Applying a GIS-based geomorphological routing model in urban catchments

Julien Lhomme*, Christophe Bouvier, Jean-Louis Perrin

UMR Hydrosciences Montpellier, Maison des Sciences de l’Eau, Université Montpellier II, Place Eugène Bataillon, Case Courrier MSE, 34095 Montpellier Cedex 5, France

Abstract

This paper discusses using a GIS-based geomorphological routing model to simulate urban stormwater runoff as an alternative to physically based routing models. Hydrological measurements have been carried out (1982–1984) in the urban catchment El Batán (52 km²), which forms part of the city of Quito (Ecuador). As detailed data on the drainage network were available, a first attempt was made using, on the one hand, complete Barré de Saint-Venant equations in the network and, on the other, the linear reservoir model for the sub-catchments. Knowing both the geometry and hydraulics of the network was proved to achieve accurate simulations. However, collecting the network data and building the whole topology (reaches, nodes, sub-catchments) of this large urban catchment is very time-consuming work. Thus, grosser representations of the network to simulate runoff were tested, but it was found that the estimation of the concentration time becomes predominant, and may result in a significant loss of accuracy. Using a GIS-based geomorphological routing model is shown to be an efficient alternative: first, physical velocities in the reaches can be derived from slopes and upstream areas; second, the integration of these velocities in a distributed lag and route model produces flood simulations that are equivalent to the physically based routing model; third, Digital Elevation Models avoid most of the tedious preliminary tasks in building the catchment topology. Further investigation is required in order to evaluate variations in the lag parameter from one catchment to another.

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Keywords: Urban stormwater drainage; Geomorphological routing model; Physically based routing model; Digital Elevation Model; South America

1. Introduction

Stormwater runoff has been modelled in urban hydrology for both drainage design and real time control applications. As drainage networks exhibit regular geometry, the physically based models using Barré de Saint-Venant (BSV) equations are often used for simulations of urban stormwater runoff when detailed data are available (Fugazza, 1993). However, processing these data and building the complete topology of the catchment by means of nodes, reaches and catchment units can be very time-consuming work, and the workload increases with the size of the catchment. Chocat and Cabanne (1999) studied
the sensitivity of the model to a reduction in the number of reaches, and concluded that no significant loss of accuracy occurs when this number decreases. In extreme cases, conceptual lumped models such as the linear reservoir model (Desbordes, 1987) are often used when no drainage data are available. However, estimation of the parameters of this kind of model may be difficult because of its lack of a physical basis, and rainfall-runoff data are generally required in order to calibrate the model.

In natural catchments, it is known that the Digital Elevation Model (DEM) can be very helpful in applying routing models. First, physical interpretation of the routing models can be based on geomorphology (Rodriguez-Iturbe and Valdes, 1979; Gupta et al., 1980; Moussa, 1997). One advantage is that the physical velocities can be derived from geomorphological characteristics of the catchment, such as slopes and upstream areas (Moniod, 1983), which DEM can easily provide. A second advantage is that a detailed representation of the flow paths can also be easily derived from DEM, (Maidment, 1993; Muzik, 1996). For urban catchments, the flow paths can also be derived from DEM, but must be modified to account for buildings and artificial networks (Rodriguez et al., 2000).

However, the DEM has not yet often been used for urban catchments, and the objective of the paper is to evaluate the performance of GIS-based geomorphological routing models through a study case based on the city of Quito (Ecuador). The first part of the paper deals with the study area and the available data. In the second part, a physically based model is performed through the CANOE package, and the accuracy of the simulations of the observed events is discussed using either a complete or partial representation of the drainage network. In the third part, the GIS-based model is described, and then calibrated and compared with the physically based model. Conclusions are drawn for a more general application of geomorphological models in urban catchments.

2. Study area and available data

The city of Quito (Ecuador) has been growing considerably over the last two decades, and has now reached almost 2 million inhabitants. The drainage network of the city has also been developed, and detailed data for both geometry and hydraulics are available. The El Batan catchment is located in the northern part of Quito and covers an area of 52 km². The altitude ranges between 4400 and 2760 m. The catchment can be divided into two distinct units (Fig. 1):

- The upstream natural unit (22 km²), which is located on the slopes of the Pichincha volcano. Here, elevations range from 4400 down to 3000 m. This unit is characterized by steep slopes ranging from 20 up to 70%, which are deeply gashed by numerous ravines. A previous study (Perrin et al., 2001) has shown that this natural unit contributes little to runoff, less than 10% of the rainfall amounts.
- The downstream urbanized unit (30 km²), which is located on a fault step at a mean elevation of 2850 m. The density of built-up areas is fairly high and the imperviousness coefficient is estimated at around 40–50%. The drainage system was installed early in the period of urban development of this area, and can be seen in Fig. 1.

This catchment was monitored continuously during the period 1982–1984, with six rain gauges (rain recorder with tipping bucket) and a stream gauge (water level recorder with floating device). During this period 31 events were recorded, whose peak flows...
at the outlet ranged from 20 to 100 m$^3$/s (Table 1). Rainfall amounts in 24 h did not exceed 60 mm at the gauges; however, this value should be considered as a 10-year return period value in this high-altitude equatorial climate (Bouvier et al., 1999).

3. Application of CANOE$^\text{w}$ model

3.1. Main features of the model

CANOE$^\text{w}$ (INSAVALOR, Sogreah Ingenierie, 1997) is an engineering software dealing with urban stormwater drainage, and can be compared with other softwares like MOUSE$^\text{w}$ (Danish Hydraulic Institute, 1995), HYDROWORKS$^\text{w}$ (Wallingford, 1997) or SWMM$^\text{w}$ (Huber and Dickinson, 1998). The CANOE$^\text{w}$ model is based on a topology of reaches and sub-catchments, each sub-catchment being connected to a node between two distinct reaches. Using it in our context, we considered that:

(i) rainfall is assumed to be uniform on a given sub-catchment, and is computed by Thiessen interpolation;

(ii) runoff from a sub-catchment can be represented by mean of a classical initial losses and constant coefficient runoff model;

(iii) effective rainfall is routed at the outlet of the sub-catchment by applying a linear reservoir model,

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<th>Date</th>
<th>Areal rainfall in 24 h (mm)</th>
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<th>Point maximum intensity in 5 min (mm/h)</th>
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of which parameter $K$ depends on the slope, the area, the length and the imperviousness coefficient of the sub-catchment; and

(iv) flow is routed in the drainage system by applying the complete 1D equations of BSV, which are solved by using an implicit finite differences scheme (six steps Preismann scheme). The matrical system is resolved by a double sweep method.

3.2. Building the catchment topology

The available data about the drainage system define a set of 864 reaches, for which the length, the slope, the Manning roughness coefficient, the type and the dimensions of the pipes and channels are known. As mentioned above, each node of the drainage system defines an elementary catchment, of which the main characteristics—area, slope, length, and the imperviousness coefficient—must then be determined in order to estimate both the runoff coefficient and the parameter of the linear reservoir model. Due to the high number of elementary catchments, a DEM was used in order to extract the area of each elementary catchment. The mesh of this DEM was $25 \times 25$ m$^2$. The first step was to modify the drainage flow paths of the cells according to the artificial drainage system. This can be accomplished by subtracting a constant depth (for example 50 m) for each cell crossed by a pipe or a channel, and then processing the new flow paths. The areas can then be processed from the DEM, knowing the coordinates of each node. The slopes and length could also have been extracted from the DEM, with an appropriate algorithm, but this was not done. The following assumptions were used: the catchment slope was set as 1.5 more than the corresponding reach, and the catchment length was derived from the area $A$ of the elementary catchment, as $\sqrt{2 \times A}$ (considering the sub-catchments are squares). For the catchments connected to the upstream node of a drainage reach, the slope was set at 25% (because the upstream catchments are located on the slopes of the Pinchincha volcano, right near the city of Quito). Finally, we obtained a set of 781 elementary catchments, whose mean characteristics are given in Table 2. Despite the fact we simplified assumptions, building the complete catchment topology proved to be very time-consuming.

3.3. Performances of CANOE® using the whole representation of the drainage system

CANOE® was first performed using all available information about the drainage system. For simplicity’s sake and because of the relatively high amounts of the rainfalls corresponding to the flood events, initial losses in the sub-catchments were not considered. The runoff coefficients $C$ were assumed to be different for main units: urban areas and natural areas, but constant in space and time within each unit. This is not necessarily the case, namely in natural areas, but Perrin et al. (2001) showed that the natural part of the catchment produces little runoff, so that the assumption of a constant coefficient does not generate much uncertainty in simulations of the complete hydrographs at the outlet of the whole catchment. For the same reason, a constant value $C=0.05$ can be adopted without significant loss of accuracy.

The runoff coefficient of the urban areas was then calibrated from the available rainfall-runoff data (31 events), using a minimization of the Nash criterion, $C_{\text{Nash}}$

$$C_{\text{Nash}} = 1 - \frac{\sum_{i=1}^{N} (U_{\text{sim}}(i) - U_{\text{obs}}(i))^2}{\sum_{i=1}^{N} (U_{\text{obs}}(i) - \bar{U}_{\text{obs}}(i))^2}$$

where $U_{\text{sim}}$ and $U_{\text{obs}}$ are the simulated and the observed variable, respectively, $N$ is the number of data to compare. In the present case, $U$ denotes the runoff volumes and $N$ the number of events.

$C=0.4$ was thus found to be convenient for urban areas, with a corresponding value of 0.73 for the Nash criterion (Fig. 2). The majority of the uncertainties are

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<th>Mean area (ha)</th>
<th>Mean slope (m/m)</th>
<th>Mean length (m)</th>
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Table 2
Mean characteristics of the 781 elementary catchments defined from a detailed representation of the drainage system.
assumed to come from spatial variability of rainfall, which is poorly grabbed from only six rain gauges (i.e. density of 8.7 km$^2$/rain gauge, and the mean inter-distance is 4.2 km). Indeed, for daily rainfalls, spatial correlation coefficients in Quito are less than 0.5 when the distance between two points is 5 km (Bouvier et al., 1999).

No calibration was made for the routing parameters. Both hydraulic and geometric characteristics of the drainage reaches were used directly, whereas the lag-time of each elementary catchment was derived from Desbordes’ formula, which was set from 21 urban catchments located in France, Europe, and the United States (Desbordes, 1974)

$$K = 5.3A^{0.3}C_{\text{imp}}^{0.45}I^{-0.38}$$

where $A$ is the catchment area (ha), $I$ is the catchment average slope (%), $C_{\text{imp}}$ is the catchment imperviousness coefficient (–).

$C_{\text{imp}}$ was considered as the runoff coefficient $C$ defined for each type of elementary catchment ($C_{\text{imp}}=0.4$ or 0.05). The complete hydrographs of each rainfall event were then computed, using a 30 s time step and 30 m space resolution for the numerical application of the BSV equations. Rainfall was interpolated in each sub-catchment by applying Thiessen method to the six rain gauges.

With these assumptions, it can be seen that both computed and observed peak flows are very close together (Fig. 3), as are the complete hydrographs (Fig. 4). An event Nash criterion between observed and computed discharge flows was computed for each event: the mean value of these event Nash criteria is 0.70. A global Nash criterion was also processed from the observed and computed peak flows of the whole set of events, and was found to be 0.82. It can be assumed that the majority of the errors on discharge rates result from the errors on the runoff volumes.

It was then shown that the model was little sensitive to the values of the lag-time of each elementary catchment. Using for example $K_1=2 \times K$ or $K_2=0.5 \times K$ instead of $K$ for every sub-catchment does not alter the hydrographs very much (Fig. 5). This can be explained by the smallness of the elementary catchments, which makes the routing in the drainage system very predominant when using the complete available data. Thus, in the case of a dense drainage system, just knowing the characteristics of the reaches is sufficient to successfully route the flows at the event scale applying BSV equations. Consequently, the description of the elementary catchments may not be very accurate, when the representation of the drainage system is as dense as it is in Quito. This can greatly simplify the use of this kind of model.

3.4. Sensitivity of CANOE® using partial representation of the drainage system

Another way to perform CANOE® more easily is not to use all the available data on the drainage system. Thus we considered a simplified configuration
(Fig. 6), where the extension of the drainage network was considerably reduced. The urban catchments are still defined as upstream areas at the nodes of the reach, but due to the simplified configuration, their number was reduced from 760 to 41 (Table 3). The slopes of these catchments were calculated using the ratio between both maximum and minimum elevation of the sub-catchment and the hydraulic length. The natural sub-catchments are the same as in Section 3.2.

Still using Desbordes’ formula, it appeared that peak flows were then underestimated by more than 20% compared with those simulated with the complete representation of the drainage system. Better results can be obtained by using $0.5 \times K$ instead of $K$.
of $K$, as shown in Fig. 7. The formula appears thus to be inadequate in this context, maybe because the slopes range beyond the domain of validity of the formula.

As a limiting case, we also performed CANOE without taking into account the drainage system, but considering the catchment as only two main units—urbanized and natural—directly connected at the outlet. The linear reservoir model was then applied to each one of these units, the slopes being calculated as described above, i.e. 25% for the natural catchment, and from the ratio between elevation and the hydraulic length for the urban catchment. It was shown that in this case, using $0.5 \times K$ instead of $K$ still led to a better simulation (Fig. 8).

Thus, although the partial representation of the drainage system may help to simplify the application of the model, it also makes the simulations more sensitive to the lag-time estimation of the elementary catchments. Consequently, the accuracy of the model depends to a large extent on the use of an adequate estimation, which is generally not warranted. The example above shows that the lag-time estimations provided by Desbordes’ formula might need to be corrected in Quito, whereas this was not necessary in the city of Lyon (France) as shown in a similar study by Chocat and Cabanne (1999).

4. Application of the MERCEDES model

4.1. Main features of the model

A GIS-based geomorphological routing model was then performed to tackle previous difficulties. MERCEDES operates on the basis of grid-cell discretization of the catchment (Bouvier et al., 1994; Bouvier and Delclaux, 1996). Similar models have also been proposed by Maidment (1993), Zech et al. (1993), and Olivera and Maidment (1999). The main features of the MERCEDES model can be summarized as follows:

(i) flow paths are derived from a DEM in order to interconnect the cells;
(ii) rainfall at each cell and each given time is calculated from the observed rainfall by the Thiessen method;
(iii) effective rainfall is derived from calculated rainfall, using a constant runoff coefficient for a given set of cells;
(iv) effective rainfall is routed directly downstream to the outlet by means of a lag and route model, with no interaction with other cell flows (Fig. 9).

Each effective rainfall input $p(t_0)$ at a given time $t_0$ and for a given cell $m$ produces an elementary hydrograph at the outlet, combining a travel time $T_m$ and a diffusion time $K_m$. The lag process operates through a linear reservoir model, of which the diffusion time $K_m$ is the parameter, so that the elementary hydrograph at the outlet may be expressed as

$$q(t) = \begin{cases} 0 & \text{when } t < t_0 + T_m \\ \frac{1}{K_m} \exp \left( - \frac{t - (t_0 + T_m)}{K_m} \right) p(t_0) \Delta x^2 & \text{when } t > t_0 + T_m \end{cases}$$

where $p(t_0)$ is the effective rainfall (m), $K_m$ the diffusion time (s), $t_0$ the time when the rainfall

Table 3
Mean characteristics of the 62 elementary catchments defined from a partial representation of the drainage system

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input appears (s), $T_m$ the travel time (s), $\Delta x$ the length of the cell (m); and

(v) all the elementary hydrographs are finally added in time and space, in order to get the complete hydrograph at the outlet

$$Q(t) = \sum_m \int_0^{t_m} \frac{1}{K_m} \exp\left(-\frac{t - (\tau + T_m)}{K_m}\right) \times p(\tau) \Delta x^2 \, d\tau$$

where $m$ describes all the grid cells of the catchment.
The travel time $T_m$ from a given cell down to the outlet can be defined as

$$T_m = \sum_k \frac{L_k}{V_k}$$

(5)

where $L_k$ is the cell length ($25$ or $25 \times \sqrt{2}$ m here, depending on whether the direction of the flow path is transversal or diagonal), and $V_k$ the velocity of the flow over the cell (m/s).

A geomorphological expression of this velocity may be used (Moniod, 1983)

$$V_k = V_0 \times i_k^{0.5} \times S_k^{0.2}$$

(6)

where $i_k$ is the cell slope (m/m) and $S_k$ the upstream area of the considered cell (km$^2$). $V_0$ is a coefficient that depends on the roughness (m km$^{-0.4}$/s).

It is also assumed that $K_m$ is related to $T_m$

$$K_m = K_0 \times T_m$$

(7)

which expresses that the diffusion increases linearly with the travel time. The diffusion emulates physical effects such as: (i) variations in velocity in a cross-section; and (ii) variations in velocity depending on the hydraulic head. The parameter $K_0$ must be considered as an empirical parameter. It is however expected that this empirical parameter will not depend on the catchment.

Note that the distributed lag and route model performs a linear transformation of the effective rainfall, in the sense that the velocities may vary for each cell, but do not vary in time at the event scale. It could be thus necessary to calibrate $V_0$ for each event in order to account for a possible non-linearity of the routing processes, i.e. the biggest floods may have a shorter response time than minor floods. This will be discussed in the following sections.

4.2. Estimation of the geomorphological velocities

As seen above, the geomorphological velocities may be derived from Eq. (6), after estimating the coefficient $V_0$.

For urban cells, $V_0$ was estimated by fitting Eq. (6) from the physical velocities of a large set of reaches. For each reach, the physical velocity was referenced as the velocity corresponding to the discharge capacity, i.e. the maximal flow that can run through the channel or the pipe. This physical velocity was then computed by the Manning–Strickler formula, considering the known features of the reach (form and dimensions of the cross-section, slope and Manning friction coefficient of the reach). Only reaches for which the slope is less than 5% were selected (515 reaches from the total set of 816 reaches), because if not, the Manning velocity may greatly overestimate real maximum velocities. The geomorphological velocities were computed by using the slopes of the reaches and the upstream areas at the terminal downstream nodes of the reaches, which were given by the DEM.

Both physical and geomorphological velocities were found to be linearly dependent, and very close
together when \( V_0 = 27 \text{ m km}^{0.4}/\text{s} \), which corresponds to a determination coefficient \( R^2 = 0.73 \) (Fig. 10). This \( V_0 \)-value was then applied for routing flows through all urban cells, whether or not they belong to the drainage system.

Thus, it appears that both slopes and upstream areas are able to characterize the hydraulic pattern of the drainage system. This highlights the fact that designing a drainage system is very dependent on local geomorphological conditions. Because of this kind of relationship: (i) the velocities in the drainage system could be derived from a DEM if no data are available; and (ii) from a practical point of view, it should be possible to calibrate \( V_0 \) with a much smaller set of reaches, and a short field survey could be sufficient in order to calibrate \( V_0 \) for ungauged catchments.

For natural cells, the estimation of \( V_0 \) was done following Moniod’s recommendations (1983), i.e. values of \( V_0 \) between 3 and 5 m km\(^{0.4}/\text{s} \). As mentioned above, runoff contribution from the natural areas is much less than from urban areas, so that the relative uncertainty of the \( V_0 \) value does not have a significant influence on simulations. We finally chose the value \( V_0 = 5 \text{ m km}^{0.4}/\text{s} \) for natural cells.

### 4.3. Calibration of the geomorphological lag and route model

In this section, the simulations performed with MERCEDES are compared to those performed by
of the catchment. No additional stream gauges being available, we used as reference the discharges and velocities computed by CANOE® to prove that MERCEDES does not depend on a scaling effect.

Thus, four additional points were defined upstream from the outlet (Fig. 13). The areas upstream from these points vary from 2.3 up to 8.0 km²; maximum velocities vary between 2.7 and 3.8 m/s according to the CANOE® modelling of the 18/10/1982 storm event. Other features of the selected sub-catchments are given in Table 4. Of course, effective rainfall is identical in space and time whether simulations are made with CANOE® or MERCEDES. The comparison of the simulated hydrographs whether using CANOE® or MERCEDES still shows very good agreement and the estimation of parameters \( V_0 \) and \( K_0 \) does not depend on scaling effects.

5. Conclusions

Two alternative stormwater routing models were compared in the urbanized El Batan catchment where detailed data of the drainage system were available. The physically based model proved to be very accurate in simulating the complete hydrographs of flood events observed between 1982 and 1984 when using the detailed representation of the drainage system. Indeed, in this case, the hydrographs do not depend to a great extent on the response of the catchment.
Fig. 13. Simulations of the 18/10/1982 event (peak flow = 35 m$^3$/s) at five catchment-points (including the El Batan outlet).
the elementary catchments, which are small. However, building the whole topology of reaches and elementary catchments was found to be very time-consuming. Thus, a second attempt was made using a partial representation of the drainage system. But some problems arose because simulations became much more sensitive to the response of the elementary catchments, which could not be estimated directly.

The distributed geomorphological lag and route model was then applied as an alternative to the physically based model. The topology was built from regular square grid cells, which can greatly simplify preliminary operations in the preparation of the geographical data. It was shown that this model could lead to very accurate simulations by using a reduced set of two parameters, which do not depend on the event. By fitting the geomorphological velocities with the expected physical velocities in different reaches of the drainage system, it was possible to determine the first parameter, $V_0$. The second parameter, $K_0$, was calibrated at this stage, and the value $K_0=0.5$ was found to be convenient for simulating hydrographs at the outlet of the catchment as well as at the outlets of four sub-catchments. The $K_0$ parameter proved to be unaffected by scaling effects, but further investigation is now needed to see if this empirical value will work for other catchments.

Thus, this distributed lag and route model could help in several ways. First, it allows simplification of the preliminary operations in building of the topology. Second, it can account for the drainage system when data are not available, by matching the geomorphological evaluation of the velocities with the physical velocities estimated from selected reaches. Third, the assumption that the spatial organization of the velocities is governed by geomorphological conditions could be used more generally when no drainage network exists in urbanized areas, which is sometimes the case in cities in developing countries; adequate case studies could supply a relevant estimation for $V_0$ in such a case.

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### References


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