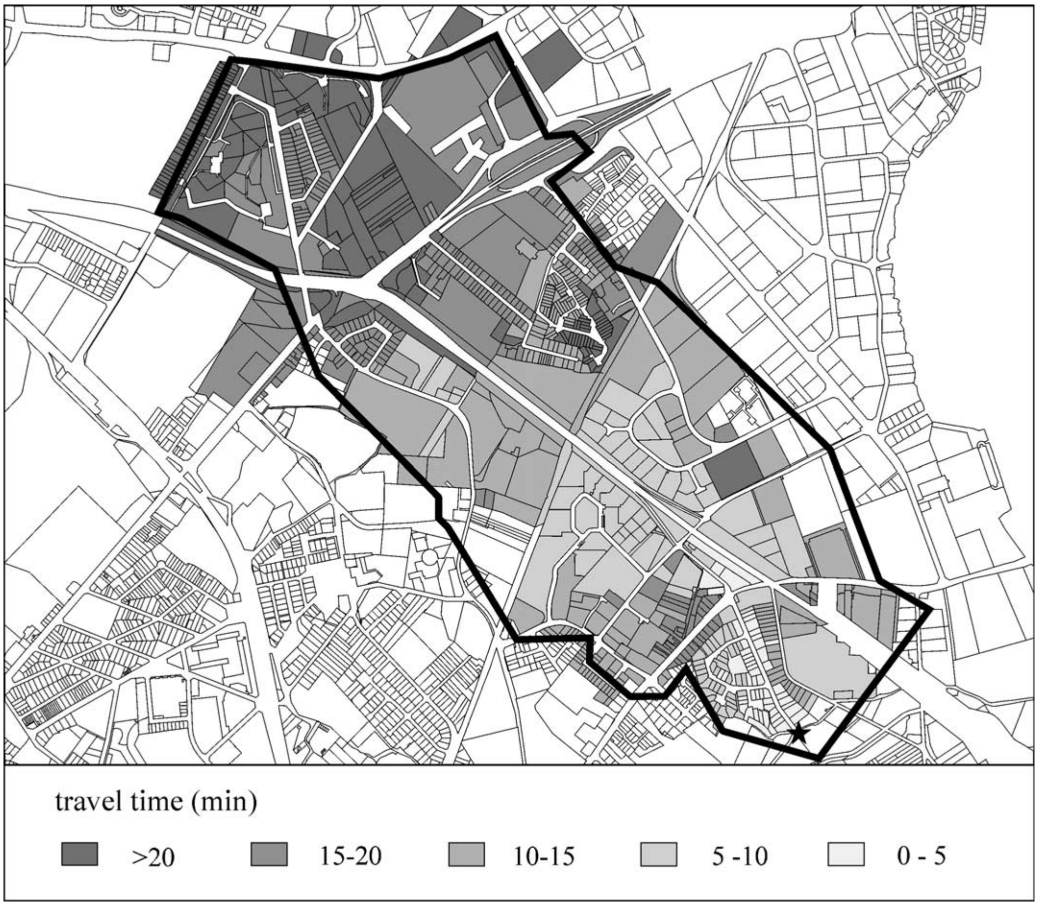

Fig. 9. Map of the *Les Gohards* catchment displaying, for each cadastral parcel, the travel time of the runoff produced to the catchment outlet (shown by a star). The street network appears in white. The dark continuous line shows the boundary of the catchment, as established by a land survey.

The URBS-UH depends primarily on geometrical parameters identified from the UDB. Fig. 12(a) and (b) display the evolution of the Nash criterion when the following parameters experience a range of perturbation extending from -50 to $+50\%$ of the value derived from the UDB:

The length $L_{i,j}$ of the RBS segments. The street and sewer segment lengths have been perturbed separately. The URBS-UH appears very sensitive to systematic errors on the distance traveled by the water flow, especially in the sewer segments. The amplitude of differences detected by the Nash criterion is highest among the tested parameters. Beyond the unlikely problem of using an incorrect scale factor or more simply an incorrect database, this result stresses the importance of the assumptions regarding flow paths along the streets and the sewers. If systematic errors are committed on the connections between these two networks, thus introducing a small positive or negative bias in the computation of the traveling distances, the resulting URBS-UH will probably reveal significant error. The length of street segment seems to be less important, because the mean number of flow paths passing through a sewer segment is four times bigger than the number passing through a street segment.

The slope $S_{i,j}$ of the RBS segments. Street and sewer segment slopes have been perturbed separately. The slope of the RBS segments apparently affects URBS-UH shape to a greater extent when it is

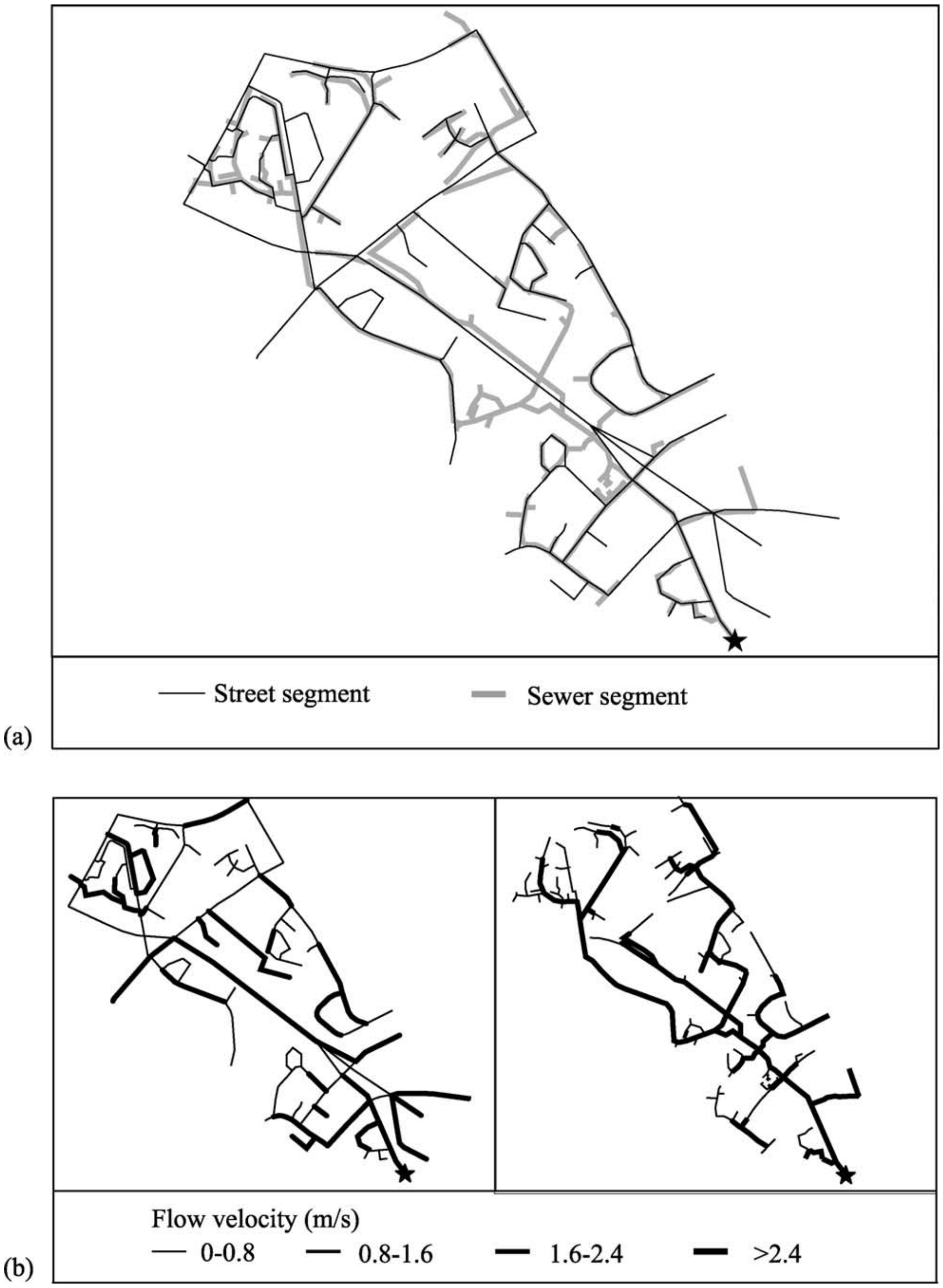

Fig. 10. (a) RBS of the *Les Gohards* catchment indicating both superimposed street and sewer networks. The RBS has the appearance of a grid or network; this is a problem inherent in the representation. First, the superimposition of surface and underground networks create some artificial loops, and second, the street network is really looped, but the modelled RBS sets the preferential connection between street and sewer segments, and avoid the creation of loops. (b) RBS of the *Les Gohards* catchment indicating the flow velocity of sewer segments (left) and the flow velocity of street segments (right), both associated with a rainfall return period of 1 year.

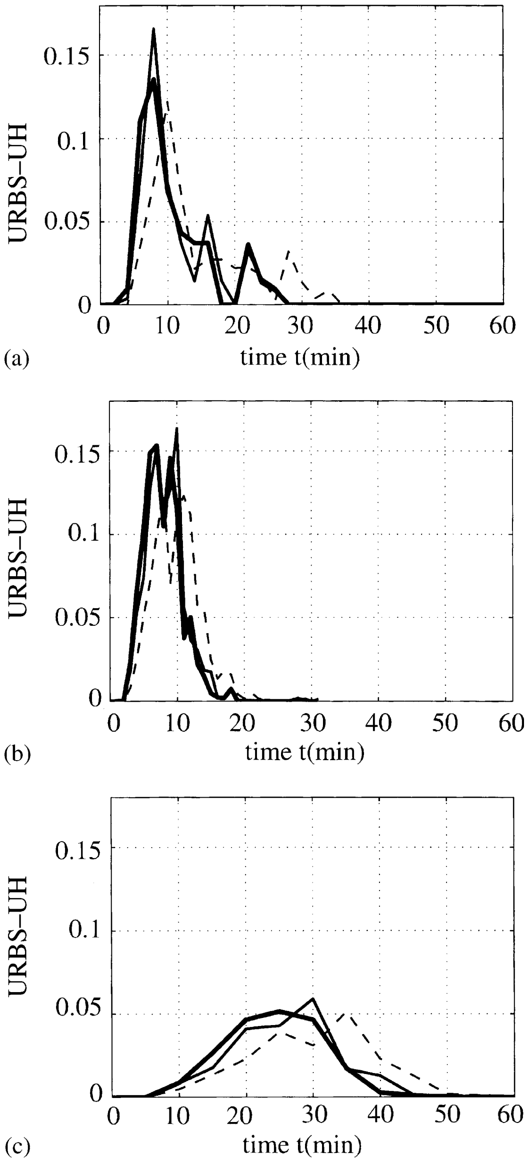

Fig. 11. Unit Hydrographs obtained for the three studied catchments: (a) *Rezé*, (b) *Les Renards* and (c) *Les Gohards*. For each catchment, three URBS-UHs are represented corresponding to rainfall return periods of $T = 10$ years (bold solid line), $T = 1$ year (solid line) and $T = 1$ month (dashed line). Y-coordinate of the UH is adimensional by definition.

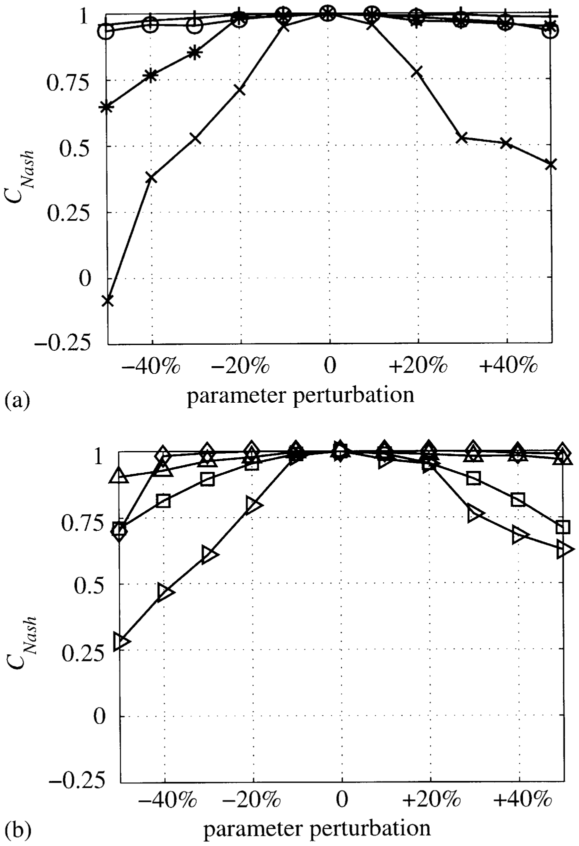

Fig. 12. Sensitivity analysis for the *Les Gohards* catchment. The Nash criterion is displayed as a function of the perturbation in percentages of several parameters: (a) length of the street segments (circles), length of the sewer segments ('x' mark), slope of street segments (plus signs), and slope of sewer segments (stars). (b) Diameter of RBS segments (diamonds), impervious surface areas of the HEs (squares), street roughness coefficient (upwards triangles) and sewer roughness coefficient (rightwards triangles).

systematically underestimated rather than overestimated. The origin of this asymmetric behavior lies in the Manning's equation, where flow velocity relates to the square root of the slope. Sewer slopes perturbation exerts more influence than street slope perturbation, for the same reason as cited earlier. This finding underscores the importance of altitude information that is not always available for the sewer system in UDBs.

The impervious fraction c_i. The impervious fraction of the various HEs affects the computation in Eq. (20) of the filling rate of a given pipe. Consequently, flow velocity depends directly on the impervious fraction of the HEs, and the URBS-UHs are modified as impervious surface areas change. As imperviousness increases, the hydrological response of the catchment becomes more intense. The Nash criterion decreases symmetrically when the surface area perturbation is either positive or negative. However, an error of 10 or 20% of the impervious fraction does not alter the URBS-UH significantly, with the Nash criterion remaining greater than 95%. The assumption of impervious surfaces as main contributive surfaces appears to be important in determining the URBS-UH. Attention should be paid to the estimation of this impervious fraction of HEs. At present, this fraction is estimated only from street and building surface areas, yet the estimation process could be improved if an urban land use geographical map with sufficient accuracy was available within UDB. New very high-resolution remote sensing techniques may contribute to this objective. It should be pointed out that the perturbation of the HE surface areas a_i would induce exactly the same effect on the URBS-UH than the perturbation of the impervious fraction c_i.

The equivalent diameter $D_{i,j}$ of the pipes and gutters. The size of flow-channeling elements starts to exert visible influence on the URBS-UH shape when it becomes heavily underestimated (by more than 50%). This effect is due to filling rates values with regard to the size of the element. Apparently, only severe underestimation of segment size have a significant effect on the flow velocity through Eq. (20).

In sum, the earlier results illustrate the moderate importance of the geometrical parameters governing flow velocity compared to the parameters governing flow length. The URBS-UH also depends on hydrodynamic parameters that characterize the roughness of the channeling structures. Fig. 12(b) displays the evolution of the Nash criterion when the street and sewer parameters experience the same type of perturbation range as above around the parameter values indicated in the literature.

The RBS roughness. The roughness attributed to street gutters K_{street} is much less influential than the sewer roughness for the same reason cited above: a sewer system segment is associated to a number of flow paths larger than that of a street segment. The sewer roughness K_{sewer} induces variations in the Nash coefficient that are comparable in amplitude and shape to the effect of the RBS segment lengths. As the roughness parameter increases, runoff velocities also rise, and does the URBS-UH peak. This finding confirms that roughness is a dominant factor in the URBS-UH determination scheme employed.

7. Comparison with deconvoluted unit hydrographs

The URBS-UHs determined using the proposed method can be compared with unit hydrographs identified from observed rainfall and flow data series recorded over the same catchments introduced in Section 5. In this study, the unit hydrographs (UHs) are identified using the FDTF-ERUHDIT method, which has been summarized in Section 7.1.

7.1. Deconvolution of unit hydrographs

The acronym 'FDTF-ERUHDIT', stands for 'first-differenced transfer function-excess rainfall and unit hydrograph by a deconvolution iterative identification technique'. The FDTF method was developed by Duband et al. (1993) and used to identify the transfer function in a number of studies like Saulnier et al. (1997), which implemented the Unit Hydrograph deduced from the FDTF method with TOPMODEL, or Moussa (1997), which used the FDTF method to validate a geomorphological approach of the transfer function on natural catchments. It is currently applied in France for managing small- to medium-sized rivers in connection with hydropower production (Garçon, 1999). FDTF is an inverse iterative method that simultaneously identifies the unit hydrograph and net rainfall series from a sample of rainfall and river flow data. An initial estimate of the unit hydrograph is obtained by assuming that net rainfall is equal to 'raw' rainfall. The deconvolution of the river flow series using this estimated unit hydrograph provides an initial series of net rainfall values. These two operations are repeated until convergence around stable values of both the unit hydrograph and net rainfall series. A sample of 10–20 rain events is generally sufficient to obtain a stable solution.

The time steps chosen to compute the unit hydrographs with the FDTF method are the same as those used for the URBS-UH determination, as seen in Section 5.1. (2 min on *Rezé*, 1 min on *Les Renards*, and 5 min on *Les Gohards*). On the *Les Gohards* and *Rezé* catchments, the observed rain events have been separated into two samples according to the rainfall rate during the time of concentration $I(T, t_c)$ (see Section 4.3): 'Intense' and 'Moderate' events. The rainfall return periods of these samples were estimated thanks to a statistical analysis of rainfall data within the Nantes metropolitan area (Mosini et al., 2000), in an indicative manner. Characteristics of these samples are summarized in Table 3. For example, 'Moderate' events typically correspond to rainfall return periods smaller than 2 months: the sample is constituted of 10 rain events, whose $I(T, t_c)$ is smaller than 7 mm h^{-1} for the *Les Gohards*. For the *Les Renards* catchment, the number of recorded rain events was too small and only one sample of 17 rain events, with $I(T, t_c)$ varying between 20 and 65 mm h^{-1}, has been used; this sample is representative of 'Intense' rain events.

The deconvoluted UHs represented Fig. 13 obviously depend on the size of the catchment, with a time scaling factor of about two between the smallest and the largest catchments. The magnitude of the rain events controls the shape of the UHs. Higher-intensity events correspond to sharper UHs with a peak ratio of roughly 1.5 and a possible time lag between the peaks, as in the case of the *Les Gohards* catchment. In the following discussion, the corresponding UHs are called 'Intense' and 'Moderate', referring to the generating rain event.

7.2. Comparison of unit hydrographs

In order to render the URBS-UHs deduced from the proposed approach comparable to the deconvoluted UHs, we were required to choose appropriate rainfall return periods. Considering the rainfall intensities indicated in Section 7.1 for all catchments, a return period of 1 month is taken as representative of 'Moderate' rain events and a period of 1 year as representative of 'Intense' events.

Fig. 14 displays, for the three studied catchments, the unit hydrographs obtained from both the URBS-UH and FDTF methods. They correspond to 'Intense' rain events for the *Les Gohards* and *Rezé* catchments and to all rain events for the *Les Renards* catchment. The unit hydrographs identified by the two methods preserve very well the time scaling as basin size increases and are in reasonable agreement with respect to shape. In term of timing, a scaling factor ranging from 1 to 4 as basin size rises from 18 to 180 ha is clearly common to both the deconvoluted and the urban UHs. In terms of shape, FDTF systematically produces smoother UHs with peak values smoothed by some 30% and with longer recession tails. These two differences may be expected from the FDTF method which: (i) statistically minimizes differences between a theoretical model and rainfall-runoff data that always present noise and (ii) is forced by an exponential function onto its recession portion. These differences are also explained by the assumption regarding water transfer along the RBS leading to the URBS-UHs. Neglecting dispersion generates more heavily-fluctuating hydrograph components, traducing the distribution of the traveling distances. The constant flow velocity of a given pipe during the determination of the URBS-UH is responsible for the short length of the hydrograph. A more elaborate hydrodynamic approach should be able to account for the variation in this velocity, and especially the drop in water speed when the quantity of water decreases in the drainage network. An intermediate approach, keeping in mind the hydrological way adopted for URBS-UH, would consist in basically introducing in the determination

Table 3
Characteristics of the samples of rain events

Catchment		*Rezé*	*Les Renards*	*Les Gohards*
Time step		2	1	5
Moderate events	Number of events	18		10
($T < 2$ months)	$I(T, t_c)$ mm h^{-1}	[0, 40]		[0, 7]
Intense events	Number of events	15	17	12
(6 months $< T <$ 2 years)	$I(T, t_c)$ mm h^{-1}	[70, 100]	[20, 65]	[9, 17]

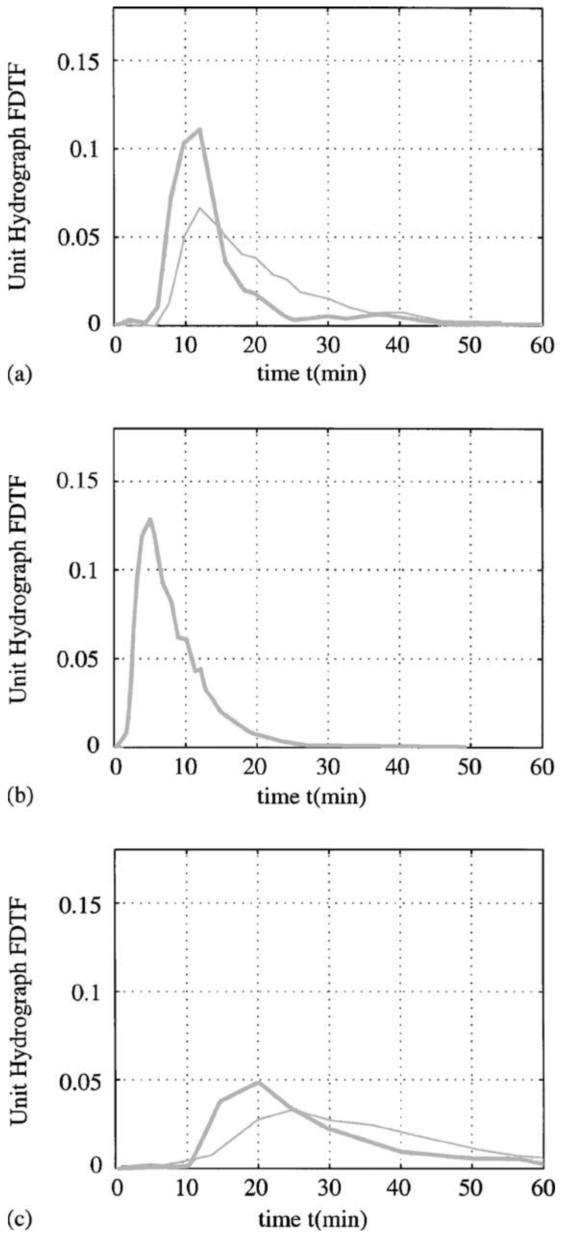

Fig. 13. Identification of the unit hydrographs with the FDTF method for the (a) *Rezé*, (b) *Les Renards* and (c) *Les Gohards* catchments. The thick lines represent the unit hydrograph derived for intense rain events and the thin lines that derived for moderate rain events.

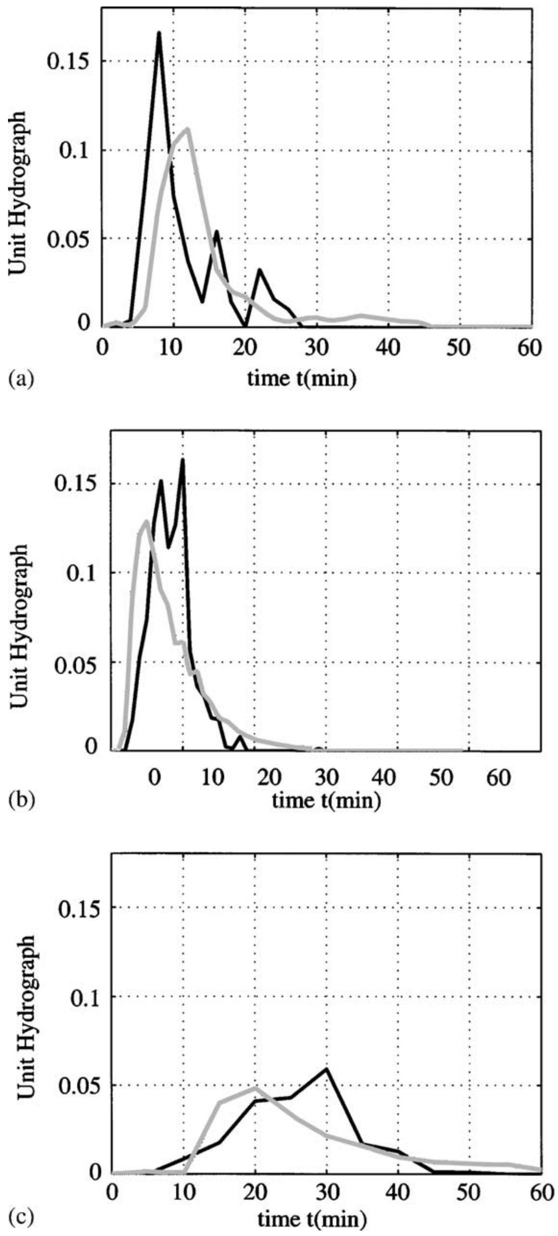

Fig. 14. For the (a) *Rezé*, (b) *Les Renards* and (c) *Les Gohards* catchments, comparison of the URBS-UHs (black line) and the unit hydrographs derived using the FTDF method (gray line) in the case of intense rain events. The URBS-UH has been computed with a rainfall return period of 1 year.

of the URBS-UH (Assumption 3, of Section 4.1) a response function, able to take into account a storage effect in the sewer system by a linear reservoir for instance (Maidment et al., 1996), or a geomorphological dispersion function (Rodriguez-Iturbe and Rinaldo, 1997). It could be helpful to reduce the peak value and improve the recession curve of the unit hydrograph.

Fig. 15 shows the case of 'Moderate' rain events for the *Les Gohards* and *Rezé* catchments. Generally speaking, the same comments apply as regards the shape and time scale. In particular, both methods indicate a sensitive extension of the reaction time of the two catchments. Nevertheless, the differences in smoothness observed for 'Intense' rain events are even more apparent in 'Moderate' events, indicating that both methods have probably reached their limits. The exponential recession imposed on the FDTF hydrographs certainly forces the UH to assimilate the base flow component that it is supposed to be filtering out.

At this point, it is worth recalling that none of the UHs can be taken as a reference in comparison with one another and that the URBS-UH does not incorporate any of the information used by the FDTF method. In other words, the URBS-UH is not calibrated in any manner.

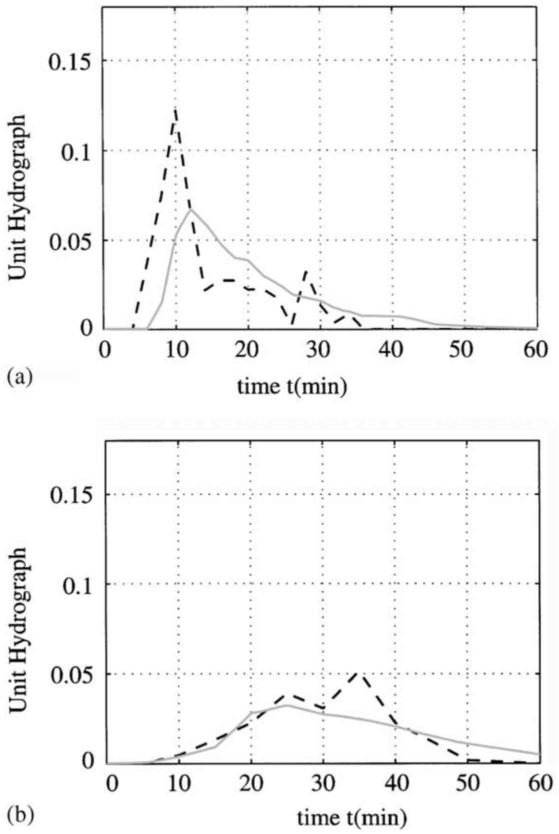

Fig. 15. For the (a) *Rezé* and (b) *Les Gohards* catchments, comparison of the URBS-UHs (black line) and the unit hydrographs derived using the FTDF method (gray line) in the case of moderate rain events. The URBS-UH has been computed with a rainfall return period of 1 month.

8. Conclusion

In this study, unit hydrographs, denoted URBS-UHs, have been directly derived from the analysis of an existing urban databank. The geometry of cadastral parcels, houses, street and sewer networks has enabled the explicit description of runoff production areas and their downstream flow paths. The Manning's equation was used to reconstruct the unit hydrograph from the length distribution of the flow paths with rainfall intensities that we, for purposes of convenience, related to return periods. The shape and the scale of the URBS-UH are primarily influenced by: (i) basin morphology, (ii) channel roughness and (iii) rainfall return period. Consequently, the transfer function is not unique but depends on the rainfall characteristics. The URBS-UH is encouragingly similar in shape and scale to the unit hydrographs derived from the rainfall-runoff measurements conducted over three studied urban basins.

From a general standpoint, this study tends to prove that the geometrical information contained in UDB is of good use in solving the problem of non-gauged or rapidly-evolving basins in urban settings. The ongoing development of high-quality databanks in towns should successfully contribute to developing morphological approaches of urban hydrology.

Furthermore, we feel that this study sheds some light on: the underlying assumptions of the morphological approach, validation issues and distributed hydrological modeling (as summarized later).

The results presented can contribute to the debate on the respective weighting of the underlying assumptions of the morphological approach to IUH modeling. Following the original papers (Rodriguez-Iturbe and Valdes, 1979; Gupta et al., 1980), it was shown that the GIUH effectively represents a combination of linear reservoirs of equivalent geometrical configurations (Chutha and Dooge, 1990). The origin of this equivalent representation stems from the assumed exponential distribution of the delay times in channels. Shamseldin and Nash (1998) rightly remarked that the GUH scale is determined according to unverifiable assumptions on the relationship between channel features and flow velocity and that the GUH theory thus concerns merely the shape of the IUH. They also questioned whether the shape itself was actually related to the morphological organization of the channels or to the assumption made regarding channel modeling. A simulation study allowed them to conclude that morphological information only marginally influences the GUH shape parameter. On the contrary, this work shows that the morphological characteristics of the catchment are of great importance in determining the shape of the UH deduced from UDB. Moreover, despite the linearity of the Unit Hydrograph concept, this work illustrates the influence of the rainfall rate magnitude on the catchment response, as discussed in Sivapalan et al. (2002).

This study also illustrates the delicate issue of model validation. The proposed runoff routing model gives runoff rates at virtually every node of the RBS according to Eq. (9). As indicated in Section 1, this local-scale knowledge can be of utility in various water management applications. The only data available to validate such a model are rainfall-runoff data over some controlled catchments, as distributed surface runoff measurements being experimentally inaccessible at the present time. Over-parameterization is recognized as a major concern in validating hydrological models with rainfall-runoff data (Loague and Freeze, 1985; Jakeman and Hornberger, 1993). It is also most probable that many different parameter sets are equivalently adequate in fitting such data series (Freer et al., 1996). In order to address this difficulty, the parameters of our model were either derived directly from the geometrical content of the UDB or set at current values of hydrodynamics parameters. The fine-tuning of these parameters, potentially distributed in space, would almost certainly have allowed the model to better fit observed rainfall-runoff data without providing any evidence the model is physically sound. Nevertheless, any improvement in the assessment of these roughness coefficients would undoubtedly help model performance.

In conclusion, this study probably lays a new brick on what could be a physics-based hydrological model for urban areas. Most existing models of urban hydrology provide a detailed description of sewer system hydraulics, yet still rely on very crude parameterizations of the upstream runoff formation and concentration. The contribution of streets had not often explicitly been taken into consideration in urban runoff modeling to the extent that roads were in natural settings (Smith and Brilly, 1992; Luce and Cundy, 1994; Moussa et al., 2002). The model proposed in this paper constitutes an initial attempt at taking this contribution into account and warrants being extended to the explicit simulation of runoff transfer at the HE scale. Such a model would provide street-scale knowledge of storm input to the sewage systems, in accordance with urban management objectives, and should be able to handle the rapidly-evolving morphology of urbanized areas.

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