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INTEREST OF SPATIALLY DISTRIBUTED DATA TO EVALUATE THE OBJECT-ORIENTED PUMMA MODEL IN THE SEMI-RURAL MERCIER CATCHMENT (YZERON BASIN, FRANCE)

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ABSTRACT

Urban growth affects mostly the periphery of large cities, leading to catchments which are a mixture of rural and urban areas, so-called periurban catchments. Increase imperviousness and the setup of various networks (drinking water, sewer systems) lead to the modification of the hydrological cycle components and of water pathways in those catchments. In this paper, we assess the relevance of the The Peri-Urban Model for landscape MAnagement (PUMMA) to represent the hydrological cycle in the Mercier sub-catchment (6.8 km²), located close to Lyon city, France, with 10% of artificialized areas. The model is tested in more rural conditions than in a previous application to the Chaudanne neighbour sub-catchment (2.2 km²), characterized by 24% of artificialized areas. The model mesh is based on an object-oriented approach. It is composed of polygons, as derived from a detailed land use map (forest, agricultural fields, urban cadastral units and lakes). The river network is composed of the natural river, ditches and the rain water network. All the units are interconnected for surface and sub-surface flow transfer, and river routing. Model parameters are specified using in situ information or the results of previous studies, without any calibration, in order to assess the relevance of various functioning hypotheses. The model is run for two contrasted years: 2008 (wet) and 2009 (dry) with a variable time step for rainfall and an hourly time step for reference evapotranspiration. Simulated discharge is compared to measurements at the outlet and statistical performance criteria are computed. The model is able to represent the contrast between higher values of base flow in winter and very low flow in summer. Annual runoff volume underestimated (-21%) in 2008 and overestimated (+10%) in 2009.

Keywords: Peri-urban catchment, distributed hydrological modeling, object-oriented modelling, functioning hypotheses testing

1. INTRODUCTION

Several hydrological models deal exclusively with either rural or urban areas. Yet in practice, due to the continuity in the development projects, “the major part of any catchment is formed by a patchwork of urban, undeveloped (natural) and agricultural lands” (Andrieu & Chocat, 2004), especially close to large cities. One consequence of this observation is the need for peri-urban or semi-rural hydrological models. Semi-rural hydrology involves rural hydrological processes as well as urban ones. In the context of mixed areas, it is necessary to properly simulate both rural and urban hydrological processes since each one can have significant and various impacts on the whole basin floods. Distributed hydrological modelling contributes to a better process understanding and water management in mixed areas. Approaches, which try to combine the best of “natural” and “urban” hydrology, have recently emerged (see Jankowfsky et al., 2014 for a short review). In these approaches, catchments are divided in urban sub-basins and natural sub-basins based on Hydrological Response Units (HRUs). The Peri-Urban Model for landscape MAnagement (PUMMA) is one of those approaches. PUMMA is an integrated distributed hydrological model developed in France. The model simulates the rainfall-runoff processes by the use of the urban model URBS (Rodriguez et al., 2008) integrated into the LIQUID modelling framework (Branger et al., 2008), which already included modules describing hydrological processes in rural areas. One of the PUMMA's advantages is its ability to explicitly represent the various landscape elements and their interactions (rural and urban areas, natural and artificial networks, sewer overflow devices, lakes and retention basins).

The PUMMA model was applied to the Chaudanne catchment (2.7 km²), a sub-catchment of the Yzeron River, located in the peri-urban area of Lyon, in France by Jankowfsky et al. (2014). The results show the importance of surface runoff from impervious areas for summer events and flow contributions from rural zones for winter events. Furthermore, the model reveals that the retention capacity of the Chaudanne catchment is larger than for classical urban catchments due to the peri-urban character of the catchment (Jankowfsky et al., 2014).

In this paper, PUMMA is applied to another sub-catchment of the Yzeron catchment: the semi-rural Mercier sub-catchment. The goal is to set up the model and assess the performance of the model in a more rural sub-catchment than the Chaudanne one. In addition, spatially distributed data are available in order to assess the PUMMA model in the Mercier catchment. Apart from discharge at the outlet, distributed series of water levels (12 measurement points) and surface soil moisture data (9 locations) are available from 2007 to 2010 for model evaluation. In this paper, we present a first set up of the model in this catchment, focusing on the mesh used and parameter specification. The model is run for the 2008 (wet) and 2009 (dry) years. We present results in terms of water balance components, in particular the computed contributions from surface and sub-surface flow, and the contributions from rural and urban areas. Some comparisons with the existing data are also shown.

2. MATERIALS AND METHODS

In the following, we present successively the PUMMA model, the case study and available data and the model set up.

2.1 Short description of the PUMMA model

The PUMMA model, specifically designed for the hydrology of peri-urban areas, is presented in details by Jankowsky et al. (2014). In this paper, only a quick summary is provided. PUMMA is built within the LIQUID modelling framework, having an object-oriented character. It is a set of four existing modules (HEDGE, RIVER1D, WTI and WTRI) (Branger et al., 2010) of the LIQUID framework, and four additional modules (URBS, TDSO, OLAF, and SISTBA) that were specifically designed for peri-urban catchments. Each of the eight modules has a specific role and all are interconnected. LIQUID allows irregular model mesh features and each process module can have its own variable time step.

In the category of existing modules, the HEDGE runoff generation module simulates the rural areas such as forests and agricultural fields, as well as hedges. The soil is represented using two interconnected compartments: the drainable porosity where the water table is computed and the micro-porosity where infiltration and evapotranspiration take place. Overland flow can occur when the soil column is fully saturated. The RIVER1D runoff routing module, based on an approximation of the kinematic wave equations, assures the routing of water towards the outlet. The lateral subsurface flow is simulated by means of the Water Table Interface (WTI) module. It uses the Darcy law to calculate the subsurface flow between agricultural fields, hedgerows and urban cadastral units. The WTRI (Water Table River Interface) is similar to the WTI interface. However, it calculates the groundwater exchange between a model unit, and a river reach or a lake. Instead of the Darcy equation, it uses the Miles approach (Miles, 1985), which considers the water table deformation close to the river based on the Dupuit–Forchheimer hypothesis.

For the additional modules, URBS (Urban Runoff Branching Structure, Rodriguez et al., 2008) is originally an independent hydrological model for urbanized areas. Each cadastral unit is divided into natural, built and road areas, each one having its own water balance. The water table level is computed as the average of the three components and is used to compute rain water drainage by sewer pipes. The Threshold Dependent Stormwater Overflow device (TDSO) simulates the storm water overflow devices between sewer network and natural streams. The overflow is calculated with a weir or orifice equation based on a control water depth threshold value (Carlier, 1972). Overland flow from the surface reservoirs of the HEDGE module and the natural part of the URBS module is calculated with the OLAF (OverLand Flow) interface. The flux between two units is computed based on the Manning Strickler approach. Finally, the SISTBA (Simulation of Storage BASins) module simulates retention basins and lakes. It represents retention basins or natural lakes with a simple linear reservoir (Dingman, 2002).

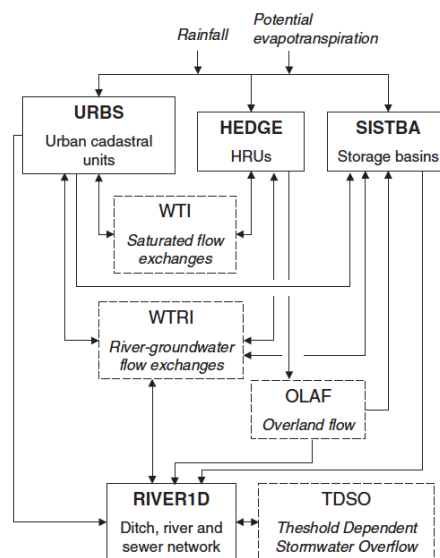


Figure 1: Structure of the PUMMA model and coupling between the modules (from Jankowsky et al., 2014)

Figure 1 illustrates the structure of the PUMMA model and coupling between the modules. The main modules, representing hydrological processes within the peri-urban objects are shown with a continuous line. Interfaces, calculating lateral fluxes between the main modules are shown in dashed lines. The arrows indicate possible water fluxes.

2.2 Study area and available data

The Mercier catchment is part of the Yzeron peri-urban basin, located in the south west of Lyon city, in France (Figure 2). The surface area of the Yzeron catchment is about 150 km² with an altitude ranging from 162 m to 917 m. The catchment is representative of peri-urban areas with a highly heterogeneous land use (Jacqueminet et al., 2013), that is dominated by forests and agricultural fields at the basin upstream. The basin is then increasingly urbanized when moving downstream, where Lyon city is located. The geology consists mainly of gneiss and granite, with some alluvial formations downstream. The soils with low depth in this area lead to a low storage capacity of the catchment. The climate is temperate and humid with continental and Mediterranean influences. The average annual precipitation is 843 mm with peaks in May and in October. The combination of climate, topography, and soil leads to rapid floods in the most urbanized portion downstream. The basin's response time was estimated to 12 h (Braud et al., 2013). Storm water management is predominantly performed through combined sewer systems with overflow devices all along in order to limit the Waste Water Treatment Plant saturation due to heavy rains.

The Mercier sub-catchment has a surface of 6.8 km² with altitudes going from 300 m to 785 m. The Mercier land use is composed of 50% of agricultural areas, 40% of forests and 10% of urban and impervious areas (Braud et al., 2013). The average annual precipitation between 1997 and 2010 was 741 mm with standard deviations of 156 mm. The average response time of the Mercier catchment varies between 1 and 3-4 hours. The catchment is part of the Observatoire de Terrain en Hydrologie Urbaine (OTHU) and is instrumented since 1997. Additional instrumentation and GIS layers acquisition were conducted in the framework of research projects (Braud et al., 2010; Dehotin et al., 2014).

Figure 2 shows the terrain elevation derived from a 2 m lidar DTM (Sarrazin, 2012), the natural and artificial drainage network and the location of the various measurement stations used in this study. Rainfall and discharge measurements are available with a variable time step, but are linearly interpolated to a 6 min time step. Hourly reference evapotranspiration was derived by Braud et al. (2013) from the national SAFRAN database (Quintana-Seguí et al., 2008; Vidal et al., 2010) using the Penman-Monteith equation (FAO, 1998). In addition to discharge at the outlet, distributed series of water levels with a 2 to 5 min time step (12 measurement points, Sarrazin, 2012) and surface soil moisture data with a 2 min time step (9 locations, Dehotin et al., 2014) are available from 2007 to 2010 for model evaluation.

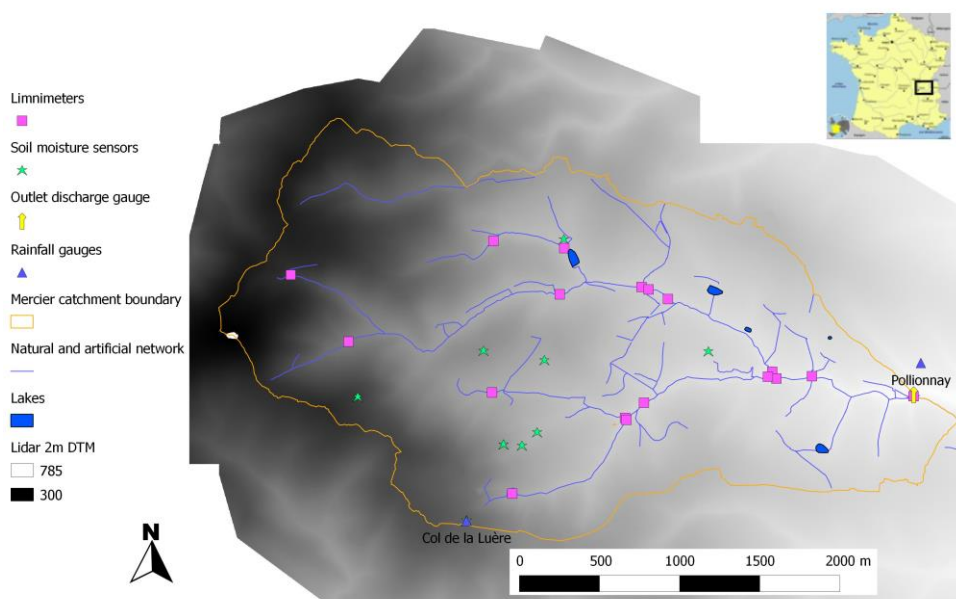


Figure 2: Location of the study area and Lidar DTM with 2 m resolution, drainage network (natural and artificial), rain, discharge, water level and soil moisture measurements stations in the Mercier catchment.

2.3 PUMMA model set up in the Mercier sub-catchment

2.3.1 Model mesh

The object oriented model mesh of the PUMMA model is composed of a combination of Hydrological Response Units (HRUs) (Flügel, 1995) for rural land use units and urban hydrological elements (UHE) (Rodriguez et al., 2008) for urban cadastral units. HRUs are obtained using GIS overlay of available land-use, geology, soil and sub-basin maps (Jankowsky, 2011). In the Mercier catchment, agricultural and road ditches were mapped using field survey and are incorporated to the natural river network. The village included in the catchment is not yet connected to the sewer system and rain water is collected in a separated sewer system, which is also incorporated to the natural river network. The rural sub-basins are calculated using the flow direction forcing technique (Kenny and Matthews, 2005) in order to determine one sub-basin for each river and artificial ditch branch (Jankowsky et al., 2013). A 2m Lidar DTM is used for this purpose. The UHEs encompass one cadastral unit (typically house plus surrounding garden) and half of the adjoining street. UHEs and HRUs are merged in order to get a non-overlapping model mesh. The object oriented model mesh consists of

irregular vector objects: polygons for HRUs/UHES and lines for the drainage network. It is shown in Figure 3 with the associated PUMMA process modules. Note that UHE exclusively composed of roads represent 18% of the URBS modules surface. The WTI/WTRI interfaces are line objects defined by intersection between polygons. Pre-processing methods were also developed to extract the interface geometries and their connections automatically (Jankowsky, 2011). The automatic preprocessing also provides the flow routing on the irregular model mesh for the OLAF module and determines the urban pipe connections. The derivation of a consistent model mesh with a correct topology and all the connections between modules is the most challenging task in the PUMMA model application. The model mesh considered in this study is based on the original land use map of Jacqueminet et al. (2013). It will be further improved using algorithms presented in Sanzana Cuevas et al. (2013) to avoid non convex and too large model units, as visible in the upstream part of the catchment. Each model elements is characterized by various geometric attributes (average altitude, slopes, etc...) which are computed using the DTM.

Note that a Sewer Overflow Device module is introduced to represent the temporary connection between an adjacent catchment and the Mercier catchment (red dot at the top of the figure), which is only active when rainfall amount is sufficient.

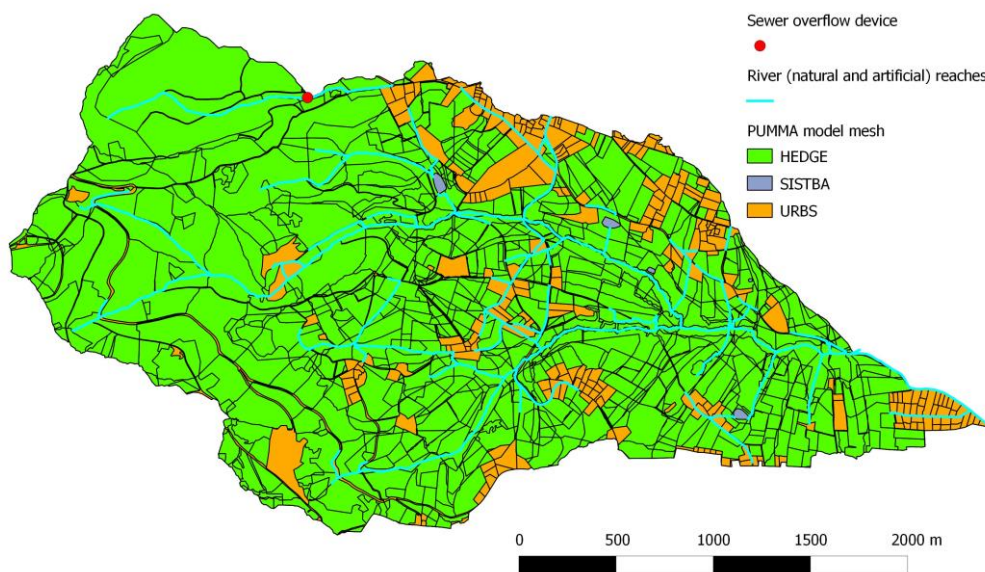


Figure 3: Mercier catchment PUMMA model mesh. The different colors correspond to the various PUMMA modules: HEDGE representing natural areas, SISTBA representing lakes, URBS representing urban cadastral units. The river network (composed of natural, rain water and ditches network is shown in blue). A SOD (Sewer Overflow Device) which has been used to simulate the connection between an adjacent catchment and the Mercier is also shown.

2.3.2 Model set up

The simulation is performed for two years from January 1st 2008 to December 31st 2009, which are contrasted years in terms of rainfall. Year 2008 is a wet year with 862 mm at the Pollionnay station (respectively 965 mm at the Col de la Luère station) whereas 2009 is a dry year with 558 mm at the Pollionnay station (respectively 679 mm at the Col de la Luère station). Note that topography induces rainfall heterogeneity with larger values of rainfall at higher altitudes. The variable time step rainfall time series were directly used as input to the model and interpolated to the model mesh using weighting averages of the Thiessen polygons. Reference evapotranspiration ET_0 , is specified at the hourly time step and is considered homogenous over the whole catchment. Crop coefficients can be used in PUMMA to modulate ET_0 , according to the vegetation type. They are set to one in this first simulation.

Model parameters are set up, similarly to what is presented in Jankowsky et al. (2014). Soil parameters are specified for each model units using a soil data base and in situ measurements. For the urban UHES, built, road and natural areas are computed from the detailed land use. Natural and road permeability are assigned values proposed by Jankowsky et al. (2014). Using a sensitivity study, those authors also showed that some parameters sets were more consistent with observations. We use their recommendation for interception reservoirs of built, road and natural areas in this simulation. We also use values of the link coefficients, representing the fraction of runoff from built and road areas which is directly connected to the network, are specified to 0.6 and 0.5 respectively. Jankowsky et al. (2014) also recommended the use of a variable soil depth, with larger values at lower altitudes. A constant soil depth of 1 m is used in this simulation and the evaluation of the variable soil depth is left for further sensitivity studies.

To determine the initial conditions, the model is run for one year using the 2008 forcing. Then the final conditions of this simulation are used as initial conditions for the 2008-2009 simulation which is presented in the next section.

3. RESULTS

The model performance is assessed at various time scales: the annual cycle and its ability to represent the seasonal variations of discharge and other hydrological components, and at the event time scale. For this the largest events recorded during this period are selected. They occurred on November 2nd 2008 (instantaneous peak discharge of $10.8 \text{ m}^3 \text{ s}^{-1}$) and February 6th 2009 (instantaneous peak discharge of $4.5 \text{ m}^3 \text{ s}^{-1}$).

3.1 Model evaluation and water balance components at the annual time scale

Figure 4 presents the simulated and observed hourly average discharge for years 2008 and 2009. It shows that the model is able to simulate the annual fluctuations of base flow with a significant base flow in winter and almost no discharge in the river in summer. Table 1 shows the values of Nash Sutcliffe efficiency and PBIAS for the two years both for hourly and daily discharge. The model performance are better in the driest year with a Nash value of 0.60 on hourly values and 0.75 on daily values. The performance is poorer in 2008 where the corresponding values are 0.41 and 0.46 respectively. These figures can be explained by the model capturing very well the large flood event in February 2009, whereas it underestimates the November 2008 event. In addition, in 2009, discharge values are very low during most of the year. In general also, the model is too reactive in summer with a peaky behavior whereas almost no hydrological response is observed in the river. In terms of volume error, the model underestimates the volume in 2008 by 21% and overestimates it in 2009 by 10%. These model performances are comparable to those of Jankowsky et al. (2014) on the neighbor Chaudanne catchment and are satisfactory for a non-calibrated model. Actual evapotranspiration, *AET*, represents 64% of total rainfall in 2008 and 78% in 2009, which is the driest year. However, we must keep in mind that crop coefficients are not taken into account in this simulation and this could impact *AET* and the other model components. Further sensitivity tests to model parameters are also required to better assess the model sensitivity to their specification.

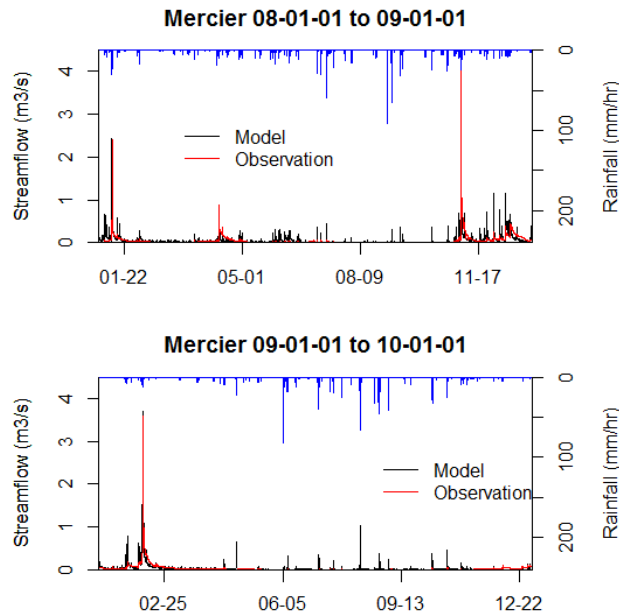


Figure 4: Comparison of simulated and observed discharge for years 2008 and 2009

Table 1: Catchment averages components of the simulated water balance for years 2008 and 2009. Those values are calculated for the whole catchment (including the upper neighbor catchment). Statistical performance criteria on hourly and/or daily discharge at the outlet. PBIAS is computed as $100 \cdot (Q_{\text{mes}} - Q_{\text{obs}}) / Q_{\text{obs}}$

Year	Rainfall (mm)	Runoff (mm)	<i>AET</i> (mm)	Nash (hourly Q)	Nash sqrt(hourly Q)	PBIAS (%)	Nash (daily Q)
2008	890	310 (34%)	571 (64%)	0.41	0.43	-21	0.46
2009	613	172 (28%)	477 (78%)	0.60	0.50	+10	0.75

Table 2 shows the components of the river discharge as calculated by the model. The percentages of each component are quite similar between the two years. Surface runoff has the largest contribution to discharge (70% in 2008 and 60% in 2009), but a significant part of the discharge is produced by sub-surface runoff (30% in 2008 and 40% in 2009). Natural and artificialized areas have a similar contribution (around 50%) with a slightly larger value for natural areas in 2008 than in 2009.

Table 2: Components of the river + lakes discharge (%) as computed by the model for the 2008 and 2009 years. The percentages are calculated with reference to the total discharge volume.

Components of the river discharge	2008	2009
Direct surface runoff from URBS elements	34	28
Built	3	3
Road	28	23
Natural	2	2
Direct surface overland flow from HEDGE	37	32
Sub-surface flow from HEDGE	11	13
Sub-surface flow from URBS	18	27
Total surface runoff	70	60
Total sub-surface flow	30	40
Runoff from HEDGE (natural areas)	48	45
Runoff from URBS (artificialized areas)	52	55

3.2 Model evaluation at the event scale

Figure 5 presents the simulated and observed hourly average discharge for the 2008 and 2009 events and Table 3 shows the statistical criteria. In both cases, the model simulated peak discharge is 2 hours in advance. The event runoff volume is underestimated (-50%) for the November 2008 event, whereas it is slightly overestimated for the February 2009 event (+14%). The peak discharge is underestimated on the November 2008 event by 67% and slightly overestimated in February 2009 (+3%). On the 2009 event, it is interesting to see that the model correctly represent the long recession.

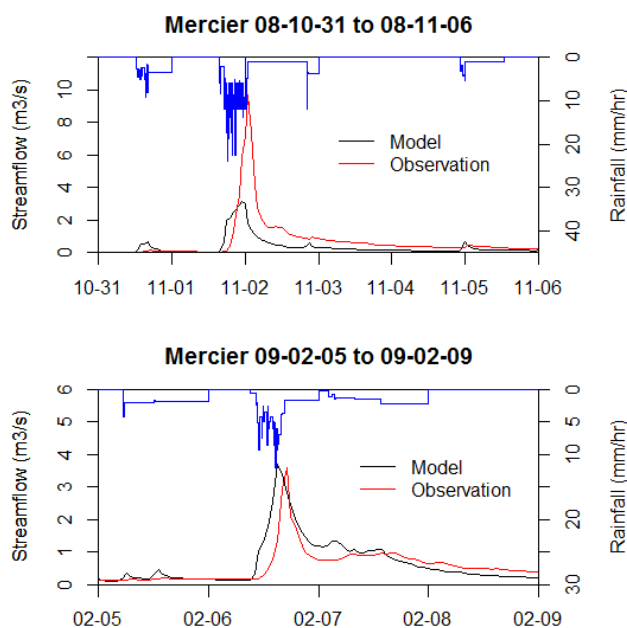


Figure 5: Simulated and observed discharge for the November 2008 and February 2009 events

Table 3: Comparison of modelled and observed discharge at the Mercier outlets for the November 2008 and February 2009 events. Statistical criteria are calculated on average hourly values

Event	Rainfall (mm)	Nash on Q	Nash on sqrt(Q)	PBIAS (%)	Peak difference (%)	Time to peak difference (h)
31/10/2008-03/11/2008	93mm (Pollionnay) 100mm (Luère)	0.35	0.43	-50%	-67%	-2h
05/02-2009-08/02/2009	58mm (Pollionnay) 44mm (Luère)	0.42	0.56	+14%	+3%	-2h

4. CONCLUSIONS AND PERSPECTIVES

In this paper, we present the setup of the PUMMA peri-urban model in the Mercier sub-catchment, characterized with a 10% of artificialized areas. Model parameters are specified mainly from a previous study performed in a more urbanized catchment (Jankowsky et al., 2014), without any calibration. Model results are encouraging, as the model is able to represent the variation of base flow between winter and summer conditions. Nash efficiency at the hourly time step reaches 0.60 for year 2009. For the most important event (November 2008 event), the model tends to underestimate the

runoff volume, and the time to peak simulated by the model is 2h in advance as compared to observation. On the other hand, the February 2009 event is pretty well simulated, although 2h in advance.

Further work will include a more in depth comparison with the data from the water level and soil moisture networks. Sarrazin (2012) computed response time using the water levels time series for a set of events. He showed that the upstream forested part was responding less frequently to rainfall than the downstream stations. It will be interesting to see if the PUMMA model is also able to represent these features. The model mesh will also be improved using the automatic tools proposed by Sanzana Cuevas et al. (2013) in order to avoid non convex and too large polygons and improve the representation of water pathways in the model.

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