Land cover mapping using aerial and VHR satellite images for distributed hydrological modelling of periurban catchments: Application to the Yzeron catchment (Lyon, France)

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Abstract

The rapid progression of urbanization in periurban areas affects the hydrological cycle of periurban rivers. To quantify these changes, distributed hydrological modelling tools able to simulate the hydrology of periurban catchments are being developed. Land cover information is one of the data sources used to define the model mesh and parameters. The land cover in periurban catchments is characterized by a very large heterogeneity, where the vegetated and the artificial surfaces are finely overlapping. The study is conducted in the Yzeron catchment (150 km^2), close to the city of Lyon, France. We explore the potential of very high-resolution (VHR) optical images (0.50 to 2.50 m) for retrieving information useful for those distributed hydrological models at two scales. For detailed object-oriented models, applicable to catchments of a few km^2, where hydrological units are based on the cadastral units, manual digitizing based on the 0.5 m resolution image, was found to be the most accurate to provide the required information. For larger catchments of about 100 km^2, three semi-automated mapping procedures (pixel based and object-oriented classifications), applied to aerial images (BD-Ortho®IGN), and two satellite images (Quickbird and Spot 5) were compared. We showed that each image/processing provided some interesting and accurate information about some of the land cover classes. We proposed to combine them into a synthesis map, taking profit of the strength of each image/processing in identifying the land cover classes and their physical properties. This synthesis map was shown to be more accurate than each map separately. We illustrate the interest of the derived maps in terms of distributed hydrological modelling. The maps were used to propose a classification of the Yzeron sub-catchments in terms of dominant vegetation cover and imperviousness. We showed that according to the image processing and images characteristics, the

calculated imperviousness rates were different. This can lead to significant differences in the hydrological response.

Key-words: distributed hydrological model, land cover mapping, impervious surface, very high resolution images, image processing methods

1. Introduction

The increase of urbanization associated with population growth is one of the major changes affecting land use around big cities. The UN 2009 world urbanization prospect predicts that about 68.7% of the worldwide population (94.1% in France) will live in urban areas by 2050. This phenomenon mostly affects periurban areas, where natural or agricultural areas are being progressively replaced by built-up areas (e.g. Meija and Moglen, 2010). These changes have an impact on the water cycle through the increase and acceleration of surface runoff or decrease of groundwater recharge (e.g. Chocat et al, 2001; Booth et al, 2002; Matteo et al, 2006; Marsalek et al, 2007; Jacobson, 2011) and an impact on water quality and bank erosion (e.g. Walsh et al. 2005; Lafont et al., 2006). Water pathways are also modified by the building of networks such as drinking water, sewer systems or roads (Jankowfsky et al., 2012).

To better understand how these land use modifications affect the hydrological cycle in periurban catchments, distributed hydrological models, able to take into account the complexity of those areas, are very useful (e.g. Ott and Uhlenbrook, 2004; Praskievicz and Chang, 2009). Land cover maps can provide useful information to set up these models, both in terms of model spatial discretization and model parameters specification. The requirements regarding the accuracy of the land cover maps will depend on the scale of interest, as detailed below (Dehotin and Braud, 2008).

In terms of catchment discretization, a first generation of distributed hydrological models was based on the Digital Elevation Model (DTM), leading to model meshes corresponding directly to the DTM grid (Abbott et al., 1986a, b), isocontours of altitudes (Vertessy et al., 1993) or Triangular Irregular Networks (TINs – Ivanov et al., 2004). In order to take into account landscape characteristics, and define modelling units which could be considered as homogeneous with regards to the hydrological processes, the concept of Hydrological Response Units (HRU) was introduced by Fluegel (1995). The HRUs are obtained by intersection and combination of raster and vector maps such as topography, land cover, soil properties, or geology, assuming that the association of these factors controls the main hydrological processes in a catchment. Landscape information is of particular importance for the delineation of HRUs. The nature of land use / land cover maps (vector or raster) and their exact use in the HRU delineation process and model parameterization is scale dependent (Dehotin and Braud, 2008). In the remaining of the paper, land use will refer to the function of the land surface (agriculture, residential, industrial, etc.) and land cover to the physical properties of those surfaces (woody vegetation, herbaceous vegetation, bare soil, building, road, etc).

For small catchments of a few km^2, object-oriented modelling approaches can be used. In this case, HRUs are derived from the intersection of polygon layers representing information such as land cover, soil type, sub-catchments and geology. Information on natural and artificial drainage networks can also be taken into account. The resulting hydrological mesh is formed by simple polygons with irregular shapes. They are able to better represent man-made features, which significantly affect hydrological processes in a catchment (Carluer and De Marsily, 2004; Lagacherie et al., 2010). This is particularly relevant for periurban or urban catchments, where the urban and rural elements have different response times (Braud et al., 2012) and where artificial networks can affect the flow direction (Gironás et al, 2009). Examples of such object-oriented models, adapted to small catchments, are the URBS (Rodriguez et al., 2003) and MHYDAS (Moussa et al., 2002) models; and models built within the LIQUID modelling framework (Branger et al., 2010) such as the BVFT model (Branger et al., 2010) designed to study the impact of agricultural drainage and hedgerows on the hydrological cycle of small rural catchments; and the PUMMA model specifically designed for periurban catchments (Jankowfsky, 2011; Jankowfsky et al., 2010, 2011). Those models are useful to test the impact of the various objects present in the catchment on the hydrological response (Clark et al., 2011).

For larger catchments of about 50 km² to more than 10000 km², used for assessing the impact of land use or climate change on the water balance, less detail on the land cover will be required. Typically, raster format data, aggregated or averaged over large surfaces are used in the HRUs delineation (Fluegel, 1995; Tolson and Shoemaker, 2007; Krause and Hanisch, 2009; Viviroli et al., 2009).

Parameters, representing the properties of the identified HRUs must be specified and land cover data is one of the data sources that can document two main hydrological processes: the partition of rainfall between soil infiltration and surface runoff, and evapotranspiration. For soil infiltration, especially in periurban areas, it is important to distinguish between pervious and impervious surfaces as it directly impacts infiltration capacity. For rural areas, vegetation type can also impact significantly soil infiltration as shown by Gonzalez-Sosa et al (2010), who suggest a spatialization method of soil hydraulic properties based on land cover. Vegetation cover has also a significant impact on evapotranspiration according to the vegetation type (forest / herbaceous / crops, deciduous / evergreen…) and the vegetation development. The latter can be described using the leaf area index (LAI), which is often derived from remote sensing images, based on the calculation of a vegetation index (NDVI) (Boegh et al, 2004).

Periurban catchments form a particularly complex system. They are composed of a mixture of agricultural, forested and more or less densely urbanized areas in complex interactions (Santo Domingo et al., 2010; Braud et al., 2012). The spatial organization of these various land covers is often fragmented and the size of urban parcels is generally much less than that of the agricultural or forested ones. The distinction of pervious and impervious areas, and of various vegetation types is also important as they correspond to surfaces with different response times. To address all these points at the two scales highlighted before, specific image processing can be necessary to get the required accuracy.

There exists numerous data on land use / land cover such as the US Geological survey land cover map or the EU CORINE land cover map. CORINE land cover map only provides information on land use (residential, industrial…) about the artificialised areas but do not provide information on the distribution of developed surfaces and pervious surfaces within different urbanization forms.

Remote sensing data are more appropriate to map biophysical surface properties. Several land use mapping studies, based on remote sensing images were developed for hydrology. Weng (2012) provides a review of the use of aerial and remote sensing images for the mapping of impervious surfaces in urban areas. He underlines the limits related to the spatial resolution of the image sensors. In periurban areas, dominated by individual housing, land cover is characterized by a large diversity and a very strong spatial heterogeneity where the impervious surfaces (built-up areas, roads) and the pervious surfaces (vegetation, bare soils) can overlap. For this reason, mixed pixels are common for coarse resolution images. The identification of build-up areas is obtained by mapping the vegetation first. The remaining areas are then considered as built-up areas (Bauer et al, 2004, Carlson, 2004, Gillies et al, 2003). Several studies tried to decompose the mixed pixel in order to extract the vegetated, mineral and impervious areas. An example is the Vegetation-Impervious surface Soil (VIS) approach proposed by Ridd in 1995 (Jacobson, 2011; Small and Lu, 2006).

The increase of the number of very high-resolution sensors is a real opportunity to identify the components of urban and periurban areas: "the fine spatial resolution images contain rich spatial information and greatly reduce the mixed pixel problem, providing a greater potential to extract much more detailed thematic information (e.g. land use and land cover) and cartographic feature (building and roads)" (Weng, 2012). A spatial resolution of 0.25 m to maximum 5 m is generally thought to be sufficient to detect or distinguish types of buildings and individuals buildings (Jensen and Cowen, 1999, Puissant and Weber, 2002). Since the end of the 20th century, several maps of urban areas have been derived using optical sensors with a resolution lower than 5 m (IKONOS, Quickbird, ORBview…), using newly developed segmentations procedures. They show the potential of those sensors and techniques to delineate buildings, roads, mineral surfaces and vegetated surfaces (Lhomme et al, 2004; Karsenty et al, 2006;

Yuan and Bauer, 2006; Chormanski et al, 2008; Lu and Weng, 2008). However, the improved spatial resolution does not always lead to easier land cover mapping, due to the high spectral variation within the same land cover class (Herold and Scepan, 2003; Van der Sande et al, 2003) and shadows caused by topography, tall buildings and trees (Hyun-Ok et al, 2005). The use of those data derived from VHR images into distributed hydrological models shows that a more accurate identification of settlement areas in a catchment together with an improved estimation of the actual imperviousness of these areas is beneficial for accurate calculations of surface runoff and flood peaks (Wegehenkel et al., 2006; Chormanski et al, 2008; Zou and Wang, 2008).

However, the use of VHR imagery for the land cover mapping of complex landscapes such as those encountered in periurban areas is less common (Moran, 2010). This requires the identification of land cover corresponding to the various agricultural, forested and urban uses. The object size is also different from one land use to the other. Those studies generally address small catchments (< 10 km^2) (Chormanski et al, 2008; Van der Sande et al, 2003) or large catchments (> 10 km^2) with a weak detailed typology of land cover (Jacquin et al, 2008).

In this paper, we address the following question: in the specific context of peri-urban areas characterized by a heterogeneous, contrasted and changing land use, which useful information can be extracted from Very High Resolution (VHR) images for use in distributed hydrological models? We propose 1/ to compare the respective inputs of three types of VHR optical images and various manual and semi-automated processing methods and 2/ to study the gain of combining the information from various images recorded at different dates, to provide land cover information suitable for the spatial discretization of distributed hydrological models adapted to periurban catchments at various scales: small catchment and larger catchment. We also address the question of the physical properties, relevant for distributed hydrological models, that can be extracted from those images. We particularly explore the relevance of VHR images in deriving impervious and pervious surfaces, as well as the characterization of various vegetation types throughout the growing season in periurban areas.

The methodology is applied to a periurban catchment, the Yzeron catchment (147 km^2), located close to the city of Lyon, France. Two scales are considered: the scale of small subcatchments of a few km^2 and the scale of larger catchments of about 100 km^2.

2. Material and methods

2.1. Study area

The study was carried out in the Yzeron catchment (147 km^2, see Figure 1), close to the city of Lyon in France (483,181 inhabitants in 2008). It is located in the Monts du Lyonnais, culminating at an altitude of 917 m in the western part of the catchment. The catchment has a contrasted land use, with wooded and cultivated areas upstream and a densely urbanized area downstream in the outskirts of Lyon city. In the catchment center, individual habitats and industrial areas are mixed with agricultural fields. The catchment urbanization has constantly increased since the 1960's with a population of 75,600 inhabitants in 1962 and 164,000 inhabitants in 2006 (Kermadi et al, 2010). The large difference in altitude of about 700 m, slopes exceeding 10% in more than half of the catchment (Gnouma, 2006), as well as a pedogeological and geological structure (clay and granite) of low permeability, provides conditions favoring a rapid rise of river discharge and flooding. Over the last few decades, the number of damaging floods has increased from 3 in the 1970-1989 period to 9 in the 1989-2009 period, especially downstream of the basin where human pressure is the highest (Radojevic et al, 2010; Kermadi et al, 2010).

The catchment was studied in the framework of the AVuPUR (Assessing the Vulnerability of Peri-Urban Rivers) research project (Braud et al., 2010). The objective was to enhance the understanding and modelling of hydrological processes in periurban catchments. In terms of modelling, one of the objective was to better represent the specific features of periurban areas within distributed hydrological models, and in particular the impact of impervious surfaces.

FIGURE 1 AROUND HERE – Location of study area: the Yzeron catchment (Lyon, France). The figure also shows the pilot catchments (Mercier and Chaudanne) where detailed land cover mapping was conducted.

2.2. Building of the data set

The land cover mapping has two objectives. First, we must restore the heterogeneity of the periurban landscape and in particular the diversity of pervious and impervious components and their spatial fragmentation. Second, we want to characterize the different types of vegetation cover (trees, herbaceous, permanent or temporary). For this purpose, we compared and combined the potential of different sensors.

The periurban space is composed of small objects, with small areas such as individual houses, narrow roads, hedges... Their identification requires the use of VHR (Very High

Resolution) images. This spatial constraint led us to choose images taken from optical sensors which presently offer the highest resolutions.

In order to be able to distinguish the various land covers (roads, buildings, water, herbaceous vegetation, woody vegetation…), we favored the VHR optical sensors offering large spectral information (visible and near infrared).

The identification of temporary vegetation can be obtained using several images, recorded at different dates within the vegetation growing season, to capture the plowing/crop rotation. However, in the optical domain, cloud cover often limits the number of usable images. Year 2008, was a very rainy year, which limited the availability of cloud free images, for use in this study.

Finally, as our objective was to develop automated mapping procedures, applicable to large catchment areas, the method had to be based on homogenous and readily accessible information. So we used satellite sensors and not airborne ones, with the exception of the aerial imagery (BD-Ortho®IGN) which covers the whole French territory and which is available to all research centers in France. However, the spectral information from the latter data base was limited to the visible wavelength, at the time the study was carried out.

Therefore three aerial and satellite images were acquired, covering the whole Yzeron catchment: (1) the aerial images BD-Ortho®IGN, 0.50 m resolution, visible bands, from May 5th 2008; (2) one QuickBird satellite image, 2.44 m resolution, visible and near-infrared bands, from August 29th 2008; (3) one Spot 5 satellite image, 2.50 m resolution, visible and near-infrared bands, from September 22nd 2008. More precisely, Spot 5 satellite imagery has an initial resolution of 5 m and is re-sampled by the data provider at 2.5 m resolution (Rosak et al, 2004).

In addition to the images, we also used information about cadastral units, managed by the Central Tax Office in France, provided by the corresponding authorities. We also acquired the RPG (2008) (Registre Parcellaire Graphique) data from the ASP (Agence de Service des Paiements), which provides information on the crop types on various cadastral units, for the farms concerned by the common agricultural policy of the European Union.

3. Methods used for land cover mapping

Specific mapping methods were proposed for the two hydrological modelling scales. For small catchments, where the land use is directly used as modelling units in object-oriented approaches, we extracted a photo-interpretation from the highest resolution image (BD-Ortho®IGN) to get the best accuracy.

For large catchments, for which coarser land use classes are sufficient, we propose to assess the inputs of the three types of VHR optical images presented in section 2.2. In addition, as periurban areas are evolving quite quickly, we have explored reproducible and automated mapping methods able to document large areas.

3.1. Small catchment

At the scale of small catchments, the modelling objective is to understand the impact of the different landscape components on the hydrological response. For this purpose, object-oriented modelling approaches, representing explicitly the landscape objects, used as basic modelling units (see section 1), are very useful. The following developments are adapted to models where the cadastral unit is used as a basis for the model mesh such as in the MHYDAS (Moussa et al., 2002), UBRS (Rodriguez et al., 2003), BVFT (Branger et al., 2010) or PUMMA (Jankowfsky et al., 2011) models. Land cover information must therefore be extracted at this scale.

The information which must be retrieved depends on the dominant land use and aims at documenting infiltration and evapotranspiration properties of the corresponding objects. For the forested areas, we tried to identify the dominant vegetation type: the broadleaved populations, the coniferous populations and clearings. For the agricultural areas, we documented the presence or absence of vegetation and its type (orchards, gardens, crops and grasslands). In the rural areas, several landscape objects, such as hedges, paths and roads, ditches, lakes, can influence water pathways by diverting the natural flow path derived from the topography or retaining water. For the built-up areas, two types of land cover were distinguished: the pervious surfaces (vegetation, bare soils) and the impervious surfaces (buildings, car parks, terraces, roads).

The BD-Ortho®IGN aerial image with the highest resolution (0.50 m) was the most suitable image to provide all this information. The cadastral units digital layer was directly superimposed to the orthorectified aerial cover. The cadastre provides information on the hydrological objects boundaries (parcels, roads….) and the image information about the land cover within these units. The mapping method relies mainly on manual digitizing. An automated extraction of land cover classes, using aerial imagery is performed in section 4 of the paper. We extracted five land cover types from this automatized processing. One of them, the areas covered with trees or bushes which can be distinguished by their specific spectral values, is also considered in this application. The asphalt roads were directly taken from the BD-Topo®IGN (IGN-France) database.

3.2. Large catchment

The method can be divided into two steps. In the first step, we produce a land cover map using one of the three images and a given semi-automatized mapping method. The quality of each map produced in step one is assessed. At the end of step one, three maps, derived from images with different spatial and spectral resolutions and/or obtained at different dates in 2008, are available. In the second step, we combine these three maps using an intersection procedure. This combination provides a synthesis map, where the land cover classes produced in the first step are improved and where new classes, related to the seasonal evolution of vegetated surfaces can be extracted.

From the three images, we developed three semi-automated image processing methods (Beal et al, 2009). We generally distinguished two types of approaches for image analysis: the first one, called traditional, is a pixel oriented analysis (POA), while the second one, which appeared at the beginning of the 21st century, is an object oriented analysis (OOA). In the first case (POA), pixels are directly labeled (e.g. classified) without considering (apart from adjacent pixels) their position within the image. Afterwards, objects are defined as sets of connected pixels with the same label using post-classification methods (Lillesand and Kiefer, 2007). In the second case (OOA), a multi-level segmentation (e.g. a partitioning into non-overlapping segments, or regions) of the image is carried out as one of the first step in the analysis. Then, classifications affect objects to a unique land cover class (Neubert and Meinel, 2003, Blaschke, 2010). The POA was led with the aid of the ENVI software on the Spot image. We compared two methods based on OOA, which was considered the most appropriate for processing very high-resolution images. The first one used the eCognition software and was led on the Quickbird image. The second one is based on the Matlab software and was led on the BD-Ortho®IGN. The eCognition software provided all integrated solutions while the Matlab software required the complete development of the processing chain (Béal et al., 2009). On Quickbird ou Spot image, we applied a different mapping method without a priori on the choice of the most suitable method according to the image type. The BD-Ortho®IGN imagery is composed of a 217 rectified aerial images of 1 km^2 mosaic. The interest of using Matlab software in this study is that it allows a customization of the processing for an application to a large number of images, as BD-Ortho®IGN data. The processing chains applied to the three images are detailed in Table 1.

TABLE 1 AROUND HERE – Algorithms of image processes applied to aerial images (BD-Ortho®IGN, 0.50 m resolution) and to satellite images (Quickbird, 2.44 m, Spot, 2.50 m).

4. Results

4.1. Small catchments

The mapping method was applied to two small catchments (the Mercier and Chaudanne sub-catchments) with a large landscape diversity. The results are presented in Figure 2. We distinguished forested areas to the west and in the center, agricultural areas and dispersed settlements in the center, and a densely urbanized zone to the east.

FIGURE 2 AROUND HERE – Digitizing of land cover objects from aerial images (BD-Ortho®IGN) in the Mercier and Chaudanne catchments.

The following difficulties were encountered during the digitizing of the landscape objects based on the cadastral map. First, the overlay of the aerial images and the cadastral map, although geo-referenced in the same map projection, did not perfectly match at all places of the catchment. Second, the delineation of parcels from the land registry is sometimes complex due to numerous land subdivisions which can exist in small areas. In these two cases, we relied on the aerial image to fix the boundaries of these parcels (hedgerows, enclosures, and change in land use). The visual identification of some surfaces proved to be difficult: the porous mineral surfaces and the impervious mineral surfaces in urbanized areas appeared in similar clear colors, and were difficult to distinguish visually.

Furthermore, we were not able to retrieve all the information useful for hydrological modelling, especially information related to water pathways. For instance, ditches were difficult to identify because the color and the linear shape were confused with the vegetation. Obviously also, aerial images were not able to provide information about underground networks, such as sewer networks, which must be added to the model using other sources of information (for instance from the local authorities in charge of their management).

However, this manual mapping was able to identify a large number of objects due to a visual analysis. It contained a rich information at a high resolution but was very time consuming. Valid for small catchments, it could not be reproduced for the larger areas (whole Yzeron catchment).

The time necessary to get the map could be reduced by including more external data to the aerial imagery. We could add several vector data on land use, if they exist at the target scale, to the cadastral data, and then perform the manual mapping to extract the objects used in the modelling. Up to now, there is no comprehensive data inventory mapping all the components (private roads, terraces) that can be found in urbanized areas. Therefore, manual digitizing remains unavoidable to map objects, relevant for distributed hydrological models at this scale.

4.2. Large catchment

Three land cover maps were produced from the three VHR images. Five land cover classes were extracted from the BD-Ortho®IGN image. Eight land cover classes were extracted from the satellite images (Fig. 3). The physical properties of the surface, and consequently the land cover classes that were derived, were directly linked with the spectral signal measured by the sensors, and the sensors resolution. The very high resolution image allowed a better object spatial delineation. However, the intra class spectral variability was increased (Weng, 2012). This strong intra class variability restricted the number of distinguished classes to surfaces having very distinct spectral signatures. This constraint is enhanced due to the large catchment area and the heterogeneity of the land cover.

FIGURE 3 AROUND HERE – Land cover semi-automated mapping from aerial images (BD-Ortho®IGN, 0.50 m resolution) and satellite images (Quickbird, 2.44 m, Spot, 2.50 m).

Water bodies (ponds, dams) were distinguished on the satellite images but not on the BD-Ortho®IGN image. In this visible canal, the identification of land cover greatly relies on one parameter, which is the color. Water, which has the same green color as the herbaceous vegetation, could not be distinguished. The Yzeron hydrographic network, deep and narrow, was not directly perceptible on the images. It was detected thanks to the river-border vegetation. For the hydrological modelling, the information on the hydrographic network was extracted from the BD CARTHAGE®database (IGN-France) or from a digital elevation model (DTM).

The BD-Ortho®IGN spectral information, limited to the visible wavelength, allowed the extraction of only two vegetation classes: the woody vegetation and the herbaceous vegetation. The input of near infrared wavelength allowed us to better define these two vegetation classes from satellite images. For the herbaceous vegetation, two classes were highlighted: the low chlorophyll content vegetation and the high chlorophyll content vegetation. We used this latter information to analyze the seasonal variations of herbaceous vegetation.

4.3. Large catchment: validation of the three land cover maps

The visual examination (Figure 3) and statistics (Table IV) of the three maps highlight differences between the results of the different classifications. We used standard confusion matrices (Congalton and Green, 1999) to assess the quality of the produced classifications. For this purpose, we compared a classified image with a reference data set, called ground truth. In numerous studies, this ground truth is collected from aerial photographs (Prasada Mohapatra and Wu, 2008; Lu and Weng, 2008) and we also used the aerial image as ground truth.

The confusion matrix is a double-entry table. Each line refers to one thematic classe of the classified image. The columns correspond to the classes of the ground truth image. The diagonal shows the percentage of well classified pixels. The commission errors indicate the percentage of pixels attributed to another class than the one they belong to. The omission errors represent the percentage of ground truth pixels no affected to the class that they belong to. The Kappa index, between 0 and 1, provides a global evaluation of the classification accuracy (Caloz and Collet, 2001).

In our study, we used the available aerial imagery, i.e the BD-Ortho®IGN recorded on the 5th May 2008 as ground truth. Although this image has been used for classification, it has the advantage to have been recorded the same year as our satellite images. However, the recording date of the ground truth data impacted the confusion matrix calculation (Tables II to V), when applied to classified images with recording dates varying from May to September. Between these three dates, the vegetation phenology evolved and the vegetation coverage of agricultural land also changed. Considering these temporal variations between classified and reference images, we proposed two Kappa index calculations, the first one taking into account all the identified classes, and the second one where the two classes: "herbaceous vegetation" and "bare soil" were gathered in only one class. 146 test polygons, corresponding to the 7 following classes: broadleaved, coniferous, herbaceous, bare soil, building, roads and water were selected using a random sampling in all the Yzeron catchment area. The Kappa indexes measured by the confusion matrix on the three classifications varied from 0.73 to 0.92 (Table II).

TABLE II AROUND HERE – Matrices confusion results by class and image. (*): the two classes "herbaceous vegetation" and "bare soils" have been assembled into only one class

The classification accuracy depends on the classes. The two forest classes (broadleaved and coniferous) were better extracted from the two satellite images rather than from the aerial images. On the aerial image, the "forest" class tended to be under-estimated (an omission error of 21.0) to the profit of the herbaceous vegetation class. The latter was therefore over-estimated (commission error of 19.8) (Table III).

The herbaceous class result varied from one image to another. The classification accuracy depends mainly on the acquisition date of the classified image. When gathering the two classes "herbaceous vegetation" and "bare soils", better validation results are obtained.

The results were much most contrasted for the "buildings" and "roads" classes. These two classes were respectively identified with 95.1% and 94.6% accuracy respectively, on the Quickbird image; 62.3% and 77.6% accuracy respectively on the Spot image; and with 48.8% and 51% accuracy respectively on the BD-Ortho®IGN (Table II).

The confusion matrices analysis of the BD-Ortho®IGN and Spot images (Table III and V) indicated a confusion between these two classes (buildings and roads) and the "bare soil" class. These three classes equally had high omission and commission errors, which revealed close spectral signatures.

TABLE III AROUND HERE – BD-Ortho®IGN confusion matrix (F: Forest, HV: Herbaceous Vegetation, BS: Bare Soils, B: Buildings, R: Roads, Err. Com.: Errors of Commission, Err. Omis.: Errors of Omission).

TABLE IV AROUND HERE – Quickbird image confusion matrix (BF: Broadleaved Forest, CF: Coniferous Forest, HV: Herbaceous Vegetation, BS: Bare Soils, B: Buildings, R: Roads, W: Water, Err. Com.: Errors of Commission, Err. Omis.: Errors of Omission).

TABLE V AROUND HERE – Spot image confusion matrix (BF: Broadleaved Forest, CF: Coniferous Forest, HV: Herbaceous Vegetation, BS: Bare Soils, B: Buildings, R: Roads, W: Water, Err. Com.: Errors of Commission, Err. Omis.: Errors of Omission).

5. Land cover mapping synthesis and discussion

We have produced three land cover maps in the same year. The Kappa indexes calculated from the confusion matrices show a better global result for the classification extracted from the Quickbird image. However, the classes "broadleaved" and "herbaceous" are respectively better extracted from the Spot and BD-Ortho®IGN images (Table II). In order to improve the information on land cover, we built a synthesis map from these three classifications. This improvement included (1) a better identification of stationary land cover classes from the three dates and (2) the exploitation of the change in vegetation cover from May to September 2008 to identify the permanent vegetation and the temporary vegetation in agricultural areas.

The three images were geo-referenced in the same projection system (Lambert II stretched). We re-sampled the three images at the Spot spatial resolution: 2.50 meters. It is the lowest resolution amongst the three available images.

5.1. Derivation of a synthesis map of stationary land cover

We performed an intersection of the three classifications and analyzed the stability of classified pixel values from these three dates. The data fusion method relies on a local statistical analysis. Each single combination of values extracted from the three classified images takes a singular value in the resulting fusion image (with a total of up to 320 combinations). The pixels having the same class value on the three classifications (or two) kept this value (dominant). For the pixels having different class values in the three classifications, we performed a photo-interpretation. We analyzed each combination by taking into account: the potential confusion between classes revealed by the confusion matrices, the image characteristics, and the images processing method. Finally**,** 7 major combinations were created: coniferous, broadleaved, permanent and temporary herbaceous, permanent bare soils, water bodies, buildings, roads. The particular processing of the herbaceous class is described more in details in the next section.

TABLE VI AROUND HERE – Percentage of classified pixels in each class for the three classified images and for the synthesis map.

This synthesis operation provides information on the various factors, affecting the classification results, such as: the spectral resolution, the spatial resolution, the image recording date, the processing method and their combinations. Their effects varied according to the mapped land cover.

In the case of forest, classification information extracted from the Quickbird and Spot images compensated the weak representation of this class extracted from the BD-Ortho®IGN. This weak representation could be explained by the highest spatial resolution which highlighted the discontinuity of tree cover where the gaps are occupied by herbaceous vegetation. The intersection of two classifications extracted from the satellite images allows the delineation of the two classes "broadleaved" and "coniferous", thanks to the information from the near infrared canal.

The percentage of the "building" class is highly variable according to the classification (Table VI). The coarser the spatial resolution of the image is, the more the urban objects (buildings, roads – car parks) came back more or less grouped and numerous. On the other hand, the 0.50 m resolution of the aerial image allowed the extraction of these objects in an individual manner (Fig. 3). However, the limited visible information of the BD-Ortho®IGN did not allow the extraction of all of the urban objects because of the diversity of human-made materials and their various colors. The input of near infrared, classically known to help discriminating vegetation, contributed to a better distinction of urban objects because of the radiometric contrast between the vegetation surfaces and the artificial surfaces increased. In addition to the spatial resolution, this also explained the low number of pixels classified as buildings and roads in the classification extracted from the BD-Ortho®IGN.

Two types of images processing methods were developed on satellite images. The object-oriented approach (OOA) applied to the Quickbird image had a more accurate reproduction of the geometry of small sized objects, as compared to the Spot image. The multi-scale object-oriented approach of the eCognition software, offered the advantage to take into account spectral information but also textural, morphological and multi-scale nesting of the various objects. The use of these attributes allowed solving the spectral confusions between for example, porous mineral areas (plowed) and impervious mineral areas (artificial areas), the urban objects being generally of smaller size as compared to farming land.

The recording date of the image played an important role. It impacted the development stage of the vegetation and especially the cover fraction of herbaceous vegetation, which grows from bare soil to low and then high chlorophyll content vegetation. For these reasons, the herbaceous class corresponded to a large number of combinations, which are described in more details in the next section. We decided to keep a "permanent bare soil" class which represents the bare mineral surfaces at the three dates. The choice of the acquisition dates was important for a good representation of the different vegetation types. We also took into account the rainfall season. The rainfall during the eight decades before the Spot image acquisition (September 22nd 2008) were two times the average; 410 mm against 219 mm. These high rainfall rates were spread out over three months. The rainfall amount was just above the average in August (86.2 mm / 69 mm), but it was three to two times the average for July and September (176.8 mm / 62 mm and 146.6 mm / 88 mm respectively) (Kermadi et al, 2010). This very humid summer favored the development of permanent herbaceous. The permanent bare soil parcels were not numerous. The identification of built-up areas and temporary vegetation was also facilitated.

Finally, the synthesis operation contributed to an improvement in the classes definition. The combination of the three classifications provided a more accurate delineation of the "building" class subjected to confusions with the roads and bare soils (Table VI). The road network was identified as 9.4 % of the surface on the synthesis map, whereas it was only 8.1% on the classified Quickbird image, and 4.4 to 5.4 % on the two other classified images. The road object is a thin and straight object, more or less well identified according to the sensor spatial resolution and the image processing method. This land cover can locally present spectral confusion with other classes (bare soils, buildings, water). According to the image recording date, it can be more or less masked by the bordered tree vegetation. As a result, it is retrieved only partially for each classification. The combination of the three images allows an increase in "roads" class retrieval.

5.2. Derivation of a synthesis map of temporary and permanent vegetation

Agricultural use is characterized by intra-seasonal variations or inter-annual variations of its vegetation cover. From sowing until harvesting, each production has its own calendar. The spectral information provided by the sensors, especially in the near infrared canal, allowed the mapping of different vegetation types according to the dominant species and their chlorophyll content at different times during the year.

We manually digitized a mask including the agricultural areas and applied it to the three classified images before further processing. Within this area, we analyzed the following class combinations: low chlorophyll content herbaceous, high chlorophyll content herbaceous, and bare soils.

The identification of temporary or permanent vegetation relies on the following information: the presence or absence of vegetation and its state, revealed by the images classified at the three dates; the *Recensement Parcellaire Graphique* (RPG 2008) and the agricultural calendar of the Yzeron catchment main productions (Cottet, 2005; Table VII). The RPG is a non-exhaustive spatial survey of crops, carried out each year by the French government (see section 2.2). From the RPG data, the main crops in the Yzeron catchment are, by order of importance: permanent grassland (61.5%), temporary grassland (25.9%), winter cereals (7.9%), corn (1.4%), and various other crops. The agricultural calendar provides information on the temporal evolution of vegetation cover for the agricultural production (Table VII). The winter cereals (wheat, barley…) and the corn have an annual cycle alternating between plowing and cultivating. The temporary grassland has an inter-annual cycle from 2 to 5 years. For this reason, in the studied year 2008, one part (not identified) of the temporary grassland had been plowed.

TABLE VII AROUND HERE – Agricultural calendar of the main agricultural productions in the Yzeron catchment (Cottet, 2005) (image acquisition periods in grey).

The synthesis of the three classes extracted from the three classifications, highlighted 6 major combinations in the agricultural area. These 6 combinations were compared with the RPG data. Table VIII shows, for each class combination, the pixel percentage corresponding to each main crop from the RPG inventory. With our method, cereals, winter crops correspond at 93.4% to the following class combination (herbaceous on the 5th May – bare soils on 31st August and 22nd September). The permanent and temporary grassland correspond, respectively at 88.2% and 70.8%, to a class combination revealing a vegetation cover present at the three dates. Therefore, the vegetation development, as described by the three classifications, is consistent with the RPG data. In the case of the grassland, being recognized as bare soil at one or two dates out of the three classifications could indicate plowing (temporary grassland), mowing or pasture, leading to a weaker chlorophyll content. The corn, a springtime crop, is represented at 51.6% by the combination class: bare soils in May and vegetation in August and September. Two reasons could explain this weak result: the image recording dates were not appropriate enough to capture the annual cycle of this crop and/or the RPG information was not accurate enough. This latter was collected by crop islands, where one or several crops can be present. The corn, a minor crop in the Yzeron catchment area, could be associated with other crops in the same island. This could alter the RPG information.

TABLE VIII AROUND HERE – Table crossing the class combinations extracted from aerial and satellite images at the three dates and the crops identified from RPG shown in percentages (H: herbaceous vegetation; LCH: low chlorophyll content herbaceous; HCH: high chlorophyll content herbaceous; BS: bare soils).

At the end of these processing, the stationary landscape components and the temporary and permanent vegetation cover were gathered into one unique map (Fig. 4).

FIGURE 4 AROUND HERE – Synthesis map resulting from the combination of the classifications of three aerial and satellite images recorded on the May 5th 2008 (BD-Ortho®IGN), August 29th 2008 (QuickBird image) and September 22nd 2008 (Spot image).

6. Use for distributed hydrological modelling

As a result of our study, several land cover maps were produced at two scales: one map of two small sub-catchments of a few km^2, and four maps for the whole Yzeron catchment (150 km^2).

In this section, we will illustrate how this land cover information was exploited within two distributed hydrological models run at the two scales highlighted before, within the framework of the AVuPUR research project (Braud et al., 2010 Braud et al., 2011) to which this study contributed (Fig. 5). However, the possible use of the produced land cover maps is not restricted to those two models, as explained in the following sections.

FIGURE 5 AROUND HERE – Flow chart of operations carried out since the extraction of land cover data from the hydrological modelling. The bottom of the figure mentions hydrological models used during the AVuPUR project (Braud et al., 2011), but other models could be used.

6.1. Exploitation for small scale models

At the scale of small catchments, the exploitation of the land cover map described in section 4.1 (Fig. 2), is illustrated using the PUMMA model (Jankowsfy, 2011; Jankowfsky et al., 2011), specifically designed for periurban catchments. However, the results presented below are also relevant to other object-oriented models such as the MHYDAS, URBS and BVFT presented in section 1. Note also the PUMMA model integrates both the BVFT and URBS models for the description of the hydrological functioning of rural and urban units respectively.

In the PUMMA model (Jankowfsky, 2011) urban cadastral units, hedgerows, agricultural fields or retention basins are modelled with different process modules. The land cover map (Fig. 2) is thus the criteria for the choice of the process module. It is also the main component of the model mesh, which consists of HRUs in the rural part and Urban Hydrological Elements (UHEs, Rodriguez et al., 2003) in the urban part. UHEs are composed of an urban cadastral unit and part of the adjoining street, which are derived from the land cover map. In the rural part, HRUs are composed of agricultural fields, forested parcels and hedgerows, directly derived from the land cover map of Figure 2. The polygon boundaries are used in the model to estimate the exchange length for the computation of lateral flow (surface and sub-surface) and must therefore be realistic. The shape of the polygons should also be as convex as possible. Additional processing chains were developed within GRASS GIS to fulfil all the geometric constraints of the hydrological mesh, while keeping as much as possible the information about the land surface objects derived from the land use map. The interested reader can refer to Jankowfsky (2011) and Branger et al. (2012a) for more details.

The land cover information was also used to derive some of the model parameters. For each UHE, the built-up area, the road area and the natural area were calculated based on the land cover map. Furthermore, in each UHE, the percentage covered by trees for each of these three parts was obtained by intersection of the vegetation cover automatically extracted from the BD-Ortho®IGN image with the manually digitized land cover map.

In the rural part, the different land cover classes (grassland, bare soils, coniferous forest, etc.) induce different crop coefficients and leaf area index time series influencing thus the simulated evapotranspiration. Look up tables based on the FAO (1998) were therefore associated to each vegetation class to describe the annual course of those parameters.

In addition, Gonzalez-Sosa et al. (2010) showed that the soil infiltration capacity within the Mercier and Chaudanne catchments was related to the land cover. They proposed a method for the spatialization of the soil hydraulic parameters which was based on a re-classified version of the land cover map shown in Figure 2 (see Figure 9 in Gonzalez-Sosa et al., 2010). This method was used to specify the soil surface parameters of the PUMMA model.

It is beyond the scope of this paper to show the results of the PUMMA hydrological model. Details can be found in Jankwofsky (2011) and Jankowfsky et al. (2011). They show that the model results were very satisfactory, without any specific calibration, justifying a posteriori the time consuming task of manual digitizing of the land use map in the Mercier and Chaudanne catchments. The results also pointed out the importance of the connection between the runoff generated on the impervious surfaces and the river network. This degree of connectivity greatly influenced the model results, but this information is not accessible from the aerial or satellite images. Jankowfsky et al. (2012) solve this question by combining GIS based terrain analysis, in situ field work and sewer system data.

6.2. Exploitation for larger scale models

At the scale of the whole catchment, the interest of the four land cover maps described before is illustrated using the J2000 distributed hydrological model (Krause, 2002; Krause et al., 2006). But the presentation would also be valid for other models using HRUs as modelling units or for models based on a grid mesh (see examples in Braud et al., 2011 in the context of the AVuPUR project).

The application of the J2000 model to the Yzeron catchment and the discussion in terms of hydrological processes is detailed in Branger et al. (2012b). Here we only discuss the part of the application related to the processing of the four land cover maps discussed in this paper. In the present case study, the HRUs were defined as sub-catchments corresponding to a reference network, corrected from the influence of sewer networks. But the HRUs could have been defined as the intersection of various GIS layers as described in section 1. The land cover maps were mainly used as input information for the specification of the model parameters.

The J2000 model is based on a reservoir type approach. It represents rainfall interception, infiltration, evapotranspiration. Within the soil surface runoff, sub-surface flow and groundwater flow are also represented. The produced runoff is routed from one HRU to the other, following topography and then routed in the river network, using a simple kinematic wave equation.

The model requires, for the various land cover classes, information about the soil permeability and the vegetation type, for which crop coefficient and leaf area index values are associated. To provide this information, the land cover maps were simplified into three dominant classes: wooded, farmland, and urban. For each sub-catchment, the percentage of imperviousness and the dominant vegetation type were extracted (see the following sections). This information was used to specify the model parameters within each sub-catchment (Branger et al, 2012b).

6.2.1. Characterization of vegetation coverage within the subcatchments

Several classes of vegetation were recognized with the help of the three aerial and satellite images: broadleaved, coniferous, permanent and temporary herbaceous vegetation. We carried out a statistical analysis to quantify the respective fraction of three vegetation components: woody vegetation, permanent herbaceous vegetation and temporary herbaceous vegetation within each subcatchment. The temporary herbaceous vegetation, as indicated by the RPG, is little represented: the percentage of areas occupied varies from less than 1% to 19% in the sub-catchments, whereas that of the forest varied from 1% to 88%, and that of the permanent herbaceous vegetation from less than 1% to 82%. A subcatchment classification according to their dominant vegetation is presented in Figure 6. It reveals a strong topography influence on the vegetation cover: grasslands and crops occupy the flat areas whereas the forest is mainly located in the steep sloped areas, westwards of the Yzeron catchment.

FIGURE 6 AROUND HERE – Distribution of main types of vegetation within the various Yzeron sub-catchments. "Very sparse vegetation" corresponds to less than 15% vegetation cover; "Sparse vegetation" to 15-45 % vegetation cover; "Dominant forest" to 50-88% forested areas; "Permanent herbaceous vegetation and forest" to 49-91% of those to classes; "Permanent herbaceous vegetation" to 35-82% of this class; "Permanent and temporary herbaceous vegetation" to 43-80% herbaceous including 10-19% temporary herbaceous.

6.2.2. Comparative quantification of impervious surfaces from the various land cover maps

The quantification of impervious areas requires the translation of the land cover types, in terms of imperviousness. The available information about land cover was used as follows. We proposed two classes: the class of pervious areas which included forest, herbaceous, water and bare soils; and the class of impervious surfaces which grouped together buildings and roads.

We quantified the rate of impervious surfaces within the various subcatchments for the four available maps and compared the results in Table IX. Table IX shows the percentage of imperviousness, of 112 subcatchments, classified into 10 classes with equal counts. The percentages calculated from the synthesis map were very close to those calculated from the satellite images (Spot and QuickBird), which have similar spatial resolution. These percentages differ from those calculated using the classification retrieved from the BD-Ortho®IGN. The largest percentage for this classification is less then 25% for the more urbanized subcatchments, whereas it reaches more than 68% for the three other classifications. The weak amount of impervious surfaces on the map retrieved from BD-Ortho®IGN is explained by the very high spatial resolution which contributes to a more accurate rendering and less spread identification of built-up areas (see § 5.1.).

TABLE IX AROUND HERE – Classification of the subcatchment percentages of impervious surfaces into 10 classes, with equal counts, for the four processed images.

FIGURE 7 AROUND HERE – Percentage of imperviousness within the subcatchments from the three land cover maps extracted from BD-Ortho®IGN, Quickbird image, Spot image and the synthesis map of the three classifications.

Figure 7 provides a map of the subcatchment percentage of imperviousness using the same color scale for the four maps. The imperviouness rate is different from one land cover map to the other, however, Figure 7 shows that they all provide the same hierarchy of subcatchments. The percentage of the subcatchments imperviousness decreases from the east towards the west. This can be related to the urbanization rates which decreases from the town of Lyon, located eastwards of the catchment area, towards the western part of the Yzeron catchment. However, the estimated values differ from one map to another. Therefore, the absolute values must be used with care within hydrological models, as imperviousness is a sensitive parameter of hydrological models in periurban areas. As an example, Branger et al. (2012b) applied the J2000 model without calibration to the Yzeron catchment, using the parameters derived from the simplified classification shown in Figures 6 and 7. They show that the total discharge is slightly affected, but that the components of the discharge (base flow, sub-surface flow, surface runoff) are sensitive to the choice of the image. BD-Ortho®IGN classification, which leads to the lowest imperviousness has a lower surface runoff and a higher base flow than the three other maps.

7. Discussion and conclusions

In this study, we used three VHR remote sensing images (BD-Ortho®IGN, Quickbird and Spot 5) to map land cover and derive physical properties of the surface relevant for distributed hydrological modelling in periurban catchments. Two scales were considered: the scale of catchments of a few km^2 and of catchments of about 100 km^2. As a whole, the optical sensors, with spatial resolution from 0.50 m to 2.50 m, were found appropriate for the mapping of the heterogeneous land cover of periurban catchments. The retrieved maps restored the large land cover fragmentation with numerous vegetal and artificial components.

For the small scale catchments, where object-oriented distributed hydrological modelling approaches are used, the method based on photo-interpretation offers the advantage of being able to select accurately the information useful at the scale of the modelling units, although it is time consuming and quite slow. Compared to the information available on cadastral maps, the 0.5 m resolution BD-Ortho®IGN image allowed the retrieval of valuable information about natural and impervious areas inside urban cadastral units, hedgerows, vegetation type and rotation and bare soils. It greatly improved the model parameterization. At this scale, given the average size of cadastral units and of the objects we want to represent in the modelling, the 0.50 m resolution of the aerial image appeared satisfactory. However, as shown with the analysis at the whole Yzeron scale, the low spectral resolution (absence of near-infrared canal) of BD-Ortho®IGN, at the time of our study, prevented the use of automatic methods due to the poor retrieval of land cover. Since then, a near-infrared canal has been added to BD-Ortho®IGN, which could solve partly this problem.

For larger scale catchments (of about 100 km^2), where the surface properties are aggregated over larger areas (HRUs), currently used hydrological models do not represent explicitly the various landscape objects but generally use percentage areas of various land cover types within the modelling units. For these models, the spectral resolution of VHR sensors has a greater impact on the quality of the derived land cover map than the spatial resolution. Thanks to the near-infrared canal, it was possible to retrieve a larger number of land cover types using the Quickbird and Spot images than using the BD-Ortho®IGN. The comparison of the results obtained using the object-oriented classification and the pixel based analysis (comparison of Quickbird and Spot mapping) showed the interest of object-oriented segmentation. They were better able to delineate the small artificialized objects encountered in periurban areas. Indeed, the results of the two maps were quite comparable in the rural areas (see Figure 3) where the object size was much larger than the image resolution. On the other hand, differences were more important in urbanized areas where the size of the objects was smaller.

In addition, when moving from a 0.5 m to a 2.5 m resolution, there is a change of scale and definition of the retrieved land covers. For instance at 2.50 m, the mapping procedure identified the built-up areas associated with one or several buildings and adjacent terraces, a part of a forest, while at 0.50 m we distinguished each building or woody component. The spatial resolution choice should therefore be done according to the hydrological model requirements, for example the delineation of built-up areas or those of each building.

The comparison of the land cover maps, obtained from the different images and by different processing methods, highlighted their variability and complementarity. The combination of several images, such as the three classifications used in our study into a synthesis map proved to increase the land cover reliability. First, the comparison of extracted maps from the three classifications allowed a cross-validation of the retrieved land cover classes. Second, the multi-temporal character of aerial and satellite images provided information on the variations of vegetation cover and increased the retrieved information by distinguishing the permanent vegetation from the temporary vegetation. Therefore, the synthesis map, which was built using images at various resolutions and recorded at various dates within the vegetation growing cycle provided the most accurate land cover mapping.

The land cover information extracted using VHR resolution images improved the delineation and identification of the areas occupied by each type of land cover or hydrological object. This also led to a better quantification of the hydrological model parameters, in particular the imperviousness rate. The synthesis map, which is the best compromise between the three compared approaches should provide the most reliable estimation of this parameter.

Hydrological models also require information about the impervious surfaces connected to the river network. Obviously, this information cannot be provided by the land cover mapping and must be obtained using other sources of information.

The final land cover classification and requirements in terms of the various modelling spatial scales are the results of a constant discussion between geographers and hydrologists. This experience highlights the interest of a shared work where the exploration of the potential of remote sensing images could help in the development of hydrological models and vice versa. The current increase in the availability of sensors with resolution lower than 1 m provides to remote sensing imagery users, and in particular to hydrologists, an accurate information about land cover and its physical properties. This multiplication of the sensors promotes the production of “land cover” data bases, which must be chosen according to the input data (spatial and spectral resolution), the mapping method (manual or automatic), the nomenclature, the date of the images and finally the validity of the produced maps. Although the spectral information brought by the new sensors is often restricted to the visible and near-infrared wave lengths, which restrain the number of classes which can be retrieved, the spatial accuracy of the provided maps is consistent with the requirements in terms of hydrological modelling of periurban catchments.

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35-82% of this class; "Permanent and temporary herbaceous vegetation" to 43-80% herbaceous including 10-19% temporary herbaceous.

Figure 7: Percentage of imperviousness within the subcatchments from the three land cover maps extracted from BD-Ortho®IGN, Quickbird image, Spot image and the synthesis map of the three classifications.

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Table VIII: Table crossing the class combinations extracted from aerial and satellite images at the three dates and the crops identified from RPG shown in percentages (H: herbaceous vegetation; LCH: low chlorophyll content herbaceous; HCH: high chlorophyll content herbaceous; BS: bare soils).

Table IX: Classification of the subcatchment percentages of impervious surfaces into 10 classes, with equal counts, for the four processed images.