The AVuPUR project (Assessing the Vulnerabiliy of Peri-Urbans Rivers): experimental set up, modelling strategy and first results

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The AVuPUR project (Assessing the Vulnerabiliy of Peri-Urbans Rivers) : experimental set up, modelling strategy and first results

Le projet AVuPUR: stratégie expérimentale et de modélisation et premiers résultats

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RÉSUMÉ

Le projet AVuPUR a pour objectif de progresser sur la compréhension et la modélisation des flux d'eau dans les bassins versants péri-urbains. Il s'agit plus particulièrement de fournir des outils permettant de quantifier l'impact d'objets anthropiques tels que zones urbaines, routes, fossés sur les régimes hydrologiques des cours d'eau dans ces bassins. Cet article présente la stratégie expérimentale et de collecte de données mise en œuvre dans le projet et les pistes proposées pour l'amélioration des outils de modélisation existants et le développement d'outils novateurs. Enfin, nous présentons comment ces outils seront utilisés pour simuler et quantifier l'impact des modifications d'occupation des sols et/ou du climat sur les régimes hydrologiques des bassins étudiés.

ABSTRACT

The aim of the AVuPUR project is to enhance our understanding and modelling capacity of water fluxes within suburban watersheds. In particular, the objective is to deliver tools allowing to quantify the impact of anthropogenic elements such as urban areas, roads, ditches on the hydrological regime of suburban rivers. This paper presents the observation and data collection strategy set up by the project, and the directions for improving existing modelling tools or proposing innovative ones. Finally, we present how these tools will be used to simulate and quantify the impact of land use and climate changes on the hydrological regimes of the studied catchments.

MOTS CLES

Suburban catchments, observation, distributed hydrological models, scenario, land use change

1 INTRODUCTION

Due to the development of urbanisation and the associated pollution, suburban rivers face an increasing pressure on the receiving waters and an enhancement of floods. In order to end up with integrated management tools, progress is still required in continuous and long term modelling of the hydrological cycle in these areas, taking into account the surface heterogeneity (mixture of rural and urbanised areas), and natural and artificial water pathways, which influence the water quality. This question is the focus of the AVuPUR (Assessing the Vulnerability of Peri-Urban Rivers) project[*]. Its aims are 1) to provide a better description of the heterogeneity of suburban catchments and of the associated water pathways using field survey, GIS and remote sensing analysis of very high resolution images; 2) to provide long term detailed simulation models of the hydrological cycle in suburban catchments to increase our understanding of the processes involved; 3) to improve existing hydrological models with a better handling of the rural and/or urbanised areas in order to derive tools usable by administrations and public agencies (Water Framework Directive, European Directive on Flooding); 4) to run long term simulations of the hydrological cycle using past and future land-use and climate scenarios and quantify the impact on the hydrological regime. Its evolution will be translated in terms of vulnerability of the river to floods and in terms of impact on the geomorphology: erosion of the banks which impact the ecological functioning. The applicability and transposability of the methods is assessed using two catchments facing a quick urbanisation. In both catchments, the downstream part is densely urbanised with an increase of urbanised zones upstream in the recent years. But they are located in contrasted climates and geologies. The Yzeron (150 km^2) catchment is situated westwards of Lyon (Figure 1a) and is characterized by high slopes upstream and a Mediterranean type climate. The Chézine (34 km^2) catchment (Figure 1b) is located in the suburbs of Nantes. It is a relatively flat catchment with an oceanic climate.

This on-going project (2008-2010) is performed by a multi-disciplinary consortium with skills in climatology, rural and urban hydrology, hydro-informatics, human and physical geography. In the following the four main topics of the project are briefly reviewed and the main results obtained up to now are highlighted.

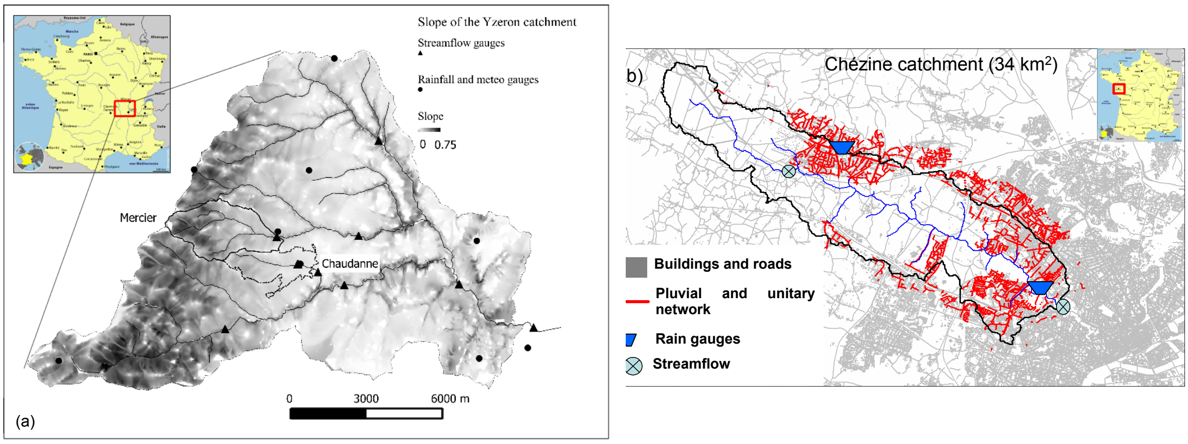

Figure 1: (a) Location of the Yzeron catchment and instrumentation. The Mercier sub-catchment (7 km^2) is covered with forests and crops and the Chaudanne sub-catchment (3.6 km^2) is occupied by a mix of crops and urbanised areas. (b) Location and instrumentation of the Chézine catchment. The red colour shows the urbanised area with two main zones: an area close to the outlet and another one in the central north part.

2 OBSERVATION STRATEGY AND DATA COLLECTION

In both catchments, GIS layers describing topography, geology, soil types, land use were acquired. In addition, urban data bank describing the rain water and waste water sewer networks, as well as the cadastre were collected from the owners of the data. The required information is fragmented between various operators and the formats are in general different. Thus a common coordinate system and format was chosen for each catchment, so that all the GIS layers became interoperable. In addition to these existing data collection, a specific work, dedicated to land use mapping for hydrological

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[*] http://avupur.hydrowide.com/

modelling was required. Indeed, a detailed information about land use heterogeneity as well as information about permeability properties of the surface was required and available information such as the Corine Land Cover or BDTopo from IGN was not providing it. To fulfil the requirements for hydrology, a land use mapping based on aerial photographs and very high resolution (VHR) satellite images was built. Two directions were investigated: the automatic classification of land use on large areas using VHR images and the diachronic mapping of land use using aerial photographs from 1945 (Béal et al., 2009). As shown in the next section, all these data are used to determine a consistent drainage network within the catchments and delineate the modelling units.

Hydro-meteorological data were also collected in both catchments and new sensors were installed if required. Figure 1 shows the location of the rain gauges, meteorological station and stream flow gauges for both catchments. For stream flow measurement, a strategy of nested catchments was set up in order to get the data necessary to assess model performance at the various scales of interest. In addition, the sub-catchments were chosen to sample various land uses. On the Chézine catchment (Figure 1b), the upstream sub-catchment, installed in 2008, covers a rural area, whereas the outlet gauge, installed in 2001, is located after a densely urbanised area. On the Yzeron catchment, two sub-catchments are more particularly studied: the Mercier catchment is mostly covered with forests and crops, whereas the second one, the Chaudanne catchment is covered with crops and urbanized areas (Figure 1a). For both of them, stream flow and rain gauges data are available since 1997, with 3 streamflow gauges on the Chaudanne catchment, corresponding to rural and urbanised areas. These data were analysed and uncertainties on stream flow data were quantified. On these ephemeral rivers, the results show that most of the current stream flow gauges have a too low accuracy for low flows, to quantify the annual cycle and water budget with a reasonable accuracy (Michel, 2009). Further studies are scheduled in order to improve low flow estimation and the annual water balance, which is important to later address quality issues.

The data were also analysed at the event scale and the corresponding runoff coefficients calculated. For both catchments, different hydrological behaviours are identified between summer and winter events. In summer, soils are generally dry and the hydrological response is mainly related to the urban area, all the more that rainfall events are often short thunderstorms with high intensities. On the other hand, soils are wetter in winter and the contribution of rural areas is larger. On the Chézine catchment, hydrographs with two peaks are sometimes observed in summer (Figure 2a). They have been related with the impact of the two urbanised areas (see Figure 1b and 5) with a quick hydrological responses but different transfer time due to their position within the catchment. In winter, rural areas contribution smoothes the response and the two peaks are no more visible and the lag-time is increased (Figure 2b). Furthermore, the average runoff coefficient (2001-2007 period) is lower in the dry period (0.06) than in the wet period (0.16). On the Chaudanne and Mercier catchments, it was found that, on the 2005-2008 period, the runoff coefficients in the rural parts are statistically similar (0.03 on average once the base flow is removed), whereas it is significantly higher for the gauge including an urbanised area (Léchère gauge with a value of about 0.05 on average).

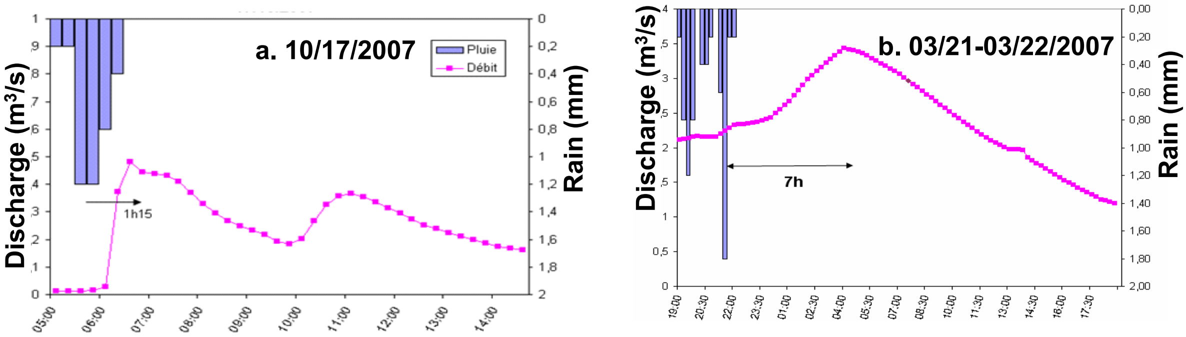

Figure 2: Example of two events on the Chézine catchment. (a) Event with dry initial conditions, showing two peaks and a short lag time of 1h15. (b) Event with wet initial conditions with only one peak and a lag time of 7h.

In addition to these traditional hydro-meteorological data, a special effort is dedicated to the documentation of hydraulic properties of the soil. A field campaign was realised on the Mercier catchment using single ring and tension disk infiltration tests. Such a campaign is under way on the Chézine catchment. The results on the Mercier catchment showed large infiltration capacity of the soils at saturation (single ring tests) with much larger values on the forested and pasture soils than on the cultivated soils, due to a larger macroporosity. This hypothesis was confirmed by the results of the tension disk infiltrometers, which evidenced a sharp increase of hydraulic conductivity when moving from near saturation to saturation (Gonzalez-Sosa et al., 2009). Geophysical techniques (electric resistivity) transects were also performed providing information on the vertical soil structure. On the Mercier catchment, it was found that in the talwegs, soils could be very deep (more than 15m) with a shallow arable layer and a thick layer of altered rocks (Goutaland, 2009). On the Chézine catchment, three geophysical techniques were compared, showing good agreement between them. Field samples are currently collected in order to fully validate the data interpretation. All these information will be useful for the soil parameter specification within the models described in section 3.

On the Yzeron catchment, geomorphological studies are also conducted in order to better understand the mechanisms controlling sediment transport and incision, and to link these processes to hydrodynamics. The objectives are to determine critical discharges of particle entrainment of streambeds and to translate them into hydrological indicators of channel stability (intensity-duration-frequency thresholds, duration of exceeding of critical discharge). Some other hydrological indices will also be tested according to different environmental contexts defined by slope and bed grain size. A first theoretical approach aims at applying traditional solid transport formulas (e.g. Bathurst et al., 1987; Schoklitsch, 1962) for small suburban channels. For this, data collection concern channel slope, channel geometry, bed-channel grain-size and roughness. A second experimental approach aims at measuring in situ the particle size put in motion by a set of floods: paint particles tracing for gravels (Liebault et al., 1999) and suspended matter automatic sampling for sand (Hicks, 1994). A turbidimeter is also used. This allows the experimental determination of the critical discharge. The two methods are applied on the Chaudanne and rural Mercier sub-catchments where hydrological data are available and environmental contexts are contrasted. Furthermore, dating of alluvial deposits (by OSL and ^{14}C) on the valley bottoms and study of land use in the last 200 years allow to propose the following model. In the recent years, there has been a decrease of ploughing lands, replaced by forests and pastures, leading to a decrease of hillslope erosion. River reaches are no more able to fulfil their transport capacity and the consequence is channel incision. These results highlight the close connection between land use and human practices and the river dynamics.

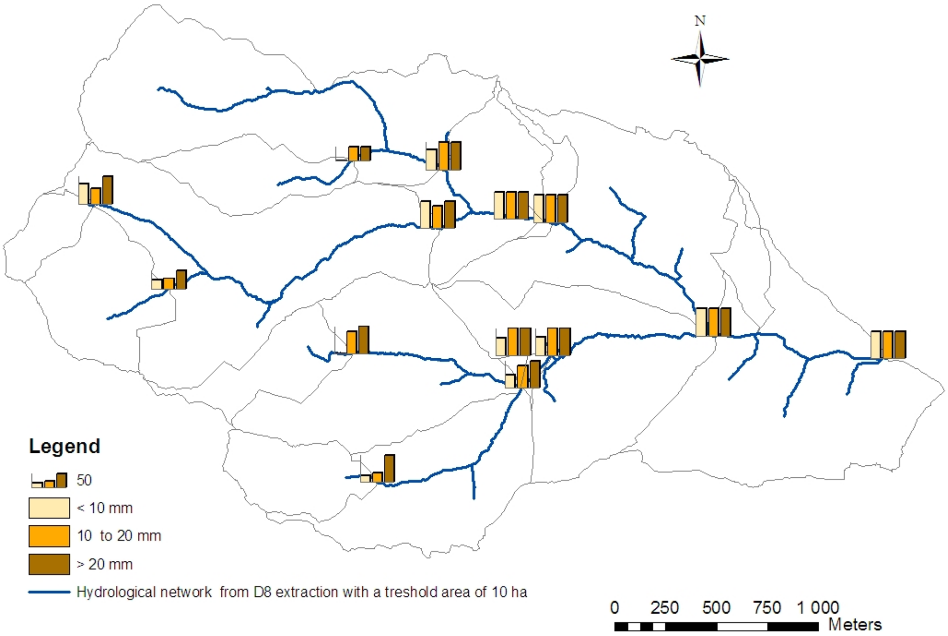

Figure 3: For the 15 limnimeters gauges, the bars show the frequency of activation of the network (ie the frequency with water within the river) for the Mercier catchment from 28 recorded rainfall events and for three classes of rainfall amounts

Finally, on the Mercier catchment, the value of lidar data (leading to the building of a 2m Digital Elevation Model **(**DTM) was assessed. The results show that lidar provides very useful information to improve the knowledge of water pathways. On the Mercier catchment, considered as “natural”, the impact of the road and lanes network is shown to be significant on the water pathways. Indeed, using a simple D8 algorithm with a threshold area of 1 hectare, more than 25 % of the extracted network is composed of ditches, lanes or roads. To better understand the relationship between hydrological responses and physiographic data, a network of limnimeters (15 in 2009) was set up on permanent and ephemeral river reaches (see locations in Figure 3). Rising and falling limbs of the limingraphers were studied showing different behaviours as function of the position within the catchment and land use. Figure 3 shows the frequency of activation of the network for three rainfall amounts classes. Whereas the network is almost active for all the events in the central and eastern part of the catchment (with crops and pasture cover), the network is not activated very often, especially for low rainfall events, on the western part of the catchment covered with forests. The use of geomorphological unit hydrographs (Gupta et al., 1980) is presently tested to see if the fine description of flow distances derived from the lidar data and simple hypothesis on transfer velocity on the hillslopes and the network can explain the dynamics observed by the limnimeter network. In addition to the insight into active hydrological processes, these data will be very useful and complementary to the data presented before to assess the realism of the simulated hydrographs by the models described in section 3.

3 TOWARDS DETAILED MODELING OF SUBURBAN CATCHMENTS

In order to understand, describe and model in detail the hydrological cycles in suburban catchments, a first step is to be able to describe the drainage network taking into account natural river reaches, ditches and artificial sewer networks (combined or rainwater sewer networks). Several strategies are tested and evaluated for this purpose. The first one is based on the traditional use of DTM to determine the drainage direction from the topography only. The second approach called “object based” uses the topography, the land use map and anthropogenic structures to delineate 2D objects (agricultural fields, cadastral urban areas) or linear objects (river network, roads, ditches, sewer networks) in order to determine the drainage directions (Rodriguez et al., 2003). The last one (TANATO, Bocher, 2005) is based on a Delaunay triangulation of the surface, starting from the topography. Then the drainage directions are modified to take into account constraints such as ditches, hedges, etc.. Recent developments performed during the AVuPUR project take into account urban areas in the algorithms (Bocher and Martin, 2009).

The three approaches were compared on the Chézine catchment, where the rain water is separated from waste water. Figure 4 shows the corresponding drainage network and highlights the impact of anthropogenic features on the catchment boundary as well as on the drainage network. With the “object-based” approach, the catchment area is strongly reduced as compared to the DTM approach, whereas the TIN approach leads to a catchment area closer to the DTM area. On the other hand, the drainage network derived from the DTM approach is unable to represent the impact of roads and ditches on water pathways. This influence is very well captured by both the “object-based” and TIN approaches, although the final result is slightly different. Figure 5 compares the distributions of distances to the outlet derived from the three approaches. The three curves show two maximum which can be associated to the two urbanised areas highlighted in Figure 1b. The second maximum is obtained for larger distances with the TIN approach than with the DTM or “object-based” approaches. These distance distributions can be used to built unitary hydrograph and/or geomorphological hydrographs (Gupta et al., 1980) for runoff routing. It will be interesting to see the impact of the various distance distributions shown in Figure 5 on this response.

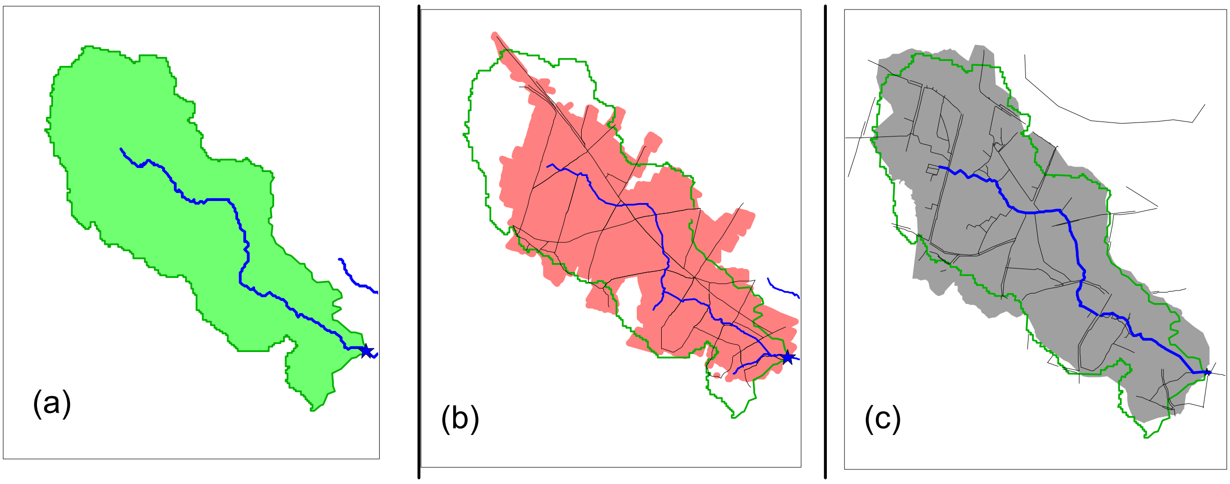

Figure 4: Drainage network of the Chézine catchment using (a) Traditional DTM treatment; (b) the object-based approach, (c) the constrained TIN approach. Outlet location is represented with a star, and the main river is in blue; DTM catchment boundary is represented in green line on each catchment.

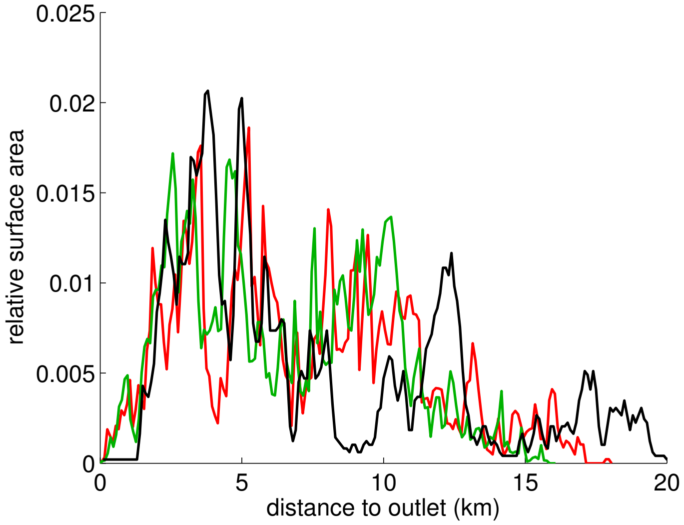

Figure 5: Comparison of the distance distributions to the outlet for the three estimations of the drainage network on the Chézine catchment (DTM approach in green, object based approach in red and TIN approach in black)

On the the Yzeron catchment, the situation is more complicated because most of the sewer networks are combined sewer networks, in general linked to the sewage plant. As a consequence, part of the catchment area is not connected to the natural river, except when the network overflows and excess water is directed to the natural river via overflow sewer devices. However, the areas close to the river are drained by separated systems, where the pluvial water joins directly the natural river. Each connection point to the river has to be determined as well as the sub-catchments corresponding to the connection points. The natural river network was extended with the artificial ditch network in order to take into account their impact in modifying water pathways as shown by the lidar data. By means of this network the natural sub-catchments were calculated. To get the final result shown in Figure 6 for the Chaudanne sub-catchment, field surveys and interviews with operators were required in order to determine the flow directions where automatic procedures were failing.

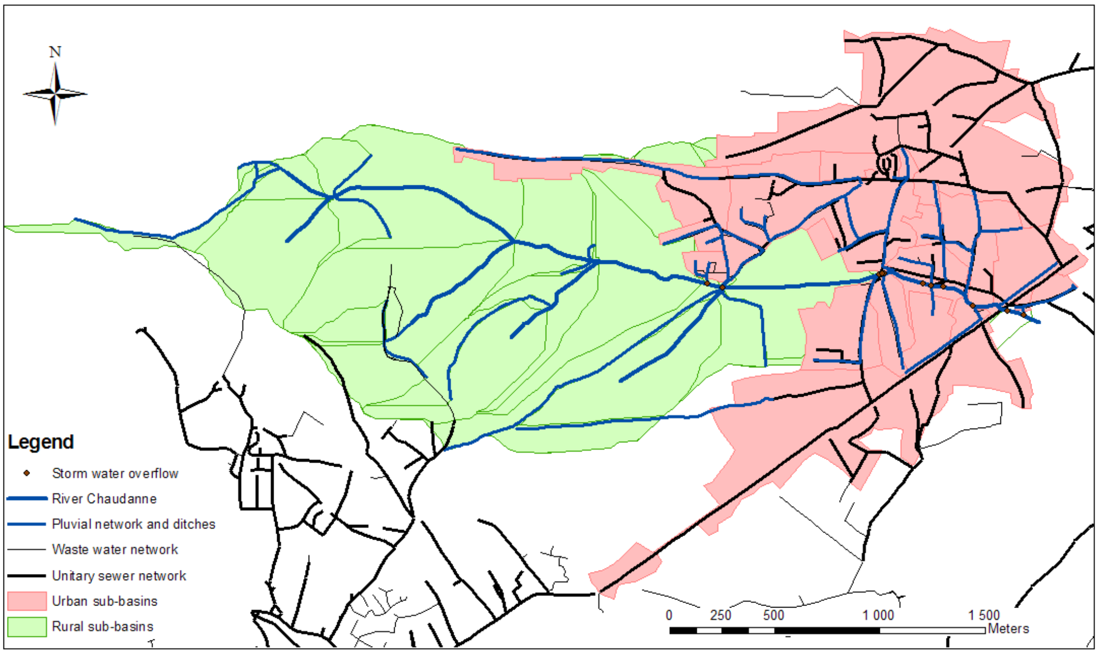

Figure 6: Delineation of rural sub-catchments including the natural river network and ditches and of urban sub-catchments connected to the overflow sewer devices for the Chaudanne catchment.

The next step in the work will be the model building itself. The PUMMA (Peri-Urban Model for landscape Management) model (Figure 7a, Jankowfsky et al., 2010) is built within the LIQUID modelling platform (Viallet et al., 2006) following the spatial discretization principles into hydro-landscapes as described in Dehotin and Braud (2008). For the small catchments of the Chaudanne and Mercier, the hydro-landscapes will correspond to the natural fields, hedges, lakes, roads and cadastral urban areas (Figure 7b). For this purpose, a detailed land use map has been derived from the manual digitalization of the IGN BDOrtho2008 data base (UMR EVS, 2009), combined with the cadastral information. This provides the distinction between different natural land uses: crops, broad leaved and coniferous forests, pasture and the identification of cadastral urban zones (with the estimation of the percentage of buildings, impervious areas and natural areas). Water flow components will be described for each "object" using appropriate descriptions. For natural land use the Richards equation describes vertical water transfer and evapotranspiration (FRER1D module, Varado et al., 2006) with a set of parameters adapted to each vegetation type. For urban cadastral areas, the URBS (Urban Runoff Branching Structure) model (Rodriguez et al., 2008) is used. Water transfer within the natural and artificial networks is described using the kinematic wave approximation of the St-Venant equation (RIVER1D module). Both networks are linked by the overflow sewer devices for which thresholds of activation must be defined. In the soil, lateral water flow can be accounted for in the saturated zone, and interactions between sewer networks and the soil are also taken into account in URBS (Figure 7a).

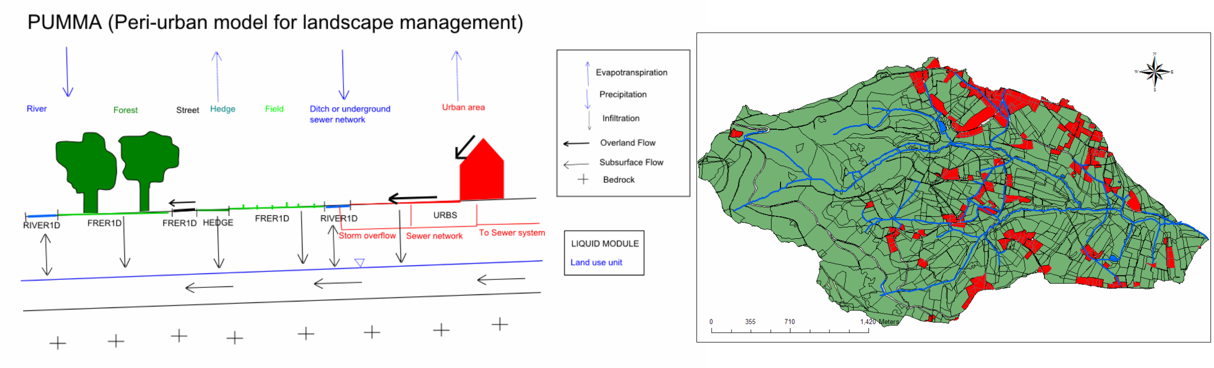

Figure 7: (a) Scheme of the model with the fluxes between the various objects. (b) Spatial discretization of the Mercier sub-catchment for the modelling. In red: urban areas where the URBS module is applied. In green: natural areas where the FRER1D module is applied and in blue: the natural river network + ditches where the RIVER1D module is applied.

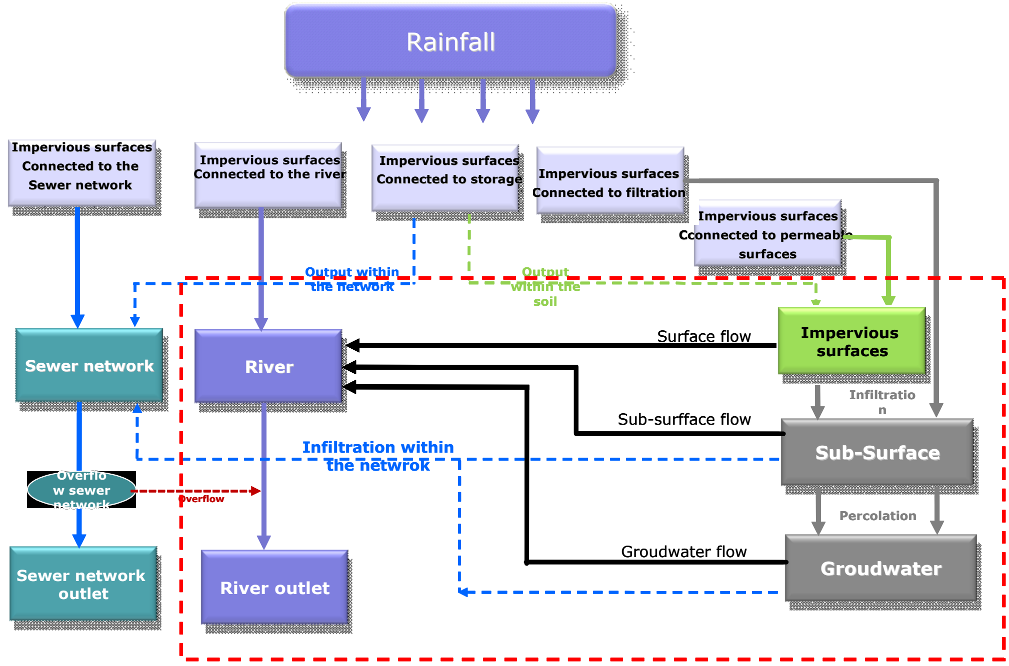

Figure 8: Conceptualisation of the elementary sub-catchment within the CANOE model

4 SIMPLIFIED MODELLING APPROACHES AT THE CATCHMENT SCALE

The modelling approach presented in the previous section will allow gaining insight into the major processes involved in order to derive new or improve existing modelling approaches at larger scale. The idea is to model the hydrological functioning at the sub-catchment scale taking into account both natural and artificialized areas. As an illustration an improved representation of rural areas, based on reservoir modules exchanging fluxes, and including surface, sub-surface and groundwater flow was proposed by Boutaghane et al. (2008) (Right of Figure 8) for inclusion in the CANOE software (INSAVALOR and SOGREAH, 1997), which computes the flow routine in the sewer network. The distinction of urban areas according to their connection to the river network was also considered (Light blue boxes in Figure 8). Previous studies had shown a deficiency in the simulation on the Yzeron catchment dynamics attributed to poor representation of rural areas (Radojevic, 2002). The new version of the CANOE software is expected to improve the model results.

Another approach currently tested is based on the ISBA-Topmodel coupled model (Bouilloud et al., 2010). ISBA simulates the soil vegetation atmosphere vertical transfers including the energy and water balance. Topmodel simulates lateral sub-surface flow. Their coupling allows lateral redistribution of soil moisture due to topography. A simulation of the Chézine catchment response assuming the catchment was purely a rural one led to a poor simulation of the catchment dynamics. The inclusion of simple hypotheses on the behaviour of urban areas provides some improvements (Figure 9). But further tests are required to draw firm conclusions.

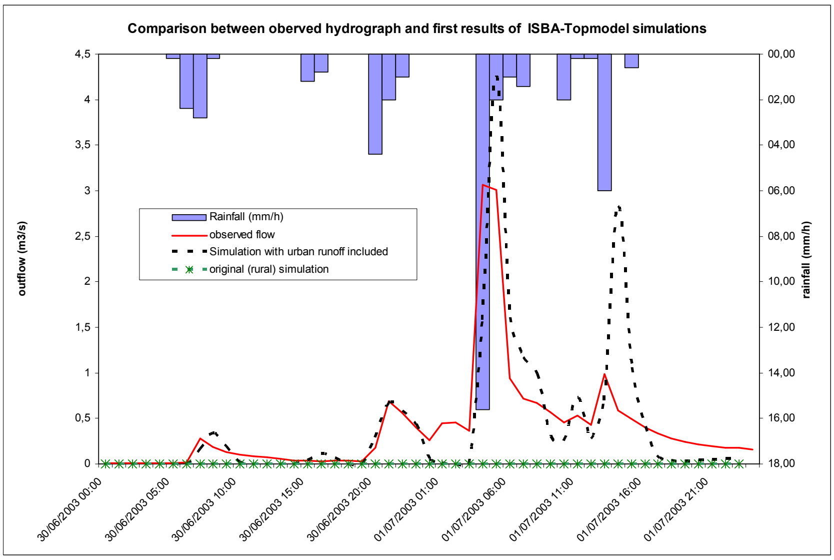

Figure 9: Comparison of the observed hydrograph (red line) with the hydrographs simulated with the ISBA-Topmodel coupled model when only rural (green line) areas are considered or when urbanised areas are taken into account (black line) for the June 30- July 1 2003 event on the Chézine catchment

5 SCENARIOS AND DERIVATION OF VULNERABILITY INDICATORS

To address the vulnerability issue, we will run long-term simulations using the models presented in the previous section and perform sensitivity studies to land use evolution and climate. Results will be translated into appropriate indicators quantifying the vulnerability of rivers. We will focus on the flow-duration-frequency curves, which also characterize the hydrological regimes of the rivers and possible alterations due to land use and/or climate change. The impact on geo-morphological characteristics will also be mapped, allowing to highlight river reaches prone to incision or aggradations. Thus, the study requires the specification of past and future climate forcing and land use mapping at a scale relevant for hydrology.

A first effort is dedicated to the derivation of rainfall fields relevant for suburban hydrology, i.e. with a high spatial (500m to 1km) and temporal scale (6mn to 1h). Two directions are currently investigated. For recent years, the suitability of the St-Nizier radar data available since 2001 at 1 km^2 and 5min resolution, located in the Beaujolais Mountains, has been demonstrated by showing a good visibility of the Yzeron catchment and a reasonable agreement when compared to pluviographers data from the Grand Lyon network (Renard et al., 2009). For previous years, a rainfall simulator, based on geostatistical principles, has been designed (Lepioufle, 2009). The parameters of the models are inferred from the statistical analysis of the Grand Lyon and Cemagref rain gauge networks and the simulations are conditioned to reproduce the observed time series at the rain gauges located within the catchment (8 gauges in 2009).

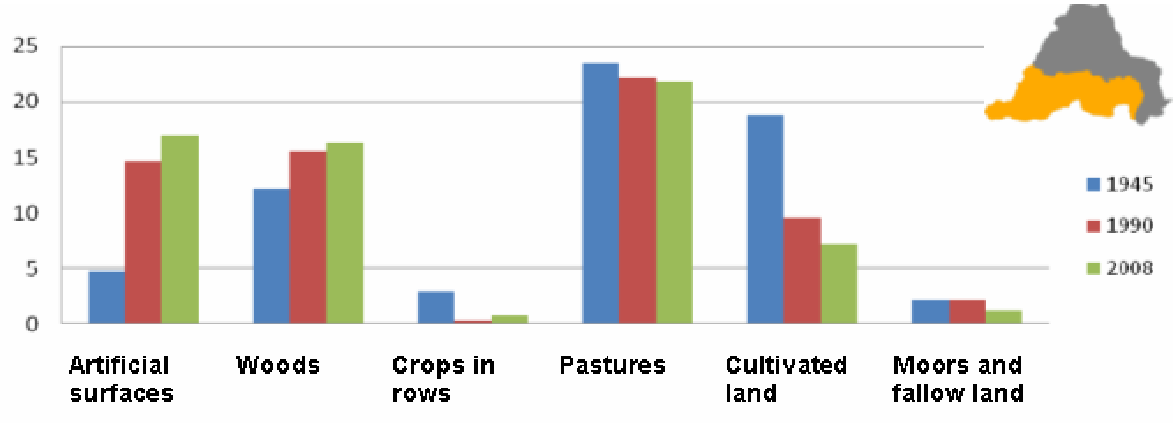

Figure 10: Evolution of land use area (km^2) on the south-western part of the Yzeron catchment (65 km^2) between 1945, 1990 and 2008

Another effort is directed towards the diachronic mapping of past land use since 1945 and the derivation of possible future land use scenarios. For past land use, aerial photographs and remote sensing images are used and processed according to the images characteristics (Béal et al., 2009). Figure 10 provides a synthesis of land use change between 1945, 1990 and 2008 on the south-western part of the catchment, corresponding to the main course of the Yzeron catchment. Figure 10 shows a large increase in artificial surfaces (area multiplied by three between 1945 and 2008), an increase of forested areas compensated by a small decrease of pasture areas and a significant decrease of row crops (mainly vineyard). Cultivated lands area was also divided by two between 1945 and 2008. These results show a quick land use dynamics on the catchment. The modelling results will allow quantifying the corresponding impact on the hydrological regime. For future land use scenarios derivation, a group of experts is being set up and models describing land use dynamics are used.

6 CONCLUSIONS AND PERSPECTIVES

The first phase of the AVuPUR project was dedicated to data collection and analysis. Many data are available, especially in urban data banks. An important effort was made to harmonize the data formats and geographical projections from the various sources and data providers. The first results presented in this paper show that the combination of all the sources of information is helpful for deriving a consistent view of water pathways within these complex catchments and of the impact of various structures in modifying these pathways. The hydrological modelling tools under construction will provide more insight into suburban catchments functioning. The two scales which are considered in the project are complementary: the small scale studies help understanding the elementary active hydrological processes and provide clues for taking into account the main features in simplified models, applicable at larger scales. We must also underline the synergy between the observation and modelling strategy. Observations are required to understand the processes and propose relevant conceptualizations within the models and to assess the relevance of the proposed approaches. This step will be tackled in the next year of the project. Models will also allow to perform sensitivity tests for conditions not sampled by the observation network. In particular past and future land use maps as well as simulated rainfall fields will be used to run long term simulations of the river hydrological regime. This project provides a first step towards the improvement of water fluxes description. The next step will be the coupling with quality problems in the context of the Water Framework Directive.

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