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SUMMARY

This paper addresses the impact of the source and processing method of land use information for hydrological simulations on the long-term water balance of the Yzeron peri-urban catchment (150 km^2), located near Lyon, France. A customised version of the distributed hydrological model J2000 was used to perform simulations at a daily time step. Five land use data sets obtained from aerial photographs BDOrtho@IGN and satellites Quickbird and Spot for the year 2008 are compared. The paper presents the methodology for model setup and the simulation results for the main water balance components of the catchment: total runoff at several gauging stations, runoff components, evapotranspiration and soil moisture. The model evaluation against discharge measurements at six locations shows a reasonable agreement between simulated and observed values, in particular for general seasonal variations, low flow periods and simulation of runoff components (surface runoff, interflow and base flow), with Nash–Sutcliffe efficiencies ranging from 0.25 to 0.51 at the daily time step and 0.46–0.82 at the monthly time step. The comparison of the model outputs for the various land use maps shows that the total discharge is not very sensitive to the data set used (−4.88% to 4.65% at the catchment outlet), except in a small and more densely urbanised sub-catchment for which a significant impact of image resolution on simulated flow is detected (+25.81%). For all gauges, the results also highlight the sensitivity of the modelled flow components, in particular regarding the amount and seasonal dynamics of surface runoff generation (8–44% of total flow at the catchment outlet depending on the data set used). As a conclusion, land use information should be selected and processed with care, with respect to the objectives of a given study, and the sizes and urbanisation rates of the target sub-catchments.

1. Introduction

Urban growth and concentration of population in urban areas is a general trend. 68.7% of the world population (94.1% in France) will live in urban areas by 2050 according to the UNO 2009 world urbanisation prospect. Multiple studies have shown the potential impacts of land use change, extension of impermeable surfaces and introduction of artificial drainage networks on catchment hydrology (Jacobson, 2011): rise and acceleration of storm peak flows (Burns et al., 2005), increases in flood magnitudes and bank erosion (White and Greer, 2006), decrease of groundwater recharge and base flow (Brandes et al., 2005), not mentioning water quality issues and ecological degradation of streams (Walsh et al., 2005). Peri-urban catchments, consisting of a mixture of natural, agricultural and urbanised areas in complex interaction (Santo Domingo et al., 2010), are particularly vulnerable (Braud et al., 2013).

Hydrological models are valuable tools for studying the processes affected by growing urbanisation, quantifying these impacts, making projections of potential future changes and designing water management policies. This is particularly the case for the long-term impacts of land use change on the water balance (Praskievicz and Chang, 2009), where assessment through a mere data analysis can be difficult due to the lack of long-term time series and multiple influences (e.g. climate variability, climate change, river morphological and rating curve changes, changes in urban drainage system) that might affect the data (Claessens et al., 2006; Braud et al., 2013).

Modelling studies of the influence of land use change and urbanisation are mainly based on land use maps obtained by re-

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mote sensing, either used directly in the case of historical evolution of land use (Brun and Band, 2000; Miller et al., 2002; Cuo et al., 2009; Im et al., 2009), and/or used as a base for simulation of future land use scenarios (Bronstert et al., 2002; Niehoff et al., 2002; Beighley et al., 2003; Ott and Uhlenbrook, 2004; Wijesekara et al., 2011). Nowadays a wide range of remote sensing products are available to the research community, obtained from various sensors with various resolutions and many possible processing methods (Jacqueminet et al., 2013). The choice of a specific image source or processing method might not be neutral and could influence greatly the results of hydrological model simulations, in particular in peri-urban areas where the detection and localisation of impervious surfaces has direct implications in terms of production of surface runoff. This question has been rarely investigated in the literature so far. Available studies deal mainly with the influence of data resolution, and are rarely specifically focused on land use (Cotter et al., 2003; Bormann et al., 2009). The few studies on land use are either focused on long-term balance but not specifically for peri-urban catchments, or deal with urban catchments but consider only storm events. For example, Wegehenkel et al. (2006) studied specifically the influence of four spatial land cover data sets (German data sets ATKIS and biotope mapping, along with the European CORINE Land Cover data set and Landsat-TM5 images) on the water-balance components of a 2415 km^2 catchment in Germany with a semi-distributed model. They observed a correlation between the simulated surface runoff and the proportions of settlement areas derived from the land use data. However, these proportions varied only from 2.5% to 5% in a catchment widely dominated by agriculture. Their results are thus hardly transposable to peri-urban areas. On the other hand, Chormanski et al. (2008) compared the impact of land use data derived from two sensors, Ikonos and Landsat ETM+, along with a map produced by the Agency for Geographical Information on the base of various sources (Landsat, CORINE land cover...) for a 31 km^2 urbanised catchment located in Brussels, Belgium. They created several land use scenarios from these maps, which were compared through simulations with the WetSpa model. They observed significant changes in hydrological response according to the scenarios. However, they studied only a few storm events and did not consider the long-term balance of their study catchment. Nevertheless, addressing the long-term water balance of a catchment is necessary when considering the impact of disturbances related to urbanisation on receiving waters (e.g. Fletcher et al., 2013).

In this context, the objective of the present study is to investigate and quantify the influence of land use data source and processing method on the modelled long-term water balance of a peri-urban catchment. Therefore we used a set of land use maps derived from aerial or satellite very high-resolution images of the same year 2008 (Jacqueminet et al., 2013) and the distributed hydrological model J2000 (Krause et al., 2006) on the Yzeron catchment in France.

J2000 is a fully distributed model developed at the University of Jena, Germany. It uses the Hydrological Response Unit concept (HRUs – Flügel, 1995) for space discretization. In comparison with the grid-based discretization of many hydrological models used for land use change and urbanisation studies, such as WASIM (Niehoff et al., 2002; Bormann et al., 2009), WetSpa (Liu et al., 2006; Chormanski et al., 2008), MIKE-SHE (Im et al., 2009; Wijesekara et al., 2011), DHSVM (Cuo et al., 2009), HRUs are natively well suited to represent the heterogeneity of peri-urban catchments. In particular, the sizes of the HRUs are usually contrasted (quite large in rural areas, but smaller in urban areas), and the drained areas present very irregular shapes due to the presence of artificial networks that influence flow directions (Jankowfsky et al., 2012). These specificities are taken into account directly by the HRU discretization In addition, J2000 is fully distributed, as distinct from lumped or semi-distributed models that are also commonly used, such as SWAT (Miller et al., 2002; Bormann et al., 2009), HEC-HMS (Beighley et al., 2003; Ali et al., 2011) or HSPF (Brun and Band, 2000; Im et al., 2003). J2000 also calculates the components of flow (surface runoff, interflow and groundwater flow) at each time step, and for each model unit of the catchment and the hydrographic network (see Section 2.2). This is particularly interesting for a peri-urban catchment where the partitioning of surface runoff and base flow is suspected to be modified. Finally, J2000 is freely available, open-source and easily customizable due to its modular design on the base of the JAMS modelling framework (Kralisch et al., 2007). Environmental modelling frameworks are designed to build and apply integrated models on the basis of reusable and exchangeable components (Branger et al., 2010). Thus J2000 seems to have a good potential to address the needs of peri-urban hydrology. Previous applications of J2000 in land use and climate change impact studies (Fink et al., 2007; Krause and Hanisch, 2009) shows its suitability for long-term water balance and water quality assessment.

The paper first presents the available data and main model concepts, the strategy that was adopted for model setup, and the main results in terms of model evaluation and comparison of the model outputs for the various land use data sets.

2. Material and methods

2.1. Application site and available data

The Yzeron catchment (150 km^2) is located in a zone of low mountains (foothills of the Massif Central range), and close to the city of Lyon, France (Fig. 1). It is representative of the French peri-urban areas, with a fast progressing urbanisation observed since 1980 (Kermadi et al., 2012). The upstream part of the basin is limited by a range of hills culminating at 917 m and covered by coniferous and deciduous forests on steep slopes. The intermediate part is mainly covered by grassland and cultivated lands (dairy and vegetable/fruit farming), mixed with urban zones expanding along the transportation network, and steep riverine corridors. The downstream part is mainly covered by densely urbanised areas, including part of the city of Lyon. The outlet of the catchment is the Rhône river at the elevation of 162 m. The geology consists mainly of crystalline formations (granite, gneiss) in the upstream part, along with alluvial and glacial formations in the eastern part, leading to a limited soil water storage capacity.

The Yzeron catchment is subject to quick Mediterranean-type flood events that can impact the downstream urbanised areas, with a response time estimated about 12 h at 130 km^2 (Braud et al., 2013).

The instrumentation of the Yzeron catchment started in the 1960s and has been completed since the 1990s by Irstea in the framework of the the Field Observatory for Urban Water Management (OTHU, Observatoire de Terrain en Hydrologie Urbaine[1]). Additional data was gathered during the AVuPUR project (Assessing the Vulnerability of Peri-Urban Rivers; Braud et al., 2010). The rainfall and discharge gauges used in this study are shown in Fig. 1. The streamflow measurement stations follow a nested sub-catchment strategy, with sub-catchment areas ranging from 4.3 km^2 to 123 km^2. For climatic data, the SAFRAN analysis database (Vidal et al., 2010) was obtained from Météo-France on a 8∗8 km^2 grid from 1970 to 2011.

The GIS data used in this study are a digital elevation model with 25 m resolution (BDTopo@IGN), a geology map in the scale 1:50,000 digitized by Gnouma (2006), and the pedological map

[1] http://www.graie.org/othu/.

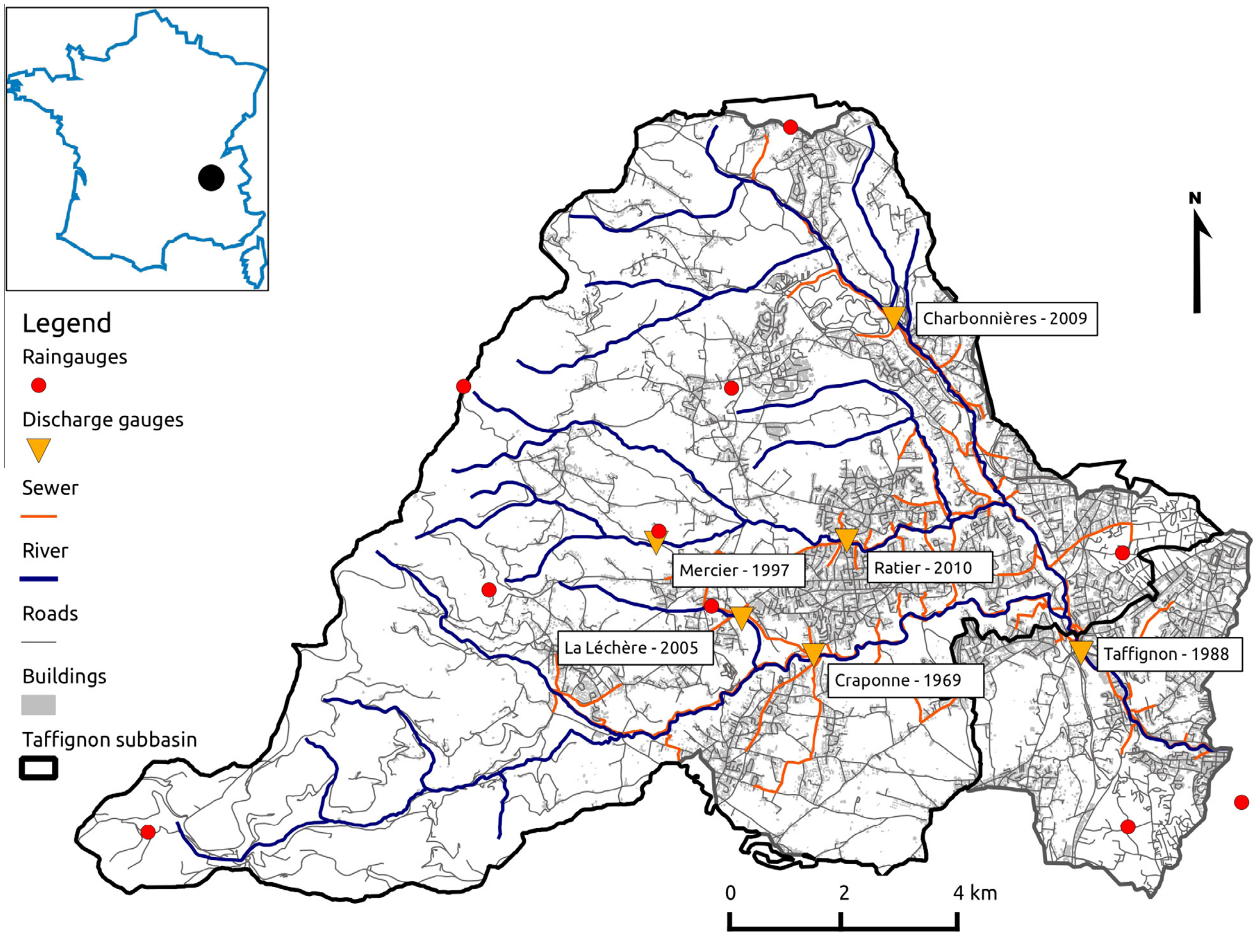

Fig. 1. Situation map of the Yzeron catchment, representing roads and built areas from IGN BD Topo 2008, the main the river and sewer networks, and the locations of the raingauges and streamflow gauges used in this study. Close to each discharge station are indicated its name and year of installation. The sub-catchment of the Taffignon outlet station includes urban zones and thus does not follow exactly the topography.

of the French DONESOL programme. Maps of the river and sewer networks were obtained from French national reference database BD Carthage and the local authorities (Grand Lyon and SIAVHY), respectively. The land use maps were derived from various remote sensing images, all from year 2008 (Jacqueminet et al., 2013): BDOrtho@IGN aerial images, 0.50 m resolution (referred to as Ortho in the following); QuickBird satellite image, 2.44 m resolution (Quickbird); Spot satellite image, 5 m resolution interpolated at 2.5 m (Spot 2.5). A 10-m aggregation of the Spot image (Spot 10) was also available from another study on historic evolution of land use (Branger et al., 2012a). It was thus added to the land use data set in order to analyse the influence of image resolution. Each image was processed according to a specific method: pixel based analysis using the ENVI software for Spot images, and object oriented analysis using the Definiens software and a Matlab-based processing chain for the Quickbird and Ortho images, respectively. A Synthesis map (Synthesis) combining the classifications obtained from the Spot, Quickbird and Ortho images was also produced and considered as the best description of land use (Jacqueminet et al., 2013). Therefore a total of five raster land use maps could be used for this study.

2.2. Model presentation

The modular distributed hydrological model J2000 (Krause, 2002; Krause et al., 2006) used in this study is available through the JAMS modelling framework (Kralisch et al., 2007) and distributed under an open-source license.

J2000 simulates hydrological processes on irregular Hydrological Response Units (HRUs), using mostly capacity-based approaches for interception, runoff/infiltration partition, evapotranspiration, soil percolation, groundwater flow and stream flow. J2000 consists of five main modules describing physical processes as shown in Fig. 2: interception, snow, soil water balance, groundwater and flow routing. The soil water module considers two storages that divide the soil porosity in two categories: middle pore storage (MPS) and large pore storage (LPS). The surface runoff/infiltration partition is controlled by the imperviousness of soil surface, the average soil saturation and a maximum infiltration rate. A depression storage can hold back surface runoff water before it flows out of the HRU. Infiltrating water is distributed in both storages according to a distribution coefficient and the MPS saturation level. Water in the middle pore storage does not flow with gravity and can be extracted by plant transpiration only. Water in the large pore storage flows with gravity and can be distributed between back diffusion to the MPS storage (controlled by a diffusion coefficient and the MPS saturation), lateral interflow and percolation to the groundwater (depending on the HRU slope, a distribution coefficient and a maximum percolation threshold). The groundwater module consists of two storages, characterised by their sizes and time constants, and that represent quick and slow reacting groundwater compartments, respectively. Percolation water is distributed in these storages according to the HRU slope and a distribution coefficient. Four flow components are calculated, namely surface runoff (RD1), interflow (RD2) and fast and slow groundwater flows (RG1 and RG2). At each time step,

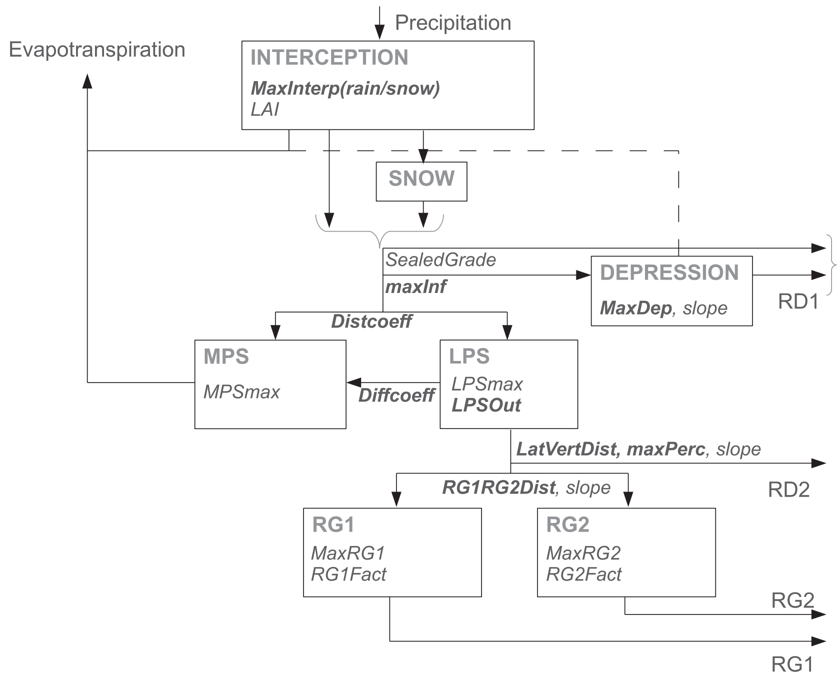

Fig. 2. Concept of the J2000 model showing the storages, the input and output flows for each HRU and the main parameters (italic). Parameters indicated in bold are lumped (1 value for the whole catchment), whereas the other parameters are distributed. J2000 provides also multiplicative lumped calibration parameters for each of the HRU outputs (RD1, RD2, RG1, RG2) and for the channel routing. These parameters were not used in this study and are thus not represented here.

the outflows of each HRU are routed laterally to the connected neighbouring HRU according to the spatial routing scheme, until the channel network is reached. The flow routing module then transfers water from reach to reach using a simplified kinematic wave approach. J2000 keeps track of the flow components from the HRU where they are produced to the catchment outlet, thus allowing the identification of flow components at each HRU and each point of the river channel. J2000 is usually used with a daily time step, although its structure allows to run it with any fixed time step (provided the process representations are suited).

In addition to the process modules, J2000 also provides a set of components for the regionalisation of climate data and the calculation of potential evapotranspiration.

For this application the classical J2000 was slightly modified to fit with the local context and available data. The components for calculation of potential evapotranspiration were removed in order to take reference evapotranspiration (as defined by FAO, 1998) time series directly as input data. A crop coefficient component was developed and added in order to modulate potential evapotranspiration according to the vegetation. The snow component was also removed and a variant of the interception module was developed for no snow conditions.

2.3. Model setup

2.3.1. Temporal resolution

A daily time step was chosen for model simulations. This time step could appear too coarse given the usual quick response of urban areas to rainfall events, and the overall short response time of the Yzeron catchment which is less than one day. However the objective of the present study is not to simulate accurately the response to some specific events, but to perform long-term continuous simulations, focusing only on the general hydrological regime and long-term water balance variables such as the seasonal variations of runoff and its components, evapotranspiration, or soil moisture. These components of the hydrological balance can be efficiently assessed at larger time scales and using a coarser time step, as the dominant processes involved have intrinsic large time scales (Blöschl and Sivapalan, 1995). For this specific purpose, the daily time step, already used successfully for small to medium-sized peri-urban catchments, as shown by Braud et al. (2013) or Barron et al. (2013), was considered as appropriate.

2.3.2. HRU delineation

With a daily time step, it was preferred to avoid simulating flow processes on areas too small. Therefore, in order to keep the model mesh consistent with the time step, sub-catchments were used as HRUs and were not segmented further. The model considers only the natural hydrographic network, so sewers were not represented. It was considered that it was acceptable for a study focussing on the water balance components of the catchment at long temporal scales,, where classically runoff production processes dominate over the runoff routing processes (Blöschl and Sivapalan, 1995). However the influence of sewers on sub-basin delineation was taken into account by applying the method described by Jankowfsky et al. (2012). First, natural sub-catchments were delineated classically using a stream burning algorithm, the DEM and the river network map. Second, the contours of sewer-influenced sub-catchments were digitized manually, using the map of the sewer network and aerial photographs. As the sewer system is mostly a combined system on the Yzeron catchment (i.e. mixing rainwater and wastewater), the outlet points of these sub-catchments were selected at the locations of the closest major sewer overflow devices along the river. The natural and sewer-influenced sub-catchments were then combined to obtain a map of mixed sub-catchments. After topological cleaning and merging of small polygons generated by the overlay operations, we obtained 96 HRUs with a mean area of 1.3 km^2. The river network was discretized into 66 reaches with an average length of 1.43 km. The natural sub-catchments were connected topologically to the river reach they drain into. The sub-catchments drained by sewers were connected directly to the river network at the locations of sewer overflow devices. The final model HRU map is shown in Fig. 3.

2.3.3. Classification of the land-use data

The original land use maps contained various classes, depending on the image source and the processing method that was applied (Jacqueminet et al., 2013). In order to obtain comparable land use information, the classes of each map were merged into three more general classes:

- Impervious (buildings and roads).
- Agriculture (pastures, annual crops, bare soils).
- Forest (deciduous trees and conifers).

The relative percentages of these classes for each HRU were then calculated. Depending on the ratio of impervious surfaces and the dominant vegetation of each HRU, five land use types were eventually defined to be used in the model: Urban, Mixed with agriculture, Mixed with forest, Rural with agriculture and Rural with forest. HRUs were classified as Urban if more than 50% of their area was impervious, Mixed if impervious ranked between 10% and 50% of the total, and Rural if less than 10%. Within classes Mixed and Rural, subclasses agriculture and forest were distinguished, depending on the dominant non-impervious land use. This classification method and threshold values were applied identically to all five land use maps. This rather coarse land use classification was chosen to be consistent with the granularity of model time step and HRU delineation given by our modelling objectives. Following our strategy for sub-catchment discretization, the subbasins in urbanised zones and in particular the sewer-drained subbasins are smaller than the naturally drained subbasins located in the upstream rural zones. Therefore, the land uses are quite homogeneous in the HRUs (in particular in terms of% of impervious areas). We can thus reasonably consider that this classification does not alter the original land use information too much. The resulting HRUs are displayed in Fig. 3 and summary statistics for the six sub-catchments defined by the discharge gauging stations (see Fig. 1) are given in Table 1.

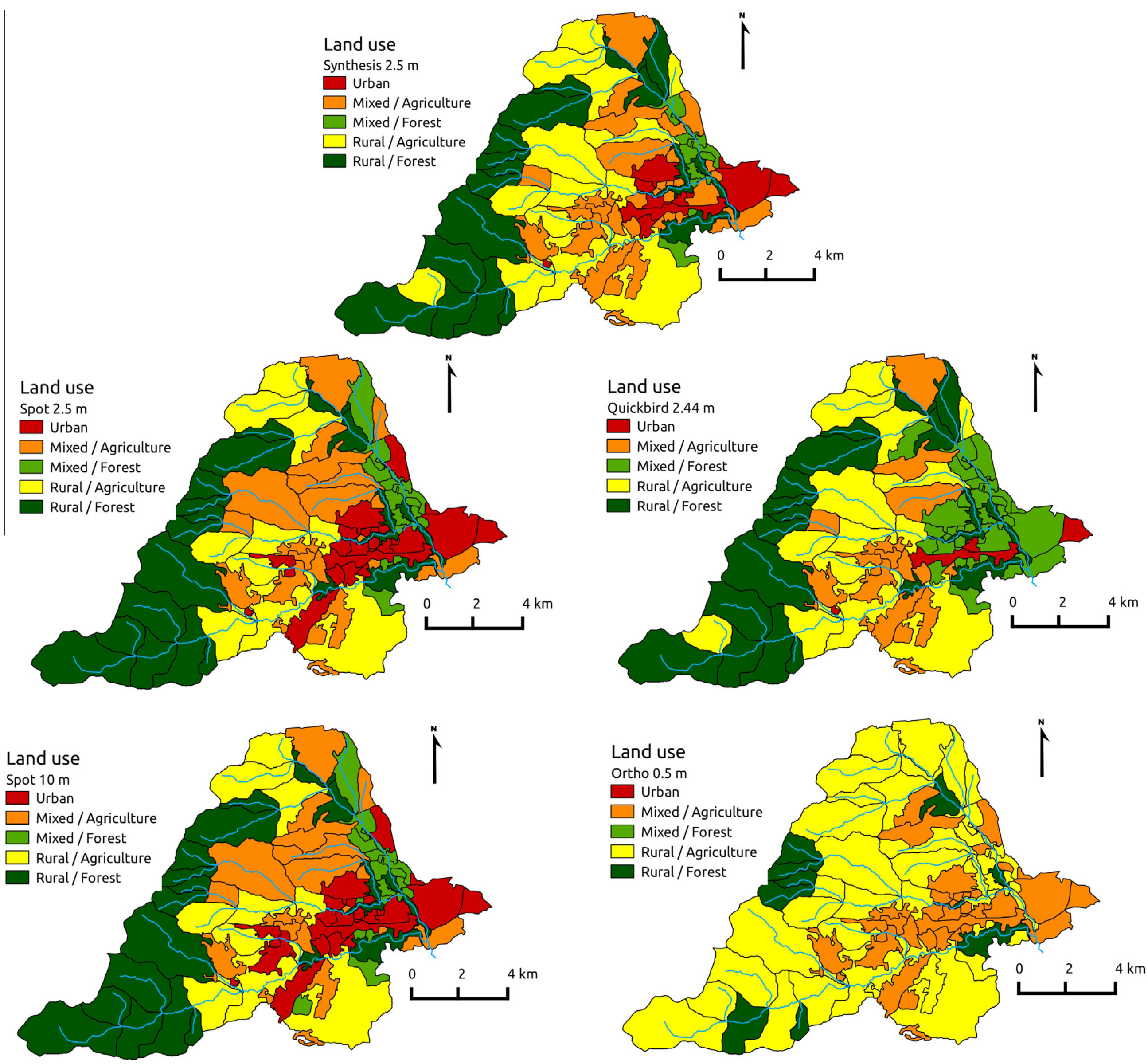

Fig. 3. Model HRUs and reaches and land use classification for Synthesis 2008, Spot 2008 (2.5 m and 10 m), Quickbird 2008 and Ortho 2008 land use maps.

Table 1
Relative percentages of land uses: impervious (buildings and roads); agriculture (pastures, low vegetation, ploughed soils, orchards); forest (deciduous trees and conifers) for the five land use maps and the six sub-catchments defined by the discharge gauging stations (see Fig. 1).

	Area (km^2)	Synthesis (%)	Spot 2.5 (%)	Quickbird (%)	Ortho (%)	Spot 10 (%)
Taffignon	124.4					
– Impervious		25	29	22	8	29
– Agriculture		42	36	34	68	36
– Forest		33	35	44	24	35
Craponne	40.9					
– Impervious		19	22	17	6	24
– Agriculture		51	46	46	71	45
– Forest		31	32	37	23	31
La léchère	4.3					
– Impervious		30	35	27	11	41
– Agriculture		58	54	51	80	48
– Forest		12	11	22	9	11
Mercier	7.8					
– Impervious		5	6	5	2	6
– Agriculture		52	50	49	65	50
– Forest		42	44	46	33	44
Charbonnières	22.9					
– Impervious		12	15	11	4	14
– Agriculture		44	40	40	65	40
– Forest		44	46	49	31	46
Ratier	18.9					
– Impervious		15	17	13	5	17
– Agriculture		44	40	38	65	40
– Forest		42	43	49	30	43

Consistent, if not strictly equal, reclassified land use maps are obtained for the Synthesis, Spot 2.5 and Quickbird images. On the other hand, the Ortho map presents strikingly contrasted results: the percentage of impervious areas is one order of magnitude lower than for the other maps, and the percentage of forests is also significantly lower, whereas agricultural areas are much more represented. This is particularly visible in Fig. 3, where there are no HRUs in the "Urban" class and almost none in the Mixed and Rural Forest classes. This is clearly related to the higher spatial resolution of the Ortho image (0.5 m) which allows to distinguish the spaces between the buildings and the trees. Many of the grass covered and bare soil areas were here classified as agriculture although they are more related to forest or impervious classes. However, as the objective of this study was precisely to compare the impact of the land use image source, it was decided to apply strictly the same classification for all the land use maps, even if the output is not fully satisfactory for the Ortho map. This is discussed in more detail in Jacqueminet et al. (2013).

The main difference between Spot 2.5 and Quickbird was a lower percentage of impervious land use and a higher proportion of forest for Quickbird, while the percentage of agricultural land is quite similar. This is observable for the various gauged sub-catchments (Table 1). As a consequence, the Quickbird map presents less "Urban" HRUs which instead are replaced by "Mixed/Forest" HRUs especially in the downstream part of the catchment. The differences can be explained by two main factors: firstly, the resolutions of the original images are different (5 m for Spot 2.5 and 2.44 m for Quickbird), and secondly, the processing methods also differ (pixel classification versus object-oriented classification). Being a combination of Spot 2.5, Quickbird and Ortho (with less weight for the latter map), the Synthesis map appears as a well-balanced compromise. Finally, the 10-m aggregation of the Spot image does not bring significant changes, except for the small La Léchère sub-catchment which has a significantly higher percentage of impervious areas.

Average vegetation parameters (leaf area index, crop coefficient for evapotranspiration, root depth) were set for each land use class according to the FAO (1998) and Ecoclimap (Masson et al., 2003) databases. Each land use class was also assigned an infiltration coefficient equal to the average percentage of non-impervious land use within the class for a given land use map (see Table 2).

2.3.4. Other data processing

The soil map contained initially 24 different soil types, including one "no data" type covering most of the urban zones at the downstream end of the catchment. This map was simplified by selecting only the majority soil types on each HRU and by merging some of the similar types. Soil types were also reconstructed for the HRUs in the urban zones on the basis of the neighbouring soil types and the geology map. We finally obtained 5 soil classes: shallow sandy loams, medium-depth sandy loams, 50–50 mixture of the two previous soils, deep silt loams, and deep alluvial silty sands. The model requires for each soil class information about the soil depth, porosity and field capacity. These parameters were estimated according to the general characteristics of each soil type described in the database and additional detailed descriptions of representative soil profiles for each soil type that are also available in the database.

As the geology of the catchment is mostly granite, we considered as a first approximation that there is no permanent aquifer in the catchment. Therefore the slow groundwater storage in J2000 was deactivated. The remaining storage was parameterized

Table 2
Values of infiltration coefficients (–) for the five land use maps.

Map/land use class	Urban	Mixed (agr/forest)	Rural (agr/forest)
Synthesis	0.427	0.668	1
Spot	0.412	0.674	1
Quickbird	0.413	0.681	1
Ortho	–	0.841	1
Spot10	0.405	0.672	1

as small-capacity aquifer with a relatively short reaction time, with only one class for the whole catchment.

Concerning climatic data, we used the data from all the rainfall gauges represented in Fig. 1. J2000's regionalisation component was used to calculate an average rainfall for each HRU taking into account the four closest raingauges and applying an altitude correction. Reference evapotranspiration (RefET) was calculated outside of the model as a uniform value for the whole catchment on the base of the 10 SAFRAN cells that intersect the catchment and the Penman-Monteith equation (FAO, 1998).

2.3.5. Strategy for J2000 lumped parameters

In addition to the distributed parameters, J2000 also uses a set of lumped parameters, with one value for the whole catchment, as represented in Fig. 2. These parameters control partly some of the processes, and can also be used as calibration parameters. In our simplified version of J2000 (without snow and with only one groundwater storage), and without considering the pure calibration parameters with no specific hydrological meaning, the total number of lumped parameters was 8. In order to reduce the model complexity and thus the number of significant parameters, simple assumptions were made. The depression storage was deactivated by setting its capacity to zero, whereas no limitations were made for maximum infiltration and percolation by setting the corresponding threshold parameters to very high values. For soil parameters, we assumed the distribution of soil water in priority to the MPS storage, which is a common assumption also made for instance in the TNT2 model (Beaujouan et al., 2002; Ferrant et al., 2011), and set medium values for the parameters controlling outflow from the soil and percolation.

2.3.6. Simulation strategy

The model was run for each land use map over a thirteen-year period (1997 to 2010), at a daily time step, using year 1997 as the warm up period. In order to maintain an explicit link between the parameter values and the available data and not to compensate for changes potentially linked to the land use data, calibration was omitted. J2000's calibration parameters were thus not used. In order to estimate the model's ability to capture the most important hydrological processes within the catchment, the simulation results for the Synthesis map (year 2008) were first compared to discharge observations at several gauging stations for the corresponding period (2005–2010). Then, the results over the whole simulation period were analysed for all the other land use maps, using the synthesis simulation as a reference.

3. Results and discussion

3.1. Model verification

In order to compare the simulated and observed discharges at several locations on the catchment for the reference land use scenario, several sets of indicators were calculated for the time period 2005–2010. Table 3 presents the values obtained for a set of classical performance indicators: Nash–Sutcliffe efficiencies to characterise the flow dynamics (with emphasis on high flows for the classical efficiency and on average flow for the efficiency calculated with the square root of discharge), root mean square error to quantify the mean error in discharge, and bias and absolute bias to characterise the mass balance. These indicators were calculated at the daily and monthly time steps, except for the Charbonnières and Ratier stations where the daily time step indicators only could be calculated due to the limited length of available time series. In addition, Table 4 presents several hydrological regime indicators as introduced by Braud et al. (2013) for simulated and observed discharges at four gauging stations: mean discharge, maximum discharge, percentage of time (in days) during which the discharge values are below a given threshold. This threshold was set as the value of low level monthly discharge with a 5 year return period (QMNA5 according to the French terminology), which is routinely calculated by the French hydrometry services. In order to analyse in more detail the flow components, the relative mean percentages of surface runoff, interflow and base flow were also calculated. These values are a direct output of the J2000 model. For the observed time series, the percentages were obtained using the Wetspro hydrograph separation tool (Willems, 2009), as described by Braud et al. (2013), using daily data for the Craponne and Taffignon stations, and 2-h time step data for the La Léchère and Mercier stations. The separation parameters were determined manually by trial and error so that the base flow fraction obtained by Wetspro was similar to the Base Flow Index calculated using the Tallaksen and Van Lanen algorithm (2004) Tallaksen and Van Lanen algorithm (2004). More detail can be found in Braud et al. (2013).

The Nash–Sutcliffe efficiencies range from 0.25 to 0.62 at the daily time step, depending on the station, which can be interpreted as mediocre to fairly acceptable. The efficiency values at the monthly time step are significantly higher (0.82 at the outlet station) and indicate that the model is able to reproduce the long-term variations of discharge (as also represented in Fig. 4) quite well, including the seasonal variations of base flow. The fraction of the base flow component is well reproduced by the model for the Craponne and Taffignon stations (Table 4). The separation of surface runoff and interflow is more approximative, but has good orders of magnitude. For the La Léchère and Mercier stations, the results are not as good. A possible explanation is the difference of time step for calculating the runoff components: 1 day for J2000 and 2 h for Wetspro. This should be investigated more in depth. In addition, the Wetspro separation could probably be analysed further for the Mercier station, as 42% of surface runoff on this very rural and forest-covered catchment seems quite high and does not necessarily correspond to the field knowledge.

The stations that are less well simulated regarding Nash–Sutcliffe efficiencies are the upstream rural Craponne station, where the discharge is systematically underestimated by the model and the small urbanised La Léchère station, where the discharge is overestimated (this is also clearly observable in the Bias results and in Fig. 4). More generally, the model seems to overestimate discharges for the most downstream/urbanised subbasins (see

Table 3
Numerical criteria for model evaluation at six gauging stations (see Fig. 1): Nash–Sutcliffe efficiencies calculated with discharge (Nash(*Q*)) and square root of discharge (Nash($\sqrt{Q}$)), root mean square error (RMSE), bias (Bias) and absolute bias (Abias) for the daily (*d*) and monthly (*m*) time steps, respectively.

	Nash (*Q*) (–)	Nash ($\sqrt{Q}$) (–)	RMSE (m^3/s)	Bias (%)	Abias (%)
Taffignon (d/m)	0.48/0.82	0.62/0.75	1.12/0.32	13.9/12.9	62.7/39.8
Craponne (d/m)	0.33/0.46	0.34/0.33	0.50/0.24	−48.8/−48.8	58.3/51.5
La Léchère (d/m)	0.35/0.59	0.32/0.41	0.05/0.01	38.1/39.2	98.6/62.6
Mercier (d/m)	0.25/0.62	0.51/0.64	0.12/0.04	−15.8/−16.4	67.2/45.5
Charbonnières (d)	0.50	0.34	0.11	−38.2	63.8
Ratier (d)	0.51	0.58	0.03	5.5	28.5

Table 4
Hydrological regime indicators as calculated by Braud et al. (2013) for simulated and observed discharges at four gauging stations (years 2005–2010): Q_{mean} is the mean discharge; Q_{max} the maximum discharge; % low is the percentage of time (days) the discharge values are under a given threshold; RD1, RD2 and RG1 are the relative mean percentages of surface runoff, interflow and base flow, respectively. The thresholds for % low were 0.013 m^3/s, 0.011 m^3/s, 0.001 m^3/s and 0.005 m^3/s for the Taffignon, Craponne, La Léchère and Mercier stations, respectively. The values of RD1, RD2 and RG1 for the observations were estimated by using the Wetspro hydrograph separation tool (Willems, 2009).

	Q_{mean} ($m^3\ s^{-1}$)	Q_{max} ($m^3\ s^{-1}$)	% Low (–)	RD1 (%)	RD2 (%)	RG1 (%)
Taffignon						
Simulation	0.681	21.322	9.17	42	16	42
Observation	0.600	46.253	14.47	38	23	39
Craponne						
Simulation	0.158	2.735	28.67	21	33	46
Observation	0.308	16.300	7.53	27	24	49
La Léchère						
Simulation	0.027	1.343	27.75	56	9	35
Observation	0.019	1.581	20.53	55	19	26
Mercier						
Simulation	0.034	0.482	35.00	17	29	54
Observation	0.046	4.198	23.33	42	22	36

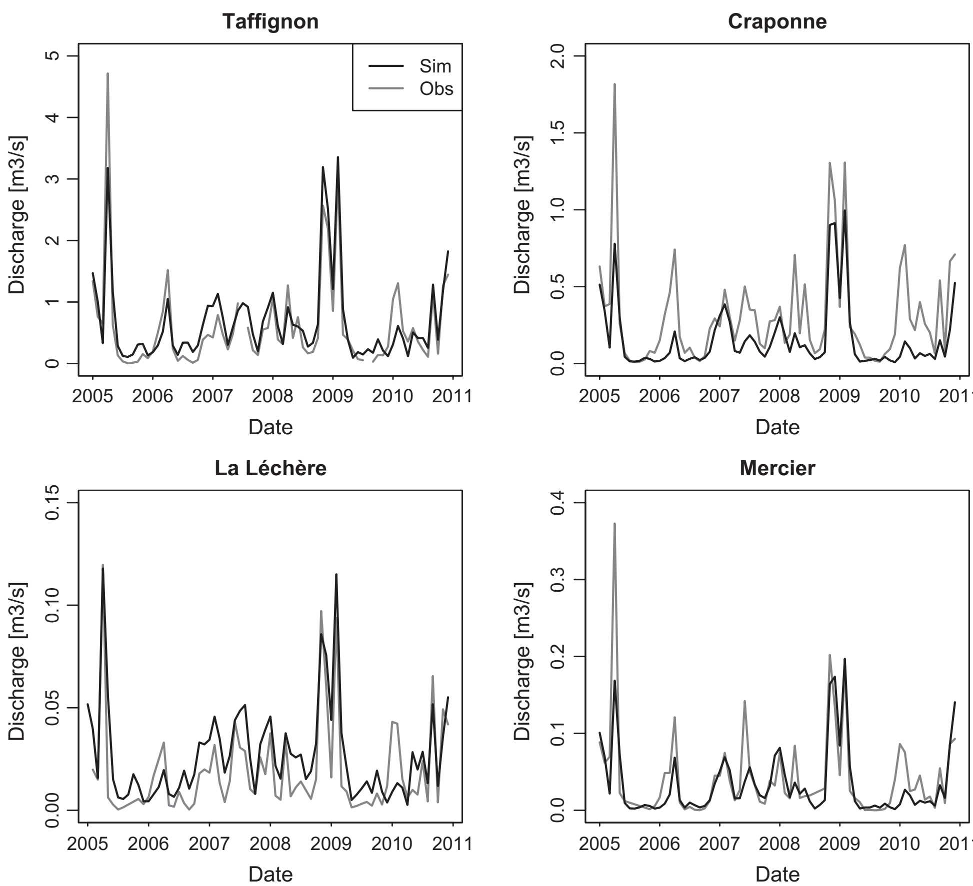

Fig. 4. Model evaluation: simulated (black) and observed (gray) monthly mean discharge values during the 2005–2010 period for the outlet station (Taffignon) and the intermediate stations Craponne, La Léchère, and Mercier.

Table 1 for the relative percentage of impervious areas), and underestimate them for the upstream/rural sub-catchments. It was found that, for urbanised sub-catchments, the model tends mostly to overestimate peak flows for small events (discharge <1 $m^3\ s^{-1}$), whereas the highest peaks corresponding to major floods are underestimated whatever the ratio of impervious areas. This would have also to be confirmed for the intermediate Ratier and Charbonnières stations when longer time series will be available. For the rural sub-catchments, the model simulates the recession and dry periods quite well, but all the peak events are underestimated, sometimes considerably. Further investigations are required to understand more precisely the reasons for this behaviour, and possibly identify the processes that are not well represented or missing in the model. Additionally, the uncertainties associated with the discharge measurement data should be taken into account, which are suspected to be quite high but not fully quantified at the moment for all the stations (Branger et al., 2012b; Le Coz et al., 2013). A possible interpretation for the overestimation in urbanised sub-catchments could be the model's simplified representation of drainage networks. As the sewers are not represented in J2000, the sewer-drained HRUs are connected directly to the river. In the real world, part of this water would remain in the sewer network and be diverted towards the Waste Water Treatment Plant, and thus not contribute to river discharge. An underestimation of the infiltration coefficients (here taken as equal to the percentage of non-impervious areas) is also a possible explanation. However, the current simple setup that was chosen in this study seems to be adequate as a first approximation, in the sense that it does not deteriorate significantly the model performance and its ability to represent the long-term processes on the catchment.

As outlined in the previous section, J2000 was not calibrated in this study. A calibration would probably have enhanced the model performance and led to higher efficiency values. However, even without calibration the values obtained here are quite comparable to the results found in other studies (although not applied to periurban catchments): for example, Wijesekara et al. (2011) obtained monthly Nash–Sutcliffe efficiencies between 0.52 and 0.94 with a calibrated MIKE-SHE model; Wegehenkel et al. (2006) obtained values from 0.27 to 0.34 at the daily time step, also with a calibrated model. As a perspective, it could be interesting to calibrate the model separately for each land use data set to investigate whether calibration can somehow compensate for the differences in the land use input data.

3.2. Influence of land use data sets

A synthesis of the simulation results for the various land use data sets is presented in Table 5. Table 5 presents these results for all the test sub-catchments (see Fig. 1), except the Ratier station, because the results for this station were found to be identical to the results for the Charbonnières station. We used the same set of indicators as for model verification (see Table 4). Additional water balance indicators (mean soil saturation, mean annual potential and actual evapotranspiration) were also calculated for the Taffignon catchment. The results are quite comparable for all the sub-catchments. The modifications induced by the land use data are quite slight, in particular for the Q_{mean} and % low indicators. The general trend seems to be a rise of the mean discharge with the rate of impervious surface induced by the land use map, and a decrease of the length of the drought periods. The fact that drought periods decrease with increasing imperviousness does not correspond to what was expected according to the literature (Jacobson, 2011). In addition, the results for the Ortho map appear to be also paradoxical. In particular, for the Taffignon, Craponne and Charbonnières sub-catchments, Q_{mean} is significantly higher for the Ortho map than for the other maps, thus not following the general trend.

This result can be explained by considering the runoff components and the seasonal variations presented in Fig. 5 for the Taffignon outlet station. The same graphs were also plotted for the other stations, but are not shown here because they are all similar to Fig. 5. In Fig. 5, we can see that the total discharge is lower for Ortho in summer (hence the increase of low flow indicator % low), but higher in winter. This is due to higher interflow and base flow for Ortho in winter. On the opposite, surface runoff is systematically and significantly lower for the Ortho map than for the other maps. This surface runoff is directly related to the rate of impervious surface on the catchments. This pattern also explains why the drought periods are shorter and the mean discharge are higher for the Spot land use data set. Fig. 6 confirms the base flow

Table 5
Hydrological regime and water balance indicators as calculated for the simulations using the five land use maps at four gauging stations (years 1998–2010): Q_{mean} is the mean discharge; Q_{max} the maximum discharge; % low is the percentage of time (days) the discharge values are under a given threshold; RD1, RD2 and RG1 are the relative mean percentages of surface runoff, interflow and base flow, respectively; soil sat is the mean soil saturation; PotET and ActET are the mean annual potential evapotranspiration and actual evapotranspiration, respectively.

	Q_{mean} ($m^3 s^{-1}$)	Q_{max} ($m^3 s^{-1}$)	% Low (–)	RD1 (%)	RD2 (%)	RG1 (%)	Soil sat (–)	PotET (mm)	ActET (mm)
Taffignon									
Synthesis	0.860	44.975	7.69	33	24	46	0.39	793	584
Spot 2.5	0.894	43.430	6.63	43	19	39	0.37	803	576
Quickbird	0.818	44.251	8.21	29	22	48	0.39	825	595
Ortho	0.890	53.979	10.55	8	28	64	0.45	704	577
Spot 10	0.900	43.765	6.51	44	18	38	0.37	804	574
Craponne									
Synthesis	0.249	11.426	24.66	13	39	48			
Spot 2.5	0.245	11.315	25.44	16	38	46			
Quickbird	0.247	11.360	24.85	13	39	48			
Ortho	0.308	13.812	22.39	5	43	52			
Spot 10 m	0.250	11.595	24.71	19	37	45			
La Léchère	0.031	1.343	25.55	48	10	42			
Synthesis	0.033	1.609	23.88	55	9	36			
Spot									
Quickbird	0.031	1.289	25.53	46	11	43			
Ortho	0.028	0.637	26.12	25	13	62			
Spot 10	0.039	2.253	23.29	67	7	26			
Mercier	0.048	2.097	31.57	12	32	56			
Synthesis	0.048	2.093	31.59	12	32	56			
Spot 2.5	0.048	2.090	31.70	12	32	56			
Quickbird	0.047	2.257	40.19	0	36	64			
Ortho									
Spot 10	0.048	2.094	31.59	12	32	56			
Charbonnières	0.129	8.444	22.07	17	21	62			
Synthesis	0.137	8.855	21.10	25	19	57			
Spot 2.5	0.129	8.410	22.16	17	21	62			
Quickbird									
Ortho	0.150	9.377	28.58	0	25	75			
Spot 10	0.137	8.864	21.08	26	19	56			

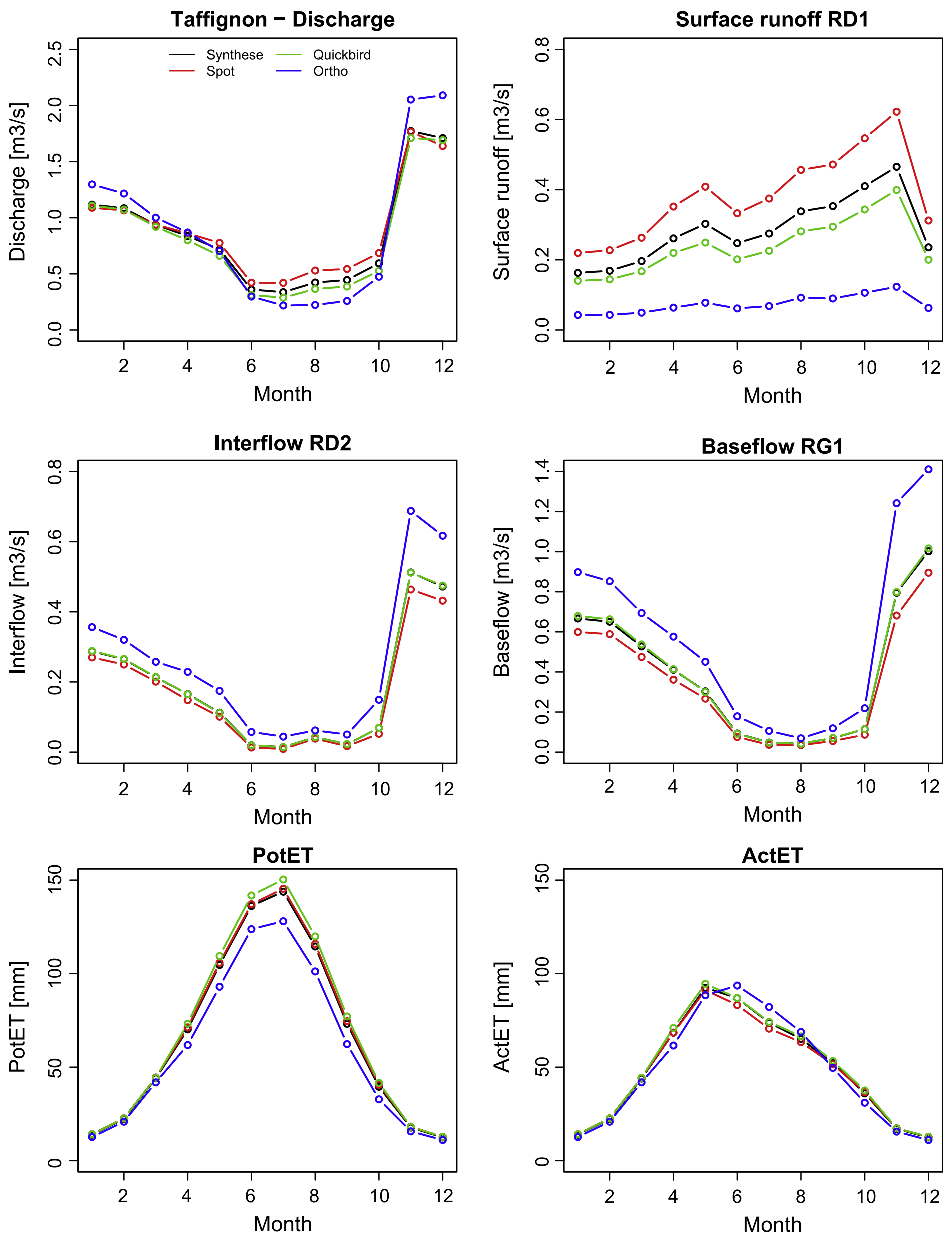

Fig. 5. Comparison of the interannual monthly mean simulated total discharge and runoff components, mean annual potential evapotranspiration (PotET) and mean annual actual evapotranspiration (ActET) for the maps Synthesise (black), Spot 2.5 (red), Quickbird (green) and Ortho (blue) at the catchment outlet (Taffignon station). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pattern and provides more detail. It shows the total discharge and base flow for two contrasted years: 1998 is a dry year with only 539 mm of rain, whereas 2007 is a wet year with 960 mm of rain. 1998 and 2007 are also both characterised by the absence of flood event, allowing an easier interpretation. Fig. 6 shows that the base flow for the Ortho map is comparable to the base flow for the other maps in summer 1998, whereas it is remains higher throughout the whole year for 2007, especially during the summer months which received a significant amount of rainfall. The base flow pattern seems thus to be governed by water availability and soil imperviousness: when there is water available, whatever the season, the low impermeability level of the Ortho map induces more infiltration and groundwater recharge, and thus more base flow.

The mass balance indicators (Table 5 and Fig. 5 bottom) allow a more in depth interpretation. Potential evapotranspiration is the highest for the Quickbird map and lowest for the Ortho map, especially in summer. This is directly linked to the rate of forest-covered surface, which is higher for Quickbird and lower for Ortho (Table 1, Fig. 3). However, the actual evapotranspiration presents a different pattern. For all maps but Ortho, the actual evapotranspiration appears to be limited by an average smaller water availability in soils. Actual evapotranspiration is therefore not significantly higher for Spot, Quickbird and Synthesis, and even noticeably reduced in summer (Fig. 5 bottom right), as compared to the Ortho map. This confirms that the higher discharge during summer months found for Spot, Quickbird and Synthesis maps is not provided by a continuous flow linked to soil moisture, but rather by intermittent surface runoff generated by summer storm events.

The flood indicator Q_{max} values (Table 5) seems to indicate that the Ortho map induces higher flood peaks for all the stations, except for the La Léchère station, where Q_{max} is significantly lower.

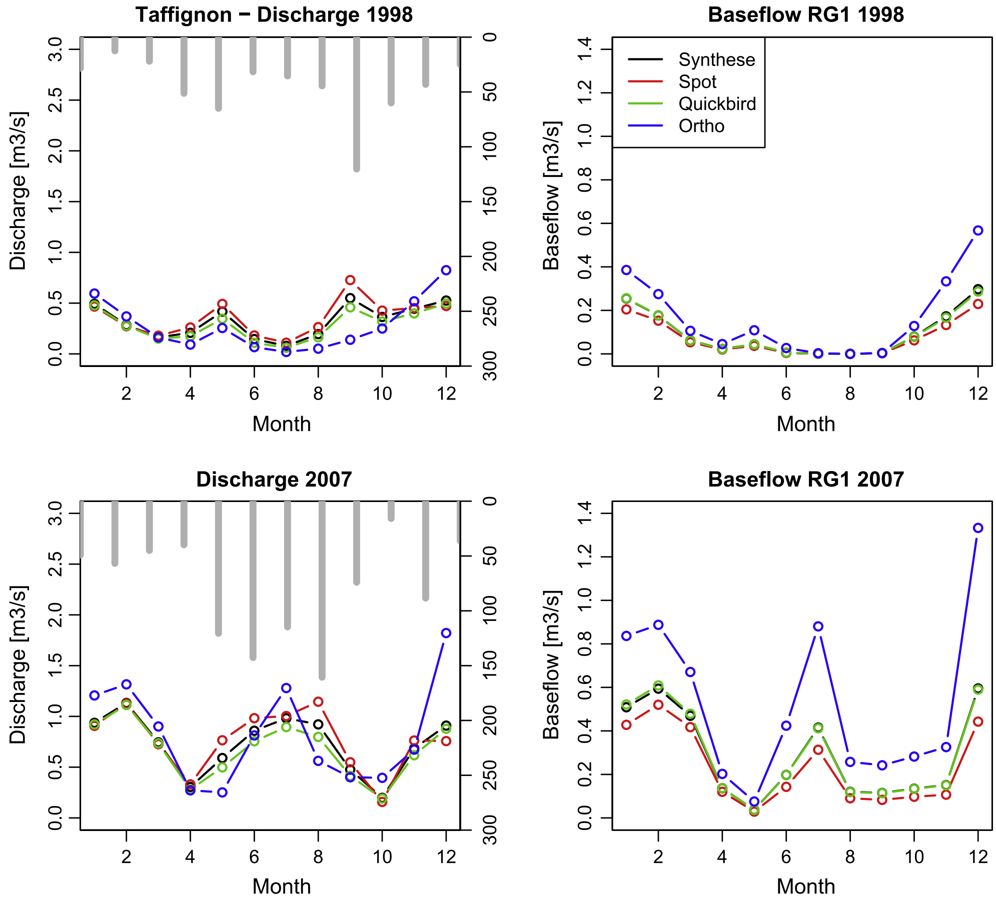

Fig. 6. Comparison of the monthly mean simulated total discharges and base flows for dry year 1998 (top) and wet year 2007 (bottom) for the maps Synthesis (black), Spot 2.5 (red), Quickbird (green) and Ortho (blue) at the catchment outlet (Taffignon station). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This could indicate that the dominant hydrological processes during flood events are completely different for the small, urbanised La Léchère sub-catchment, and for the other sub-catchments where the dominant land use is still rural (either agriculture or forest, see Table 1). For the La Léchère sub-catchment, the main contributor to peak discharge would here be surface runoff (interpretable as a dominant contribution of urbanised areas), whereas for the other sub-catchments interflow and base flow would be the main contributors (linked to rural land use). However, this is quite difficult to conclude as the model was not set up for the simulation of flood events and does not perform well for this specific indicator (see Table 4). Therefore, we cannot have full confidence that the model represents well the hydrological processes for floods.

The results for the Mercier and La Léchère catchments can also be compared. The Mercier and La Léchère are the two smallest test catchments in our study (7.8 and 4.3 km^2, respectively). Compared to the other test catchments, they have rather homogeneous (but contrasted) land uses: very rural for the Mercier catchment with less than 5% of impervious areas according to the Synthesis map, and quite urban for the La Léchère catchment with 30% of impervious areas. For the Mercier catchment, Table 1 already shows that the relative percentages of the various land uses are quite similar for all the land use maps. The simulation results are in good agreement with that (Table 5), with only very slight differences between the maps for some of the indicators (the other indicator values being strictly identical). On the other hand, the La Léchère catchment appears to be quite sensitive to the land use map used in the model, in particular regarding the simulation of flow components. It is also the only catchment for which the impact of the image resolution (Spot 2.5 and Spot 10) is perceptible (see Fig. 7 and Table 5 for the other sub-catchments). The coarser image resolution of the Spot 10 map induces a higher discharge throughout the year and particularly during summer as compared to the Spot 2.5 map. This is due to a systematically higher surface runoff throughout the year, only partially compensated by relatively lower interflow and base flow during the winter. The conclusion that can be drawn from this particular result is that:

- For a small and very rural catchment such as the Mercier, the choice of a specific image source and processing method seems to be of low importance for a water balance study.
- It can have an important effect for larger or more urbanised catchments, the key factor being the rate of imperviousness which can be estimated with the land use map.
- Even if the very high resolution images that were used in this study (0.5–2.5 m) provided valuable information, we could have done the same study with a coarser resolution (up to 10 m) when not considering the small and highly urbanised catchments for results analysis and interpretation. The results would have been the same for most of our test catchments, except the La Léchère one. Again, the estimation of imperviousness rates and hence infiltration coefficients is the key factor that explains such a high sensitivity to the image resolution for this small catchment.

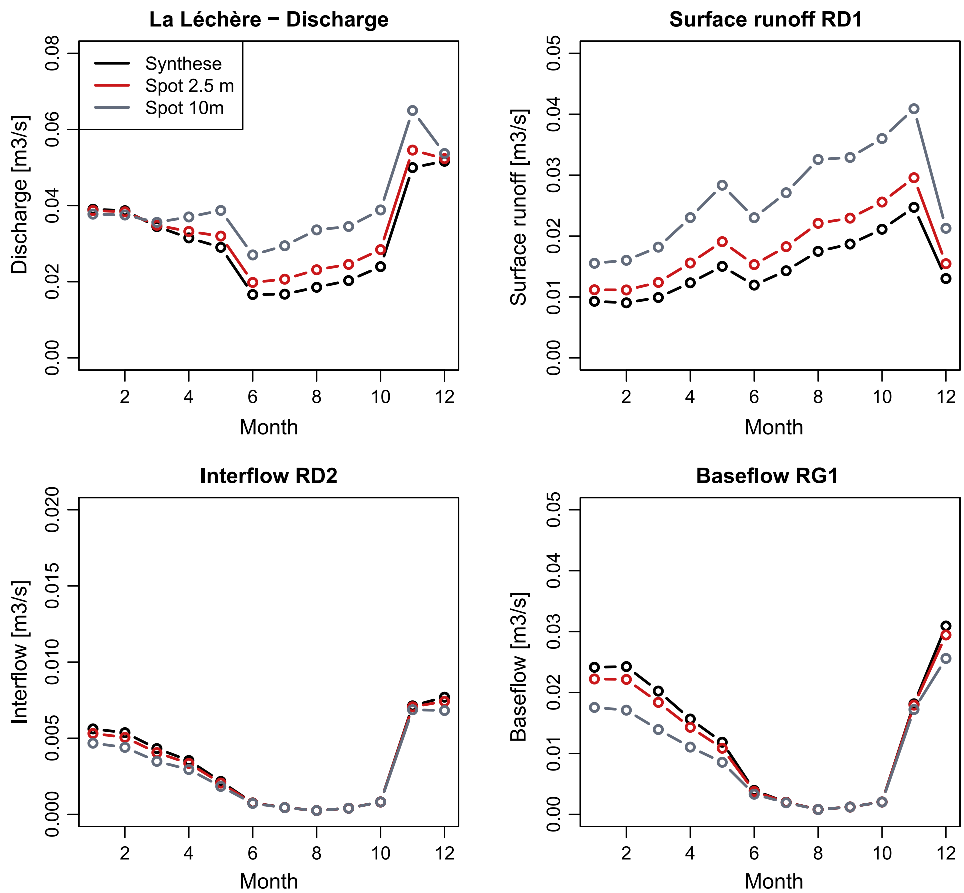

Fig. 7. Comparison of the interannual monthly mean simulated total discharge and runoff components for the maps Synthesis (black), Spot 2.5 (red), and Spot 10 (gray) at the La Léchère intermediate station. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, it must be kept in mind that the coarse spatial discretization (sub-catchments as HRUs) that was used in this study probably influences these results. The coarse land use classification into 5 classes and the averaging of imperviousness rates smooth the discrepancies between the maps. Yet the conclusion that highly urbanised areas are more sensitive to land use data resolution than rural areas remains valid.

4. Conclusions and perspectives

The objective of this study was to analyse the influence of land use data on the simulated long-term water balance of the peri-urban Yzeron catchment, using the J2000 distributed hydrological model. Five land use maps derived from Spot, Quickbird and BDOrtho@IGN images were compared. Given the long-term objectives of the study and our focus on water balance components that can be assessed at large time scales, the model was set up with coarse temporal and spatial resolutions: a daily simulation time step, large sub-catchments as HRUs, and a reclassification of the land use information into five classes only.

In spite of this rough set up, the J2000 model appeared to be an appropriate simulation tool for this water balance study. Although it was not designed specifically for peri-urban areas, its structure and parameters proved to be quite adequate. It was also easily customizable and its adaptation to our application case was quite straightforward thanks to its modular structure and the underlying JAMS framework. The model evaluation against discharge measurements at several locations showed a reasonable agreement between simulated and observed values, in particular for general seasonal variations, low flow periods and simulation of runoff components (surface runoff, interflow and base flow). As expected, the daily simulation time step could not reproduce well the flow dynamics at the event scale (all the more that the response time of the Yzeron catchment is less than one day), and thus flood events were less well reproduced.

The comparison of simulation results for the different land use maps showed that the choice of a given data set can induce important changes in the model response. The differences may not be necessarily spectacular in terms of total discharge at the outlet of the catchment, although more visible for the small urbanised sub-catchments. The results also highlighted the high sensitivity of the respective contributions of flow components (groundwater flow, interflow and surface runoff) to the land use information used. Surface runoff generated on urban surfaces is likely to carry a wide range of contaminants, all the more that it is mixed with waste water through the sewer network as it is the case for the Yzeron catchment. Therefore, the impact on water quality and stream health may be particularly important, especially in summer when the river's main water providers happen to be the sewers. The choice of a given land use map is thus not neutral. The main factor appeared to be the degree of imperviousness estimated for each land use class in the model. The nature of vegetation (and the forest/crops ratio) appeared as a secondary factor governing the evapotranspiration processes.

The test of several land use data sets can also be seen as a sensitivity analysis for the model and help us identify the most important factors governing the model's response. This gives us directions for understanding the dominant processes in the catchment and possibly improving the model parameterisations and/or process representations. This is also an advantage of using an uncalibrated model, as there is no bias introduced by the calibration process on the parameter values. Using the model as an hypothesis testing tool (e.g. Clark et al., 2011), it is more straightforward to identify whether the shortcomings of the model can be attributed to the parameters of the process representations – and to try to improve them. In particular, we could observe that simulations with the Ortho map, with higher infiltration rates and higher interflow and base flow contributions, would allow improved simulations for high flow conditions on the rural upstream sub-catchments. Therefore a possible direction for improving the simulation of large floods with an important contribution of rural upstream zones could be to revisit the parameterization of soil and groundwater reservoirs in order to increase soil water storage. However, the model structure should probably be adapted first to event simulation (in particular with a reduction of the simulation time step).

It is difficult to conclude on a "best" land use data set which should be preferred. The Ortho map clearly emerges as an outlier from our comparison, probably because its very high resolution is not adapted for the basic calculation of imperviousness rates at the sub-catchment scale, as already discussed by Jacqueminet et al. (2013). As it was also the map which was the most difficult to process (although we can expect that the improvement of processing techniques will overcome this soon), it should probably be avoided for further studies of the same type. Yet such maps do have a relevance, for example for the setup of detailed hydrological models on small catchments (Jankowfsky et al., 2011). Regarding the Quickbird and Spot 2.5 maps, the model was quite insensitive to the differences in the maps, which were minor. The specific interest of the Synthesis map does not appear very clearly in the current setup of the model, but could be more significant with a shorter simulation time step and a more detailed spatial segmentation with smaller HRUs. The image resolution (2.5–10 m), which was tested for Spot images, is neither very important at the scale of the whole catchment nor for small sub-catchments with a rural land use. However, it seems to play an important role for the small and urbanised catchments. As a conclusion, the land use map should be chosen with care, with respect to the objectives of a given study (interest for the outlet only or also for sub-catchments, sizes and urbanisation rates of the target sub-catchments, focus on water quantity only or possible interest for water quality issues etc.).

This work calls for many perspectives. The first perspective would be to further validate the model, and undertake a more in depth analysis to understand in detail what are the processes that were well or badly reproduced, including the consideration of uncertainties. We could also test other commonly available land use data sets, such as the European CORINE Land Cover data base, or Landsat satellite data. For this study we favoured very high resolution data, but these are not necessarily representative of the data that are commonly (freely) available for hydrologists and modellers.

Another direction is to adapt J2000 more specifically to small and medium-size peri-urban catchments, in particular by adding a representation of sewers, integrating an improved representation of surface land use patterns and infiltration coefficients and introduce the various rainwater management options that can be chosen by local authorities. This would require a reduction of the simulation time step to 1 h or less, and the delineation of smaller HRUs with higher spatial resolution. The use of very high resolution land use images could be more relevant in this context. This could possibly improve the model performance in urbanised areas, the simulation of flood events, and would also allow to better represent historic conditions and to create robust and reliable projections of impact of future urban development.

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