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Development of a suburban catchment model within the LIQUID® framework

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Abstract: The world-wide trend towards a growing urbanization mainly affects suburban areas. These areas are subject to rapid modifications such as an increase of impervious areas, concentration of runoff in sewer systems, river regulations, but also a decline of agricultural areas causing a forest increase. These changes have an impact on the local hydrology and can induce floods, pollution or decrease of groundwater resource. Distributed hydrological models are useful tools for water management in these areas. They can simulate floods or the impact of land use scenarios on the water balance. This paper presents the PUMMA model (Peri-Urban Model for landscape MAnagement), dedicated to the hydrology of suburban catchments. The model is built within the LIQUID® modelling framework. LIQUID® facilitates the development of PUMMA by providing a set of modules for different hydrological processes, templates for easy development of new modules and module coupling mechanisms. PUMMA follows an object-oriented approach. The landscape is discretized into cadastral units in urban areas and irregular hydro-landscapes, resulting from intersection of land use, geology, soil and sub-basin maps in rural areas. Each model unit represents one implementation of a module. The considered hydrological processes are infiltration in natural soils and hedgerows; overland flow in urban zones and over roads, storage in storm water retention basins and flow routing within networks consisting of ditches, natural rivers and sewer pipes. Several drainage networks can coexist and interact, which allows the modelling of complex suburban drainage systems. The paper presents the model structure and a first application to a simple test case.

Keywords*:* Suburban; LIQUID®; distributed hydrological modelling; sewer system; ditches;

1. INTRODUCTION

All over the world people migrate towards cities, causing an encroachment of built-up areas in their peripheries and a change in agricultural practices. This has an impact on land use, like an increase of impervious areas and a decline of agricultural areas for the benefit of forests. The change in land use influences the hydrological processes in a catchment. Furthermore, urbanization is often followed by installation of sewer systems, river regulations or more recently construction of retention basins. Often, a faster catchment response is the result of these anthropogenic modifications, causing floods, a decrease of groundwater resource and a higher risk of water contamination. The optimization of water management in these areas can be obtained by application of distributed hydrological models. They offer the possibility to take into account land use or climate change, and more particularly to consider urbanized areas [Franczyk and Chang, 2009; Semadeni-Davies et al. 2008]. Regarding suburban areas, several questions arise: How to handle the landscape heterogeneity in suburban areas? How to deal with different time scales with fast hydrological response in urban zones and slower response in natural zones? How to simulate different parallel drainage systems with multiple outlets and interactions, such as overflow sewer devices? How to integrate the fast changes in suburban areas into the model? Regarding all these questions, an adaptable modelling approach seems appropriate. Using a modelling framework instead of a single model has the advantage that different processes can easily be coupled and that new processes/objects can be added without much difficulty. We propose an object oriented approach based on the LIQUID$^{®}$ modelling framework [Viallet et al, 2006]. Among all the existing modelling frameworks (WaterCAST [Cook et al., 2009], JAMS [Kralisch and Krause, 2006], OpenMI [Gregersen et al., 2007], etc.) LIQUID was chosen due to several reasons: It can handle irregular geometries, physically based and conceptual approaches can easily coexist, each process has its own time step, feedback between process modules is easily possible, water flow paths do not have to follow topography, all code is written in C++ and new process modules can be added straightforwardly. Furthermore, the computation time can be minimized by use of irregular time steps, which allows computations to be performed only when required. The LIQUID framework is presented in more detail in a companion paper [Branger et al., 2010b]. This paper presents the Peri-Urban Model for landscape MAnagement (PUMMA) built within the LIQUID$^{®}$ framework and adapted to small suburban catchments. First a description of the model discretization, retained for suburban areas is given, then the structure of the model and the model components are presented. In section 3 the model is applied to the Rezé catchment, France and the results are discussed.

2. DESCRIPTION OF THE PUMMA MODEL

2.1 Model mesh

The model mesh of the PUMMA model consists of irregular hydro-landscapes [Dehotin and Braud, 2008] representing hydrological response units (HRUs). In the rural area the HRUs are created by intersection of detailed land-use maps, geology, soil and sub-basin maps. The sub-basins are calculated using the stream-burning technique [Hutchinson, 1989] in order to obtain one sub-basin for each river and artificial ditch reach. The urban area is discretized into urban hydrological elements (UHE) [Rodriguez et al., 2008] encompassing one cadastral unit (typically house plus surrounding garden) and half of the adjoining street. The UHEs are connected to the closest drainage network, which can consist of a sewer pipe or a natural ditch.

2.2 Model

The Peri-Urban Model for landscape MAnagement (PUMMA), intended for the detailed simulation of water fluxes in suburban areas, is under development within the AVuPUR (Assessing the Vulnerability of Peri-Urban Rivers) project [Braud et al., 2010]. It is an extended combination of the BVFT model [Branger et al., 2008], which was developed for the assessment of the hydrological impact of landscape management practices and of the URBS model [Rodriguez et al., 2008] for urban areas, which was integrated into the LIQUID$^{®}$ framework. As in the BVFT model the choice of the modules in PUMMA depends mainly on the land-use properties. Five main modules are involved: URBS for urban hydrological elements, FRER1D for natural surfaces, HEDGE for hedgerows, SIMBA for retention basins and lakes and RIVER1D for the drainage network. Figure 1 shows a vertical landscape profile with the applied modules and modelled water flow paths. Each model unit (HRU/UHE) represents one module instance. We can see that infiltration is the main process in forests and fields, modelled with the FRER1D module. By setting the soil hydraulic conductivity to zero, FRER1D can also model overland flow, for example on streets. URBS, which is applied on each UHE, models overland flow and infiltration. The natural river and the artificial drainage network are modelled with RIVER1D. HEDGE is applied to vegetated field borders and riparian zones. The subsurface flow exchange is modelled with interfaces, explained in part 2.4. The next two paragraphs explain the modules in more detail, their connections, and the construction of the final model.

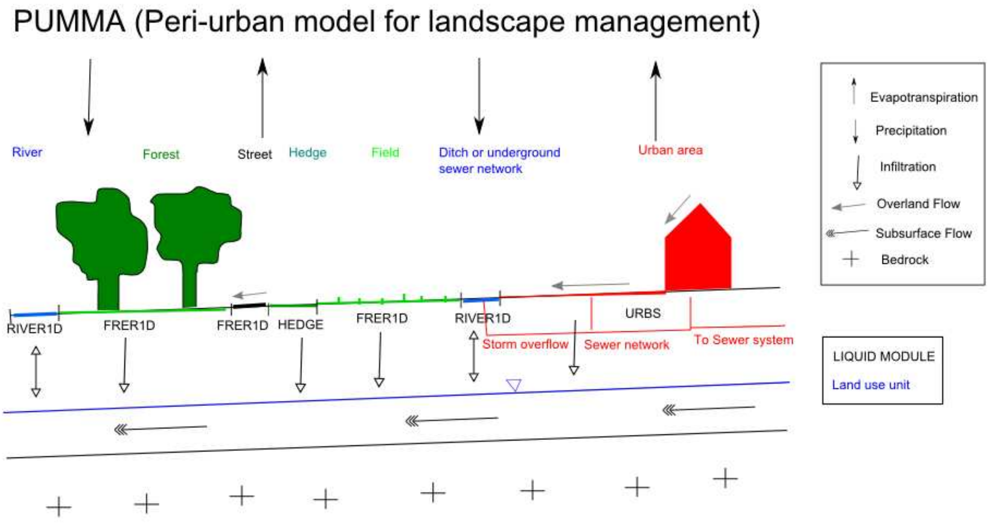

Figure 1. Vertical landscape profile with different land-use units and the corresponding modules. The arrows indicate the modelled rainwater fluxes.

2.3 Modules

The URBS module [Rodriguez et al., 2008] calculates the components of the rainwater flux at the UHE scale. The UHE is divided into three land-use classes: street, impervious area and natural area. Each land-use class is represented by four reservoirs (tree, surface, vadose zone and saturated zone), which are connected due to vertical water fluxes. With this representation it is possible to describe the following processes: interception by trees, evapotranspiration, surface runoff, soil infiltration and infiltration into sewer pipes due to sewer defects. The ideal drain approach [Gustafsson et al., 1996] is used for the calculation of the network infiltration, which can be observed in most sewer systems due to cracks. The FRER1D module represents vertical infiltration over natural surfaces using a 1D resolution of the Richards equation [Ross, 2003; Varado et al., 2006]. As input of the FRER1D module, the evapotranspiration is calculated in an extra set of modules, integrating the effects of crop rotation and root extraction. Following the approach of Viaud et al. [2005], the conceptual HEDGE module calculates the water table dynamics and evapotranspiration processes below hedgerows. Lateral flow in the saturated zone is considered in HEDGE, FRER1D and URBS modules due to source/sink terms. The SIMBA (SIMulation of storage BAsins) module, developed especially for the PUMMA model, uses a simple linear reservoir equation to simulate retention basins or natural lakes. It has a lower outflow depending on the hydraulic head and an overflow. Evaporation, precipitation, irrigation and water exchange with the groundwater table are taken into account due to source/sink terms. Natural river network, ditches and sewer system are modelled with the RIVER1D module [Branger et al., 2008], which calculates a solution of the one-dimensional kinematic wave approximation [Moussa and Bocquillon, 1996]. The flow velocity is calculated with the Manning-Strickler equation. The drainage network is divided into several reaches that can receive lateral surface and subsurface flows. Each reach can have a different cross section (rectangular, trapezoidal or triangular) and Manning coefficient value.

Input modules allow the distribution of rainfall and potential evapotranspiration over the model units. Nearly all the current state variables such as soil moisture content, river reach discharge and actual evapotranspiration can be extracted as distributed output.

2.4 Spatial coupling

The spatial coupling between different modules is realised by means of interfaces (Figure 2). They simulate the subsurface flow between adjacent model units. The Water Table Interface (WTI) uses the Darcy law to calculate the subsurface flow between agricultural fields, hedgerows and urban cadastral units. The water exchange between river, or lake and adjacent agricultural field/hedgerow is computed in the Water Table River Interface (WTRI) based on the Miles [1985] approach. The calculated flow direction depends on the hydraulic head inside the model units and is thus bidirectional. Depending on the flow direction the computed discharge, which is taken into account in the receiving modules due to source or sink terms, is positive or negative.

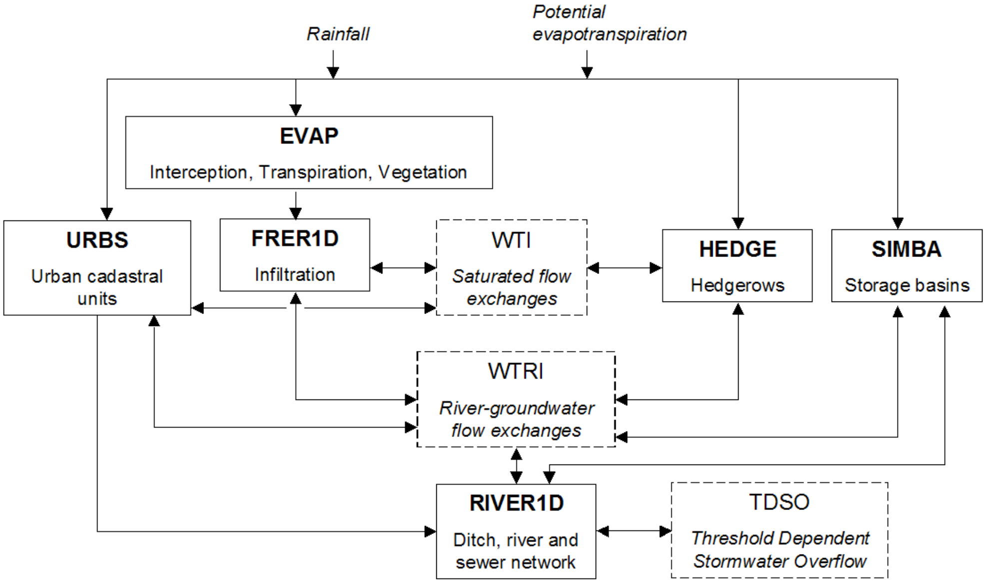

Figure 2. Structure of the PUMMA model and couplings between the modules.

At the moment, the surface outflow and network infiltration of the URBS module are directly injected into the drainage network. Several rivers (implementations of RIVER1D module) can coexist and exchange water via source and sink terms. This facilitates the representation of an artificial drainage network besides a natural river. Sewer overflow devices are simulated by an interface between sewer network and river streams. The overflow is calculated with a weir or orifice equation based on a control water depth threshold value. The connection between river and lake is modelled by interrupting the river network at the lake inlet and by starting a new river at the outlet.

3. MODEL APPLICATION AND RESULTS

3.1 Test case

The model is assembled gradually by adding new modules and connections. A simple test case was designed for this first version of PUMMA, consisting of a combination of the URBS, RIVER1D and SIMBA modules.

In order to compare these first results to measured data, the Rezé catchment [Berthier et al.,1999], located in the suburbs of Nantes, France was chosen (Figure 3). It consists of 70 cadastral parcels connected to either street or sewer network. As the pre-processing of the geographic data has still to be done manually, the catchment was conceptualised into ten equally parameterised cadastral parcels connected to ten drainage reaches for this first model test. The outflow of each cadastral parcel (sum of surface runoff and network infiltration) was multiplied by 7 and added as source term to the adjacent drainage reach. The parameters of the URBS module correspond to the retained parameters in Rodriguez et al. [2008]. The depth of the drainage pipe was set to 1.2m and the saturated zone depth was 0.7m. The drainage network was represented by a rectangular cross section of 50cm width with a slope of 0.5% and a Manning value of 0.011. The precipitation is the average of three rain gauges [Berthier et al., 1999] and has a time step of 5 minutes. The evapotranspiration data come from Météo France. All state variables were initialized to zero. The results were compared to measured flow data, see Figure 3 for its location. An hypothetical planning scenario has been tested, by introducing a retention basin downstream of the last drainage reach in order to highlight the simulation results of the SIMBA module. No measured data were available for comparison. The retention basin of 2m depth had a bottom outflow. Two simulations were run with retention parameters of 500 and 1000 s for a rain event on the 3rd of January 1991 including a three day warm-up period to eliminate the effect of the parameter initialisation. No lateral subsurface exchange was modelled, except the infiltration into the sewer pipes.

Figure 3. The Rezé catchment with its cadastral parcels, buildings and flow measurement station.

3.2 Results

This first test allows the assessment of the correct functioning and interaction of the modules. Each implementation of URBS (UHE) signals the sum of the surface runoff and network infiltration towards the closest drainage reach. RIVER1D routes the received water from one reach to the next and transmits then the discharge to the hypothetical retention basin.

Figure 4 shows the rain event and the simulated discharge at the outlet of the Rezé catchment versus the measured discharge. The total amount of precipitation during the simulation period was 21.3 mm. The modelled discharge corresponds to the main peaks of the observed discharge, however it fluctuates too much. This is probably caused by the conceptual representation of the catchment, due to which the correct simulation of the flow routing is not possible. The full distributed application of the model to the Rezé catchment, which is in process and which will be presented during the conference, should improve the model results. Another important point is the variable time step of the model. Here, we plotted the instantaneous values. Using averaged values for 5 minutes intervals should equally even the flow curve. The flow volume during the simulated period could be reproduced to 98.8% for this specific rain event.

Figure 5 presents the different flow components of one UHE. A short response of surface runoff to the incoming precipitation can be observed for the UHE, which is typical for urban areas. The built surface contributes to 40.6% to the runoff, the road area contributes to 29.1% and the network infiltration contributes to 30.3%. The response of the road surface is delayed in comparison to the built area, which is due to the parameterization of the UHEs (maximum size of surface reservoirs). The natural area does not contribute to the surface runoff because the soil is not yet saturated. However, the rising water content in the natural soil reservoir provokes an increasing infiltration into the sewer pipes. This response is much slower than the surface response. The discharge of each UHE is added as source term to the closest drainage reach and routed downstream.

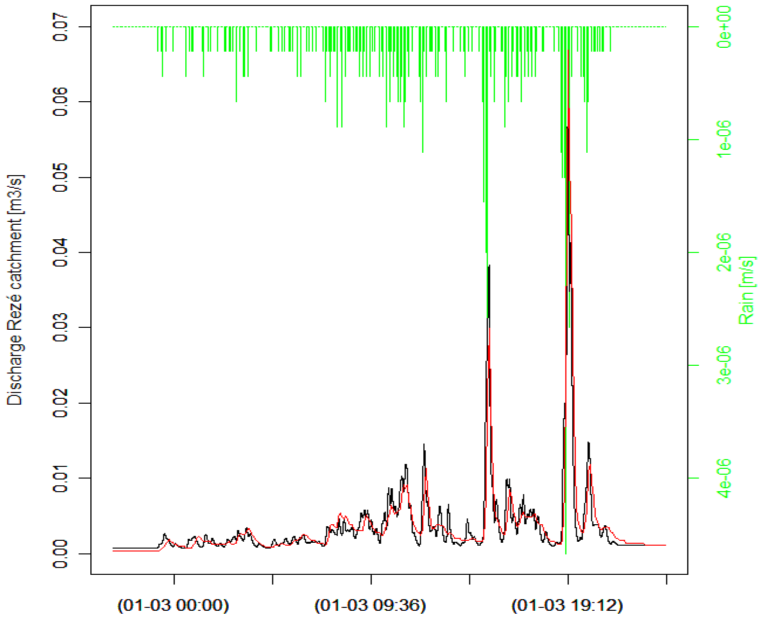

Figure 4. Simulated (black) versus measured (red) flow data and the precipitation (green) during the simulation run (3/1/1991). The simulated discharge corresponds to the RIVER1D output at the catchment outlet.

Considering the hypothetical planning scenario using the SIMBA module, a retention effect can be simulated. Depending on the retention parameter chosen for the module, the retention effect of the hypothetical basin is more or less strong. A retention parameter of 500s results in a peak reduction of 36% and a retention parameter of 1000s in a reduction of 49% combined with retardation and dispersion effects.

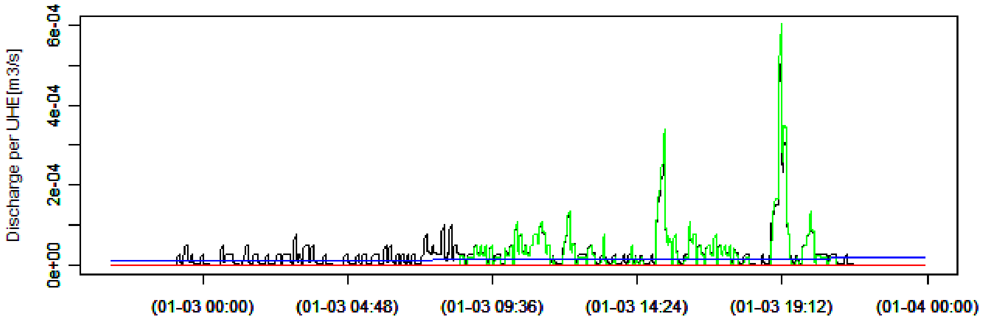

Figure 5. The discharge of one UHE divided in network infiltration (blue) and surface runoff from built areas (black), the road (green) and natural areas (red).

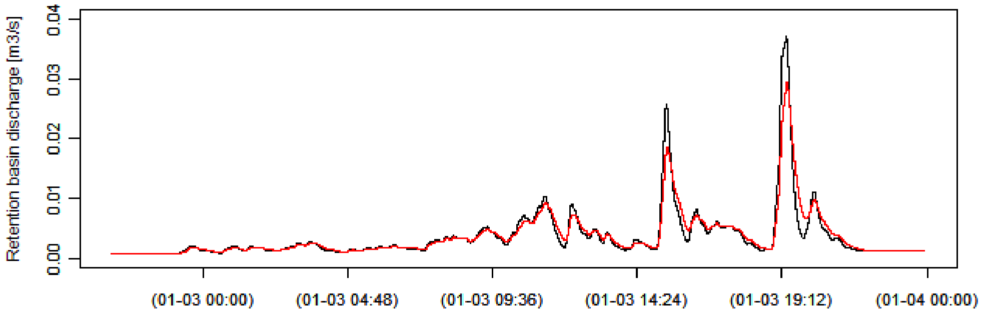

Figure 6. Discharge from the hypothetical retention basin with 500s (black) and 1000s (red) as retention parameter.

4. CONCLUSIONS AND PERSPECTIVES

PUMMA is a distributed model under development describing hydrological processes in suburban areas. It is constructed using the LIQUID® modelling framework. The model is composed of different interacting modules (URBS, FRER1D, HEDGE, SIMBA and RIVER1D). Each of them represents a different hydrological process depending on the land use property. Each module has its own time step, facilitating the simulation of different time scales regarding the hydrological processes. The model mesh consists of a mix of HRUs and UHEs with irregular geometries, which allows to represent the landscape heterogeneity in suburban areas. Different parallel drainage systems can be modelled by repeated implementation of the RIVER1D module. As the flow does not depend directly on topography, anthropogenic features as ditches and sewer pipes with pumped water can easily be simulated. Due to the modelling framework, new modules describing anthropogenic features as for example sewer overflow devices can be added straightforwardly.

A simplified version of the model was applied to the Rezé catchment and compared to measured data. Despite a very simple representation of the model mesh and a homogenous model parameterization, it was possible to reproduce the measured flow peaks. However, the simulated flow fluctuates too much because of the conceptual representation of the model mesh and the variable time step. This will be improved in a model application using the real Rezé model mesh. This application allowed to verify the correct functioning of the modules and their interactions. The results are encouraging as the model reflects well the involved hydrological processes. Due to the distributed character of the model and the great number of necessary input parameters, the model application remains restricted to small catchments of several square kilometres dedicated to research purposes. This is also partly explained by a still time consuming pre-processing of geographical data. An automation of the pre-processing is under development, using the GRASS geographical information system. The application to the two suburban sub-basins Chaudanne (4.1 km^2) and Mercier (6.8 km^2), located in the periphery of Lyon, France, is under preparation [Braud et al., 2010]. The complete model can then be validated with measured data. With this kind of model a detailed description of the processes in suburban areas is possible. The impact of soil impermeabilization, planting of hedgerows, installation of ditches, sewer systems or retention basins on catchment hydrology can be quantified. The results of these models can be used to understand the major hydrological processes and derive simplified approaches for use in larger catchments.

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