Development of a distributed hydrological model based on urban databanks - Production processes of URBS

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Abstract

The objective of this study is to present a distributed hydrological model especially dedicated to urban catchments, and able to represent hydrological processes usually neglected in urban modelling, such as evapotranspiration, infiltration in roads, or direct infiltration of soil water in sewers. This model, called URBS (as Urban Runoff Branching System) is distributed considering the spatial variability of land use which is well known thanks to urban databanks managed by GIS. The production function is detailed at each cadastral parcel scale, and the runoff produced is routed by a simple transfer function. The estimation of the input parameters of the model is mostly based on physical considerations, and the model has been first applied on a small sub-urban catchment (Rezé, 5 ha) in order to evaluate the performance of this production function. Both the water fluxes from the different land use types and the saturation level have been analysed and compared to those data, the results are encouraging.

INTRODUCTION

The rainfall-runoff transformation on urban catchments involves various physical processes. Soil-atmosphere interface processes encompass evapotranspiration and interception by the vegetation. Soil surface processes regroup infiltration of water in the soil, surface runoff and evaporation of surface and soil water. Sub-soil processes consist in the interflow, and the drainage of the soil water by trenches and sewer pipes defects. Urban rainfall-runoff models do usually not take into account all these processes. The most usual concept of modelling is the constant runoff coefficient concept (Desbordes, 1987) considering a water budget to be defined by initial constant losses, which occur at the beginning of the rainfall event, and a subsequent runoff coefficient. This type of models has proved to be satisfactory for design studies, but encounters difficulties in correctly simulating the response of urban catchments, especially in case of moderate events (Rodriguez et al., 2000). Linear runoff production functions are not able to reproduce the variability observed in the flow coefficient (Hollis and Ovenden, 1988; Becciu and Paoletti, 1996), the flow coefficient being defined as the ratio of the volume of outflow water to the volume of precipitated water during a rainfall event. Classical urban models ignore the water flow in the vadose zone, or represent the surface infiltration of natural zones in a simple manner, for instance by using Horton infiltration equation in CANOE (INSAVALOR et al., 1997). A more physically based approach seems to be necessary for a better understanding of the hydrological behaviour of urban catchments, taking into account the physical processes listed before. The hydrological response of a catchment is indeed sensitive to these processes, such as the role of soil in the generation of runoff (Berthier, 1999), and especially the infiltration of soil water in sewers (Belhadj et al., 1995). Determining this infiltration makes it necessary to know the saturation level. Moreover, evapotranspiration and interception were often ignored in most urban hydrological works, despite their significant role in the hydrological budget (Grimmond and Oke, 1991). However, some researches were recently developed in this field : Jia et al. (2001) present a distributed hydrological model which takes into account both water and energy transfer processes, to simulate spatially variable water and energy processes in watersheds with

complex land use covers. The rainfall interception by urban forestry has been modelled by Xiao et al. (2000) and proves to be significant.
Parallel to these statements, the continuous growing of cities makes it necessary to integrate innovative stormwater techniques in their practices. These techniques favour infiltration of rainwater, in order to reduce runoff volumes and/or rainwater pollution. By the way, urban planners have to face to new questions : is it possible to store rainwater in the soil at any location of one catchment? To take into account theses new requirements, hydrological modelling practices have to be adapted. Especially, they should focus on a more physically based approach, including both a better description of the urban spatial and temporal variability, and a more detailed representation of physical processes at local scale. The available geographical information in cities could be very useful to achieve this aim : urban environment is well-documented, thanks urban databanks. This documentation allows for a detailed description of surface characteristics of urban elements, and makes it easier a distributed approach of hydrological modelling.

The aim of this work is to present a hydrological model based on urban databanks and able to reproduce the spatial and temporal variability of hydrological processes on urban catchments. This distributed model, called URBS as Urban Runoff Branching Structure, includes a morphological description of the urban environment on a hydrological point of view (Rodriguez et al. 2003). The main objectives of the model are (i) to determinate continuously the different components of rainwater fluxes, such as the surface runoff coming from the different land use types, and the soil runoff, coming from the infiltration of water into water systems through sewer defects (ii) to indicate the saturation level and the capacity of soil to infiltrate water on long data series. This paper is devoted to the description of the production function of URBS. The first section introduces the main descriptive elements deduced from urban databanks. Then, the hydrological processes represented in the model are introduced. The third section is devoted to the application of the model on a small urban catchment and the first results of this are presented.

DESCRIPTION OF AN URBAN HYDROLOGICAL ELEMENT (UHE)

The urban databanks (UDBs) available in cities enable to represent an urban catchment through elementary runoff concentrating surfaces and the hydrographic network. This representation is based on the main structural elements of the city, i.e. the cadastral parcels and the street network. The urban cadastre map available in many French urban databanks (Figure 1a) encompasses the main geographical elements required to describe hydrological processes in an urban catchment (Rodriguez et al., 2003) : (i) cadastral parcels, houses, street sections and possibly vegetation serving for a 2D description of the urban surface, and (ii) topography, street segments, storm sewers and rivers for the description of the hydrographic network, hereafter designed as Runoff Branching Structure (RBS). The RBS is a vector map of water flow paths along street gutters and inside the sewer network, from each UHE up to the outlet (Figure 1b). Elementary runoff concentrating surfaces are called Urban Hydrological Elements (UHEs), each of them encompassing one cadastral parcel and its corresponding adjacent street portion. Each UHE is connected to the street and thus to the RBS. The geometrical characteristics of this UHE encompass surface area, impervious fraction including building and street surface area (covered by trees or not), vegetation fraction, slope and length, the connection point to the RBS and the depth of the drainage network at this point. These characteristics allows for both a surface representation of the UHE and its cross section. This cross section is then decomposed in three land use types, including house, street and natural soil, each of them being possibly covered by trees (Figure 2a). Three vertical profiles corresponding to each land use type are defined for each UHE. Each vertical profile is discretised into 3 reservoirs representing the surface, the vadose zone and the saturated zone of the soil. This representation is illustrated in Figure 2b. In this paper, we will focus on the modelling of the hydrological processes inside one

Hydrological Element, the transfer processes on the catchment being described by Rodriguez et al. (2003).

DESCRIPTION OF THE HYROLOGICAL PROCESSES IN THE MODEL

Physically based hydrological models generally have an explicit representation of the vadose zone behaviour. To do that, the resolution of Richards equations is traditionally made by using a numerical method, with finite volumes or elements (Berthier, 1999). The main objectives of the model being to represent all hydrological processes on long data series and with short time steps, a simple method has been implemented here. This method assumes a schematic representation of both the soil and the water flow processes, based on a vadose zone reservoir which maximal depth is a priori not limited. Each vertical profile belongs a vadose zone inside which the water content is uniform. The hydrological processes are described along the following steps.

Firstly, rainfall interception by trees has been modelled by using the model of Calder (1977).

Then, water flows through each land use type (denoted *) have been modelled following the same vertical scheme (Figure 2b):

- The surface is represented by an interception reservoir filled by rainfall P_t* which throughfall under the possible vegetation, and emptied by evaporation E*, infiltration I_{NSZ}* and surface runoff R*. The evaporation flux is assumed to be proportional to potential evapotranspiration and to the water stored in the reservoir. The infiltration flux is both controlled by atmospheric conditions and by land use conditions. Surface runoff occurs when the surface storage exceeds the maximal capacity S^*_{max}
- The vadose zone of the soil is represented by a reservoir filled by infiltration from the surface and by capillary rises I_{SZ}* from the underlying saturated zone, and drained both downwards by percolation I_{SZ}* (the fluxes are calculated by Darcy's law) and upwards by transpiration TR from the root zone in the natural soil profile (root depth z_{root}). The water content in this zone is assumed to be vertically uniform, and the Brooks and Corey relations (Clapp and Hornberger, 1978) exhibit the variation of suction head and hydraulic conductivity with the volumic water content. The vadose zone is mainly parameterised by the hydraulic conductivity at natural saturation K^*_S (null for the house land use type).
- The level of the saturated zone of the soil is represented in the model. It increases with the contribution of the upperlying vadose zone and decreases both by capillary rise and by direct drainage in sewers if surrounding soil has become saturated. This direct drainage has been estimated by considering the pipe to act like an ideal drain (Gustafsson et al., 1996) :

$$I_{sew}(t) = K_S\ (z_{SZ})\ \Delta t\ \frac{\lambda}{L_i}\left(z_i - z^i_{net} - z_{SZ}\right)^{\mu},$$

where z_{sz} is the saturated level, $z_i - z^i_{net}$ the sewer network depth, L_i the UHE length, λ and μ two parameters depending on the type and the status of the drain and the trench containing the drain. This drainage may be separated into 2 components, drainage into the wastewater drainage network and drainage into the rainwater drainage network. We introduced a factor $f_{sew\text{-}rw}$ able to represent the fraction of these two components, depending on both the presence and the relative positions of drainage networks, and possibly deduced from UDBs.

At each time step and for each UHE, the saturated level is averaged from the saturated levels encountered in each land use type, permitting the lateral fluxes in the vadose zone.

The runoff at the outlet of one UHE is the sum of the different flow contributions, encompassing the runoff flow of each land use type, and the groundwater drainage.

$$Q(t) = A^{hou}\ R^{hou}(t) + A^{str}\ R^{str}(t) + A^{nat}\ R^{nat}(t) + A^{tot}\ f_{sew\text{-}rw}\ I_{sew}(t),$$

where A* represents the surface of each land use type in the UHE, and R* the runoff produced by each land use type.

IMPLEMENTATION OF THE MODEL

Principles

This work is aimed at evaluating a production function model able to simulate both the different components of runoff flow, and the hydrological behaviour of the subsurface soil. This model has been elaborated through a realistic representation of hydrological processes in urban catchments, this representation being parameterised by among 15 parameters. Most of them may be estimated from literature review or field measurement, and from a previous explicit modelling of this UHE (Berthier, 1999). A sensitivity analysis has been led in order to compare the influence of the different parameters on the simulation of both runoff flow and saturation level. This analysis shows the importance of the parameter governing direct infiltration into sewers (λ) and of the soil hydraulic conductivity ($K^{nat}{}_S$). A comparison between observed and measured hydrological variables will serve as a basis for this evaluation. No calibration procedure has been implemented in this work.

Case study

A small urban catchment (5 ha) serves for the application of the model. It's located in the French city of Rezé, near Nantes (western France). The drainage network of this catchment is composed of separate sewers, and its land use consists of single-family housing. The impervious surface connected to the drainage network is 37% and the soil is considered as a silty clay. This catchment has been continuously monitored since 10 years (Berthier et al., 1999) and has already been used for hydrological modelling tests (Rodriguez et al., 2000; Rodriguez et al., 2003) The data measured encompasses : (i) the rainfall intensity and the discharge at the outlet from 1991 up to 2002; (ii) the daily water table level through three piezometers installed at two locations of the catchment, from September 1995 up to December 1998; (iii) groundwater drainage runoff, measured during three winter periods in wastewater drainage network (Belhadj et al., 1995), and provides a good estimation of both rain- and waste-water drainage (Berthier, 1999); (iv) meteorological data such as Penman evapotranspiration, collected from the meteorological station located 5 km from Rezé. Figure 3a regroups the different measurements and shows the catchment morphology.

Application of the model on Rezé catchment

Given the homogenous type of housing (Rodriguez et al., 2003), the 70 cadastral parcels of the catchment have been represented by a single UHE which morphological features, deduced from UDBs, are presented on Figure 3b. The response time of this catchment is short, i.e. inferior to 10 minutes; as this work focus on the production function processes, no transfer process was taken into account for this application. Continuous simulation has been performed during 10 years using a 1-hour time step. The base run has been initialised thanks a realistic set of parameters, listed in Table 1. The parameter λ has been adjusted in order to minimize the deviation between observed and simulated volumes.

FIRST RESULTS

All results presented below are dependent on the chosen parameter configuration, and constitutes a first attempt to explain the hydrological behaviour encountered on this catchment. Three comparison criteria were used for this model's evaluation : the Nash criterion (denoted C_{Nash}), the correlation coefficient (denoted R^2) and a bias criterion (denoted C_b). The rainfall events have been selected through an automatic procedure and the values of flow rate volumes and flow coefficients have been determined. From 1991 to 2000, the rain event sample is constituted of 850 events which rainfall intensity exceeds 1 mm/h.

Simulation of a rainfall event

The simulation of a rain event with the base run is presented in Figure 4. This graph plots the different contributions to runoff at the outlet of the catchment due to a rainfall event of February, 1996, and shows the importance of traditionally neglected processes, such as the base flow, reproduced by the infiltration of water into drainage network I_{sew} and especially notable in winter. Moreover, the contributions of impervious surfaces are quite similar, because these surfaces were already wet at the beginning of the event. For this event of 35 mm rain depth, the surface runoff caused by non-covered surfaces is delayed but important, because of the saturation level, which varies from –0.7 m at the beginning of the event to –0.55 m at the end of the event.

Simulation of runoff flows

Three types of results have been compared. Firstly, the instantaneous hourly flow rates Q have been compared to the observed ones. Then, for each rain event, the flow rate volumes V and flow coefficient C_F have been compared to the observation (Table 2). There is a good correspondence between simulated flow rate volumes V or instantaneous flow rates Q and the observations. The URBS model reproduces half of the observed flow coefficient variability (R^2=54%), and the shape of the simulated histogram is close to the observed histogram, both similar to a gaussian distribution.

Moreover, the model allows for the comparison of the main hydrological fluxes for the given analysis period. The Figure 5a represents the simulated fluxes occurring in the representative UHE. Values are expressed as a percentage of gross rainfall on the whole period, and the results are indicative, because dependant on the parameter configuration used. However, the simulations show some interesting point. For instance, the total evaporation represents 50 % of the gross rainfall and the rain interception by trees is not totally negligible (2.7%). The main contribution to the flow rate encompasses the runoff on streets (7.5%) and the runoff on houses (15.1%) but the direct infiltration into sewers represents more than 10% of the total rainfall. These fluxes are not really validated because of the lack of appropriate data, but are in correspondence with experimental results (Hollis and Ovenden, 1988; Belhadj et al., 1995).

Simulation of saturation levels

Due to the representation of the catchment with one sole UHE in the model, the simulated saturation level is assumed to be uniform, since the piezometric measurements are located on two points on the catchment. The comparison will consequently focus on the dynamical evolution of saturation levels during two years of available data (Figure 5b). Both the simulated and observed levels increase during winter and decrease during summer. The variation of simulated level agrees with the observations, except for summer 1998 where the model is not able to reproduce the particularly strong and fast decrease of the saturated level; this decrease could be of anthropic origin (for instance, pumping).

CONCLUSIONS

This first application of URBS model to a small urban catchment proves the possibilities offered by this kind of modelling. The Reze catchment has been modelled by a single UHE and the main rainwater fluxes has been simulated continuously during 10 years. The model has been evaluated through the comparison of these simulations with observed flow rates during the whole period and with observed saturation levels during two years. The model allows for the representation of water fluxes often neglected in urban areas (evapotranspiration, soil infiltration into sewers) and shows that they could be significant, in accordance with previous experimental studies. The application of the model to a larger catchment has not been presented here but has highlighted the relevance of distributed modelling (Morena, 2004), by showing a spatial representation of most hydrological variables, such as the capacity of soil to store water. This model could contribute to create a development-aid tool for urban catchments, and a possible application of this is the representation of innovative stormwater technologies and the determination of their influence on the hydrological behaviour of an urban area.

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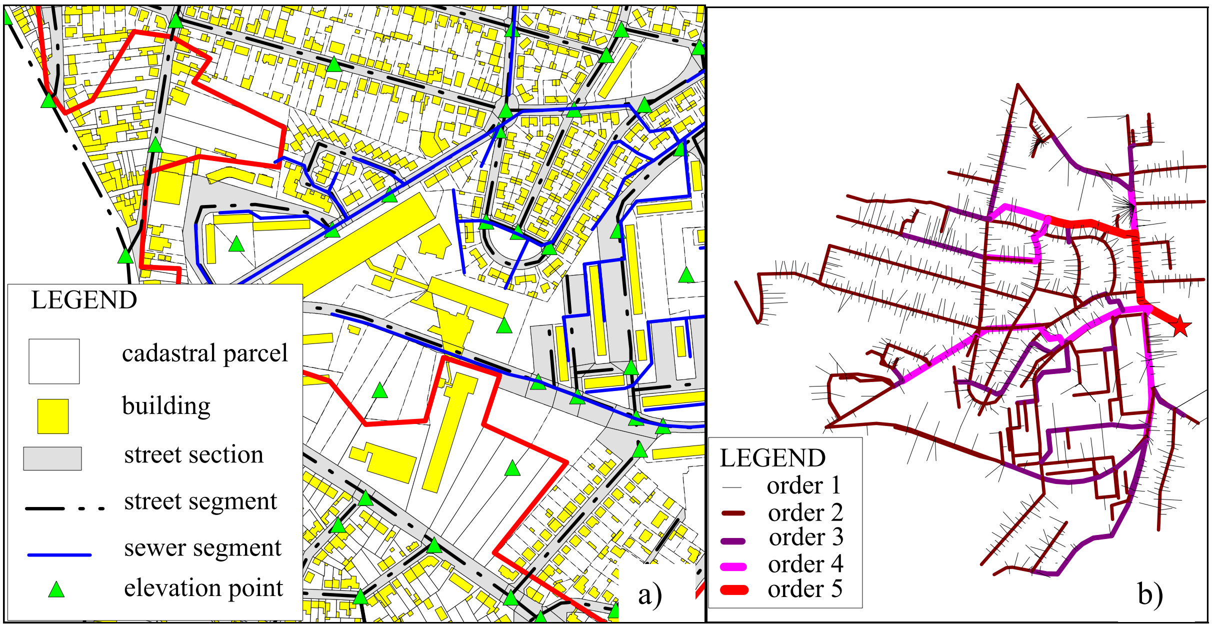


Figure 1 - a) Presentation of the main elements of urban databanks (city of Nantes); b) Illustration of the RBS map of an urban catchment, ordered with Strahler scheme

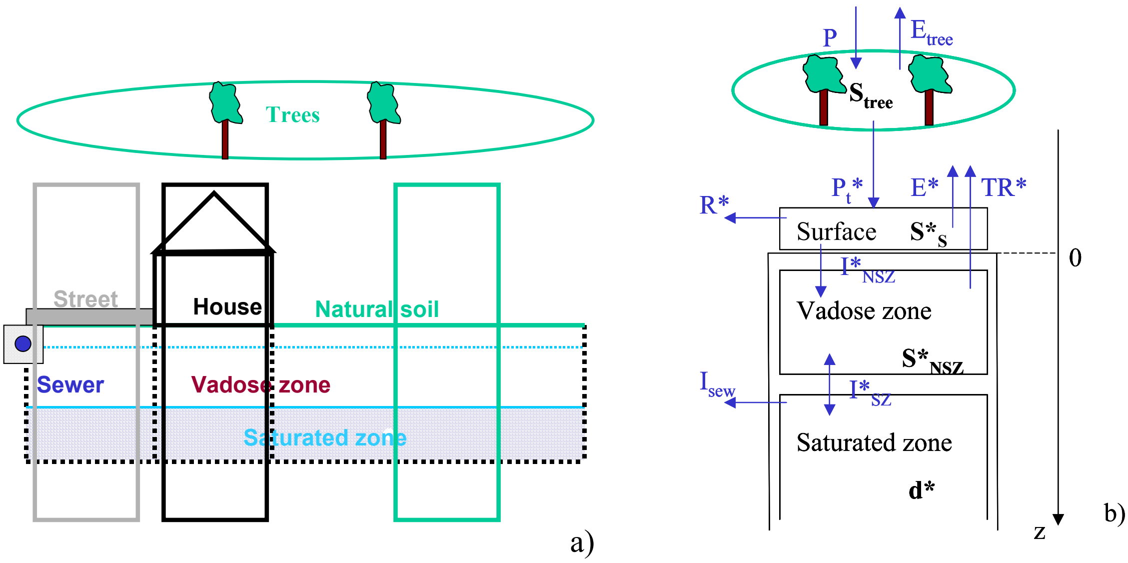


Figure 2 a) UHE cross section ; b) Detail of one vertical profile with associated water fluxes

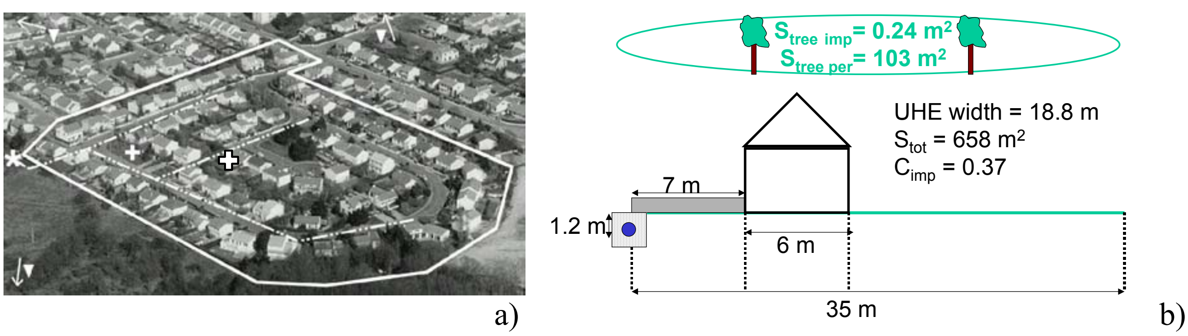


Figure 3 – a) Rezé catchment : crosses shows the piezometers location, the star the outlet, and triangles the pluviometers; b) Morphological characteristics of the representative UHE

Table 1- Parameters of URBS model applied to Reze

	parameter		natural soil	street	house
Surface	S^*_{max}		5.0	3.5	0.5
	K^*_s		1.3 E-05	7.5 E-08	0
soil	θ_S	0.43			
	Ψ_e	0.20			
	b	5.00			
	M	0.20			
	z_{root}	1.30			
sewer	λ	4.00			
	μ	2.00			
	f_{drain_sew}	0.37			

Table 2 – Comparison criteria for simulations of runoff volumes, flow coefficient and instantaneous flow rates for the whole period

	C_b	R^2	C_{Nash}
V	+1.40 %	0.95	0.95
C_F	-0.48%	0.54	0.50
Q	+2.02 %	0.88	0.86

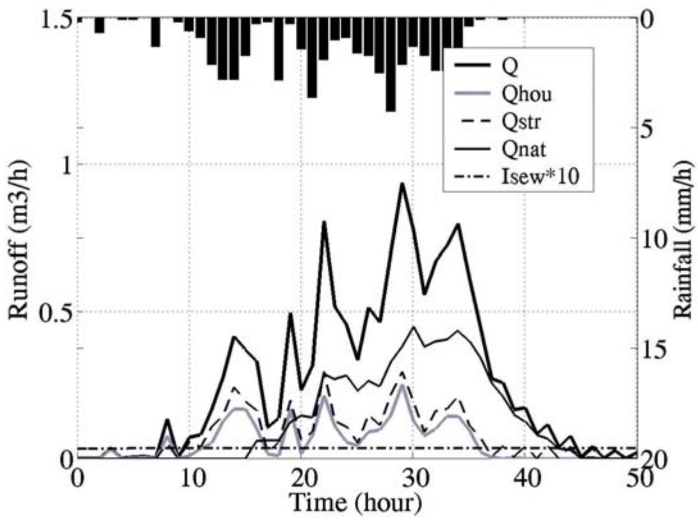
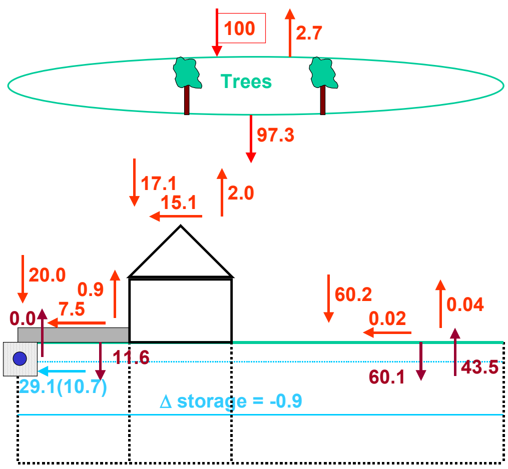
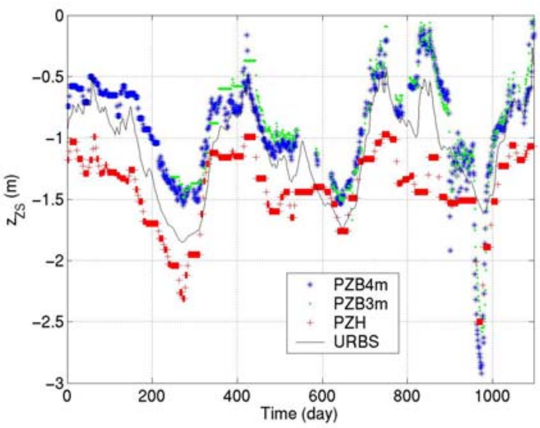


Figure 4 –Runoff contributions simulated with URBS model on Rezé catchment (23/02/1996)



a)



b)

Figure 5 – a) Simulated rainwater fluxes on Reze catchment (01/01/1991 – 31/12/2000) ; b) Evolution of simulated and observed saturation levels (01/01/1996 – 31/12/1998) - PZB4m, PZB3m and PZH represents the differents piezometers -