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Development of the Integrated Urban Hydrological Model URBS: Introduction and Evaluation of a Transfer Module in the Saturated Zone

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ABSTRACT

Development in sustainable stormwater management in cities needs adapted modelling tools, which can consider urban water cycle in an integrated manner, by modelling hydrological fluxes as well as hydric state of the urban soil. The latter become particularly important when stormwater is handled with innovative point of view treating the resource or/and climatic aspects of rainwater. Yet circulations of rainwater within urban areas are complex and are not described in a detailed manner. Integrated urban hydrological models keep on being updated. This paper presents our work as a contribution to the development of such a model. A saturation module has been implemented to the integrated model URBS. The new model runs continuously at a short time step over long periods. Model evaluation is based on its capacity to reproduce saturation level and runoff measurements. This study shows the importance of modelling groundwater movement that is highly influenced by buried sewer networks. This attempt on module implementation demonstrates the potentiality of constructing integrated model by coupling existent models in appropriate ways.

KEYWORDS

Urban hydrology, groundwater drainage, integrated model, URBS, distributed, saturation

INTRODUCTION

Progress in the understanding of hydrological processes on urban catchments and new challenges in urban water management face to climate change stimulate the development of best management practices for stormwater (Marsalek, 2013). These new practices, favoring infiltration of rainwater in the soil, require more understanding of urban water cycle as well as development of integrated modelling tools capable of considering urban hydrological processes as a whole.

Urban runoff as a reaction to storm events depends not only on characteristics of the precipitation it-self but also pre-event moisture state under the ground. This well-know relation in rural catchments hydrology can be extended to urban catchments, despite of the main contribution of impervious surfaces to water runoff. From this point of view, urban soils, recharged continuously by infiltration from land surface, can no longer be neglected in urban runoff analysis, as suggested in (Berthier *et al.*, 2004). Under influences of underground infrastructures such as the sewer networks, circulation of subsurface water is far from being easily understood. Interactions between sewer system and groundwater remain current topic of research. Groundwater flow representation as an integrated part should be benefit for an urban hydrological modelling tool.

The present paper shows a work dedicated to the development of an integrated urban hydrological model. A groundwater flow module is introduced to the URBS model in order to represent water flux of the saturated zone in an adequate and parsimonious manner.

MODEL DEVELOPMENT

A brief recall of the URBS model

URBS, short for Urban Runoff Branching Structure, is a distributed hydrological model for urban catchment developed since about 10 years. Detail model descriptions could be found in (Rodriguez *et al.*, 2008).

Based on urban data banks, URBS models the rainwater fluxes and hydric states of urban soil (saturation level, storage capacity) at the parcel scale, and then coupled with a detailed description of the hydrographic network. A parcel, acting as an urban hydrological element (UHE), is divided into three vertical profiles based on land use: natural soil, street and house. Each profile is composed of four reservoirs representing respectively trees, ground surface, vadose zone and saturated zone. The model capability to correctly simulate flow rate and saturation levels has been proved for Rezé and Gohards catchment of Nantes city (Morena, 2004; Rodriguez *et al.*, 2008).

Soil processes modelling in URBS and implementation of the saturation module WTI

The soil is represented through a parameterization of the vadose zone and the saturation deficit. Sewer system is represented by its drainage effect for groundwater. The hydraulic conductivity at saturation is K_s^{nat} is assumed to be isotropic and decrease exponentially with depth, as inspired by work on Top Model (Beven and Kirkby, 1979).

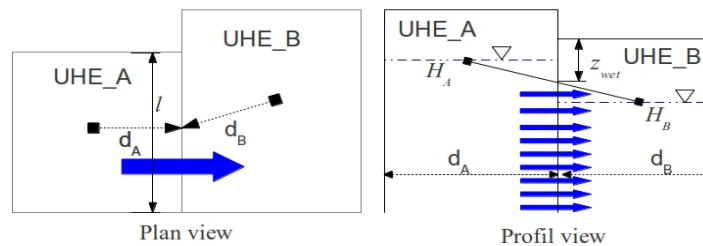


Figure 1. Schematic diagram of the implementation of WTI in URBS.

Lateral flow of the saturated zone between adjacent UHEs is not represented in URBS and the saturation level could be abruptly different from one UHE to another. An attempt on coupling URBS and MODFLOW[®] has been realized by Le Delliou (2009). The coupling results were not totally satisfying due to various reasons among which we can quote the difference in soil conception in the two models. A suitable approach for developing the saturation modeling should keep the soil configuration of URBS as well as its spatial discretization. Branger (2007) developed, for the platform LIQUID, a water transfer module that can simulate lateral flows among irregular flow-generation elements. The so-called WTI (Water Transfer Interface) module has proved to be adequate and robust (Branger, 2007; Jankowfsky *et al.*, 2010). Considering the similarity between the flow-generation elements in LIQUID and UHEs in URBS, we adopted the WTI module for URBS.

Figure 1 illustrates the principles of the module implementation. At each time increment, water flow between adjacent UHEs A and B is calculated basing on Darcy's law that is applied on their intersection surface, called “interface”. Darcy's equation is given by:

$$Q_{A \rightarrow B} = K_{int} \cdot S \cdot \frac{H_A - H_B}{d_A + d_B}$$

where $Q_{A \rightarrow B}$ is the water flow from UHE_A to UHE_B that can be positive or negative, K_{int} the hydraulic conductivity applied on the interface, S the area of the interface, H_A and H_B the hydraulic heads, $d_A + d_B$ the distance of the geometry centers of the UHEs. With respect to the initial model, K_{int} kept the exponential decay in depth. Thus, the volumetric flux through the whole interface was the integration of the flux through each unit surface of the interface.

In URBS, water table is modeled by saturation deficit and substratum is not represented. This

configuration has been kept for WTI module, i.e. no bottom limit was set for an interface. The total flow through an interface was computed by the improper integral of elemental flows on the interface, as illustrated in Figure 1, and expressed as:

$$Q_{A \rightarrow B} = \int_{z_{wet}}^{\infty} -K_s \cdot l \cdot \frac{H_A - H_B}{d_A + d_B} \cdot \exp(-z/M) dz$$

where l is the length of the interface and z_{wet} the wet level of the interface, which is estimated by the weighted average of groundwater levels of UHE_A and UHE_B. Since the limit to $-\infty$ of exponential is 0, the integral converges and the antiderivative is given by:

$$Q_{A \rightarrow B} = K_s \cdot l \cdot M \cdot \frac{H_A - H_B}{d_A + d_B} \cdot \exp(-z_{wet}/M)$$

At the end of each time step, the equation was applied for every interface. The total quantity of water in or out of one UHE was obtained by summing on its interfaces with neighbor UHEs. The saturation level of the UHE was then updated for the next time step.

MODEL EVALUATION ON A BASE RUN

Methodology for application and evaluation

In order to evaluate the impact of the saturated module to the model (URBS-WTI herein after), a base run has been carried out on Pin Sec catchment for the period 01/01/2006-31/12/2010 at a 5-min time step (Figure 2).

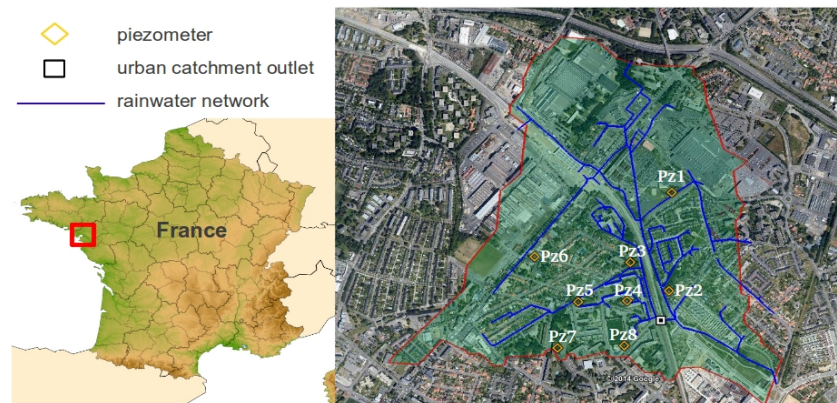


Figure 2. Hydrogeological watershed of Pin Sec.

Pin Sec is an urban catchment located in the East part of Nantes city in France. As an experimental catchment of the ONEVU (“Nantes observatory of urban environments”), part of the research federationIRSTV, Pin Sec contains a separated sewer network and has been monitored since several years. The data measured comprises: (i) rainfall intensity; (ii) water table level observation by eight piezometers; (iii) discharge at the outlet of the rainwater drainage network; and (iv) climate data such as Penman-Monteith evapotranspiration.

The urban catchment of Pin Sec is contained in a hydrogeological watershed (120 ha) which is delimited topographically. The model was applied on the whole hydrogeological watershed for which a zero-flux boundary condition has been set. Given the proximity of Pin Sec to Rezé and Gohards catchments (see “A brief recall of the URBS model”), the same parameter values (Table 1) have been kept for the base run. Only the parameters related to WTI module are retained in Table 1.

Evaluation of the saturation module focused on four types of results: (1) water budget, (2) volumetric discharge at the stormwater network outlet during rainfall events, (3) saturation levels at the piezometers and (4) standard deviation of the simulated saturation levels of the UHEs.

Results of the base run

Water budget evaluation. With WTI implemented, the model produced almost the same water budget as its initial version, as illustrated in Table 2. Evapotranspiration (ET) represents more than 40% of the total rainfall. Natural land use, as well as impervious surfaces, contributes to runoff. This natural soil contribution, somewhat surprising by its importance (16.6%), is coherent with the results for Rezé catchment presented in (Morena, 2004), where natural soil runoff amounts to 10% of the total rainfall with initial parameters before calibration. Groundwater drainage (Q_{drain}) represents 9.9% of the total rainfall, as divided between the wastewater (6.6%) and stormwater (3.3%) networks.

Discharge simulation. Comparisons of flow volume during rainfall events were based on three criteria: bias criterion (C_b), Nash criterion (denoted C_{nash}) and the determination coefficient R^2 , as showed in Table 3. The WTI module did not a priori change flow rate simulation of URBS, with relatively low C_b as well as high C_{nash} and R^2 .

Saturation level simulation. Simulated saturation level at each piezometer is obtained by the average of UHEs situated within a 50-meter circle. The variations in simulated saturation level have certain agreements with observations for both URBS and URBS-WTI, with a mean R^2 value of 0.7 (Table 3). However, the simulations overestimated saturation levels in the piezometers, with weak C_{nash} (not presented here).

Table 1. Physical parameters and values of URBS-WTI on Pin Sec watershed.

Parameter	Unit	Description	Value	Variation range
K_s^{nat}	m/s	Hydraulic conductivity at saturation of the natural land use	1.3e-5	0.2 – 3
M	-	Scaling parameter of the hydraulic conductivity	0.2	1.e-8 – 1.e-4
λ	-	Groundwater drainage coefficient	4	0.05 -10
Z_s_{ini}	m	Initial uniformed saturation level for the catchment	0.65	0 -100

Table 2. Water budget simulated by the base run, expressed in percentage of the rainfall.

	Q _{roof}	Q _{str}	Q _{nat}	Q _{drain}	ET	Δ storage	P
URBS/URBS-WTI	16.6	13.9	13.6	9.9	44.9	1.1	100

Table 3. (1) Comparison criteria of runoff volumes during rainfall events at the stormwater network outlet of Pin Sec; (2) R^2 of saturation levels of the eight piezometers (Pz1 – Pz8).

	Runoff			C_b	C_{nash}	R^2			
	Pz1	Pz2	Pz3	Pz4	Pz5	Pz6	Pz7	Pz8	mean
URBS/URBS-WTI				0.20/0.21	0.724/0.719	0.856/0.863			
URBS/URBS-WTI	0.54/0.54	0.74/0.74	0.64/0.64	0.58/0.58	0.54/0.54	0.83/0.83	0.82/0.82	0.88/0.88	0.70/0.70

Homogeneous effect of WTI. Figure 3 shows the standard deviation σ of the ground water levels in the UHEs simulated by URBS and URBS-WTI. With WTI, the model had the σ slightly reduced. Seasonal variations of σ have not been palliated. One possible explication is the relative shallow level of the groundwater: compared to climate factors such as precipitation, subsoil water flow may play less important roles to the groundwater level.

Summary of the model base run. The base run results of URBS-WTI for the 5-year period with default parameter values were not totally satisfying and revealed a couple of information: (1) the new module WTI did not influence the general behavior of URBS model (neither deteriorate its simulation quality); (2) contrary to our exceptions, the homogenization effect of the saturation module was not important. The flow exchange generated by WTI module seemed to be overtaken by other processes. In adjusting some parameter values, the model should function differently. A parameter sensitivity study presented below will show us if the

model sensitivity has been impacted by the saturation module, as well as if some of the parameters could strengthen its homogenization effect.

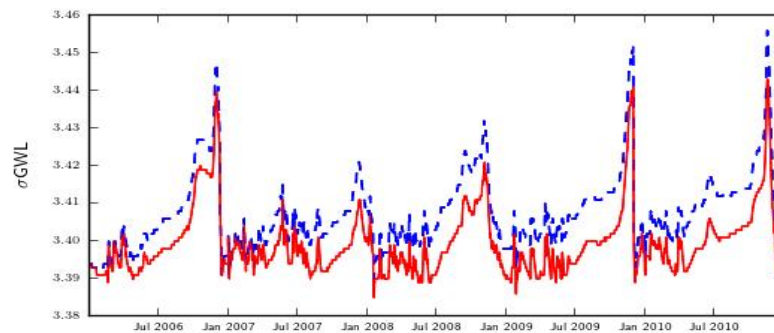


Figure 3. Standard deviation of the ground water level (GWL) simulated by URBS (dotted line) and URBS-WTI (solid line).

SENSITIVITY ANALYSIS

Methodology

The model sensitivity should not be different but only for parameters that operate on WTI module, i.e. the hydraulic conductivity at saturation K_s^{nat} and its scaling parameter M , controlling the exponential decrease of the hydraulic conductivity. Given the direct control of the lateral conductivity on WTI flows but not the vertical one, a new parameter K_s^{lat} was introduced to present the lateral hydraulic conductivity. The drainage coefficient λ controls water drainage by sewer network and must have direct impact on groundwater levels.

The simulations have proved to be quite time and memory consuming. Meanwhile, Morena (2004) has demonstrated that the model warm-up period was less than 3 months. For these reasons, the sensitivity analysis was based on one-year simulation of 2010. The one-factor-at-time method has been adopted to evaluate the effect of each parameter. The results of each simulation were compared to the base run results based on the outlet flow volume during rainfall events and the saturation levels of the piezometers. For the saturation levels, the criteria (C_b , C_{nash} and R^2) are represented by their mean value of the eight piezometers. For each parameter set, the results of URBS and URBS-WTI were compared.

Results and discussion

Some 40 tests have been taken out with different combinations of values for the three parameters mentioned above. Table 4 summarizes the most meaningful results.

Regarding the model parameter sensitivity, URBS-WTI has not changed much compared to URBS. Both models are sensitive to soil parameters, especially for values which increase water flows, i.e. strong values of K_s^{lat} , M and λ . Meanwhile, with high water flows, URBS-WTI tends to get better results than URBS for flow rate: criteria values had a tendency to be higher. R^2 of saturation levels are also improved by WTI. C_{nash} of saturation levels are still weak. This could be explicated by the fact that Nash criterion is more influenced by strong bias. In adjusting certain parameter values, we were able to upgrade C_{nash} for certain piezometers. But improving the simulation quality for every piezometer at the same time was practically impossible. Note that the saturation level has been initialized uniformly at the watershed, a distributed saturation level initialization seems worth to be tried.

Based on the sensitivity study results, the “best” parameter set was defined (Table 5). With the calibrated parameter values, criteria values have risen significantly for saturation levels, and in a slight manner for runoff volume (Table 5). Figure 4 illustrates saturation levels at each piezometer simulated both by URBS and URBS-WTI, compared to measurement data. Simulations of Pz3 and Pz5 had satisfying agreement with the observations both in temporal

evolution and in absolute water table level, except the fact that some certain increase and decrease were not well reproduced. Pz1, 2, 4, and 7 were well reproduced for their seasonal evolutions, but not the absolute saturation levels. Simulations of Pz6 and Pz8 were mediocre. As mentioned in the previous paragraph, seeking better simulations results for some of the piezometers in adjusting parameter values were always accompanied by deteriorating simulations in other piezometers. The “best” parameter set was selected from a general view on comparing the criteria values. As for sharp increase and decrease in observation data that were not reproduced, Rodriguez *et al.* (2008) proposed two explications. Whether it is due to climate reasons, e.g. dry (wet) periods causing rapid decrease (increase) groundwater levels that could not be reproduced by the model, or to observation data, e.g. natural variations being fluctuated by unnatural factors (underground construction for example), the phenomena is worth of examinations in future studies. Performance regarding the flow rate has been kept, strong agreement as found between simulation and observation during rainfall events with low values of bias criterion and high values of C_{nash} and R^2 .

Generally speaking, with WTI the model has improved its capability to simulate groundwater level: the simulated saturation levels by URBS-WTI agreed better to measurement data than that by URBS, except for Pz2 where the two models have given almost the same curve. Figure 5 illustrates the standard deviation of the simulated saturation levels of the UHEs by the calibrated run. With WTI, saturation levels seem to be efficiently homogenized. Further statistical analysis on the distribution of the saturation level over the catchment through more powerful mathematic methods may be interesting and will be subject of future studies.

Water budget with this calibrated parameter set is presented in Table 6. The main contribution to runoff stems from impervious surfaces, with 16.7% from roofs and 10.3% from streets; the natural soil contribution to flow rate is close to zero. Groundwater drainage by sewer network reached to 30% of the rainfall, which is consistent with the results found other studies (Braud *et al.*, 2013; Hollis and Ovenden, 1988; Rodriguez *et al.*, 2008). This result reconfirmed the important drainage role of the underground sewer network to soil water.

Table 4. Results of the sensitivity analysis.

			Saturation levels			Runoff volume		
			Cb	C _{nash}	R ²	Cb	C _{nash}	R ²
Ref (K _s ^{nat} =1.3e-5; M=0.2; λ=4)			-0.72/-0.73	-33.9/-35.4	0.700/0.700	0.20/0.21	0.724/0.719	0.856/0.863
K _s ^{lat}	1e-4	URBS/URBS-WTI	-0.64/-0.63	-26.0/-26.1	0.867/0.868	0.04/0.05	0.889/0.890	0.916/0.922
	1e-6	URBS/URBS-WTI	-0.76/-0.73	-38.4/-35.3	0.749/0.776	0.37/0.38	0.410/0.399	0.788/0.795
M	0.1	URBS/URBS-WTI	-0.73/-0.73	-35.2/-35.2	0.762/0.762	0.31/0.31	0.541/0.535	0.829/0.829
	2	URBS/URBS-WTI	-0.50/-0.43	-14.9/-13.5	0.844/0.821	0.07/0.08	0.882/0.897	0.915/0.932
λ	0	URBS/URBS-WTI	-0.78/-0.76	-41.5/-40.1	0.660/0.701	0.08/0.53	0.082/0.167	0.522/0.832
	30	URBS/URBS-WTI	-0.65/-0.65	-27.3/-27.3	0.786/0.786	0.04/0.04	0.889/0.889	0.916/0.916

Table 5. Comparison criteria for simulation with calibrated parameters.

Calibrated parameter values: K _s ^{lat} =1.3e-5 m/s; M=2; λ=30								
			Saturation level			Runoff volume		
			Cb	C _{nash}	R ²	Cb	C _{nash}	R ²
URBS/URBS-WTI			-0.13/-0.07	-4.54/-2.91	0.656/0.733	-0.06/-0.03	0.901/0.904	0.913/0.917

Table 6. Water budget simulated by calibrated run, expressed in percentage of the rainfall.

	Q _{roof}	Q _{str}	Q _{nat}	Q _{drain}	ET	Δstorage	P
URBS/URBS-WTI	16.7	10.3	0.4	30.9	37.2	4.5	100

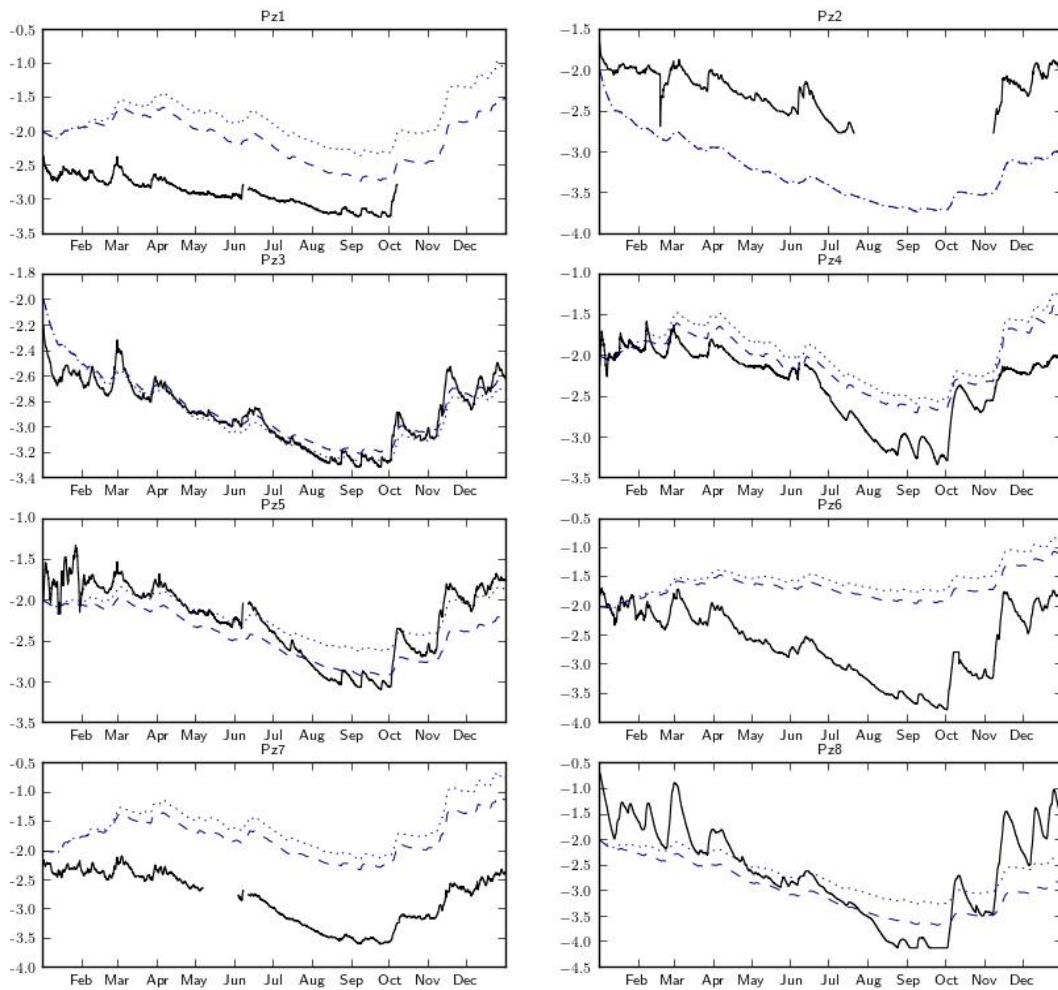


Figure 4. Saturation levels observed in piezometers (solid lines) and simulated by URBS (dotted lines) and by URBS-WTI (dashed lines) for the calibrated run.

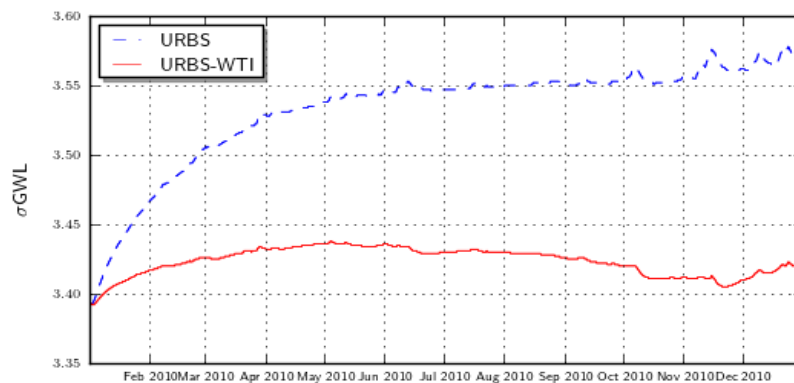


Figure 5. Standard deviation of the groundwater level simulated by WTI (dashed line) and by URBS-WTI (solid line).

CONCLUSION

This study has presented a development of the integrated urban hydrological model URBS. A saturation module has been implemented into the model. This module computes water transfer between two water production units (UHEs) corresponding to urban parcels. This module uses Darcy's law that is applied on all the interfaces of two UHEs. The modelling results were

compared to piezometric and flow observations on the experimental catchment of Pin Sec based on various criteria. The comparisons confirmed the effectiveness of the module to reproduce saturation levels, particularly its homogenization effect, while keeping the performance in simulating flow rate and water budget of the initial model.

The modelling results confirmed the drainage role of sewer network on groundwater. Meanwhile, the assumption according to which water circulation within the urban saturated zone is fully controlled by sewer networks need further examination, as sharp increase and decrease on the observation curves have not been able to be reproduced by the model. Other processes rather than drainage need to be examined.

The evaluation of such module proved to be difficult. On one hand, numerous available observation data by piezometers offered us large possibilities to compare the simulation results; on the other hand, the different evolutions in the piezometric observation made it impossible for the model to reproduce. Urban soil can be highly heterogeneous and groundwater circulations could be quite complex and controlled by various factors, including human activities. Considerations of these factors into the model would be beneficial, but challenging. A comparison with a more detailed 2D-3D groundwater model, such as models based on variable Richard's equation, would possibly offer another angle for judging the performance of URBS-WTI. But representing underground facilities in such models would not be easy work.

In the context of rapid progress in sustainable stormwater management, integrated modelling tools capable of representing the whole water cycle, including subsurface water circulations controlled by drainage processes, as URBS-WTI, could offer a model coupling example and contribute to urban hydrological modelling development.

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