An original urban land cover representation and its effects on rain event-based runoff and TSS modelling

Marlène Rio, Christian Salles, Flavie Cernesson, Pierre Marchand, Marie-George Tournoud

An original urban land cover representation and its effects on rain event-based runoff and TSS modelling

Marlène Rio*[1], Christian Salles[1], Flavie Cernesson[2], Pierre Marchand[1], Marie-George Tournoud[1]

[1]HSM, Univ Montpellier, CNRS, IRD, Montpellier, France

[2]TETIS, AgroParisTech, CIRAD, CNRS, IRSTEA, Univ Montpellier, France

*Corresponding author

E-mail addresses: marlene.rio@umontpellier.fr (M.Rio), christian.salles@umontpellier.fr (C.Salles), flavie.cernesson@teledetection.fr (F.Cernesson), pierre.marchand@umontpellier.fr (P.Marchand), marie-george.tournoud@umontpellier.fr (M-G.Tournoud)

Abstract

During rainfall events, a wide range of contaminants generated by urban areas are transferred into rivers. Modelling tools are increasingly required by decision makers to assess the effects of urban development and mitigation measures on urban runoff quality. However, representing the spatial heterogeneity of urban land cover in water quality modelling is a real challenge. This study presents a methodology to analyze and characterize the land cover of an urban catchment within a water quality model. The application site is the urban river Verdanson located in Montpellier city (France), where the climate is Mediterranean. Firstly, a time effective original method of identifying homogeneous urban surfaces in terms of build-up/wash-off processes from an existing land-use map and aerial photo interpretation is presented. Secondly, the sensitivity of model outputs to the discretization of a catchment into homogeneous land cover types, called Water quality Response Units (WQRUs), is tested. The results reveal that discretizing the catchment into WQRUs enhances the relevance of hydrological outputs and provide more flexibility for a calibration of Total Suspended Solids wash-off parameters. The findings open interesting opportunities to integrate catchment-scale land cover data into the modelling of wash-off processes and allow urban runoff managers to assess the influence of urban land use planning scenarios on water quality.

Keywords: Hydrological model; Mediterranean climate; SWMM; Urbanized catchment; Total Suspended Solids; Wash-off

Highlights

- Water quality response unit vs hydrological response unit to model wash-off processes
- Time efficient method of land cover analysis in urban catchments
- Water quality response unit–based model more flexible for calibration process
- Methodology easily transposable elsewhere
- Supporting tool for urban land use planning impacts on water quality

1. INTRODUCTION

Urban areas have been widely shown to impact the water quality of urban rivers during rainfall events, by transferring a wide range of contaminants accumulated on impervious surfaces and released into drainage and sewage networks (Gasperi et al., 2014; Mancini et al., 2005). Since cities are unceasingly expanding, as in the European Union where 75% of the population live in urban areas, aquatic ecosystems are increasingly threatened. Consequently, decision makers need clear and effective tools to manage water quality in urban areas and reach the objectives set by the Water Framework Directive. Such supporting tools must be adapted to climatic conditions, particularly under a Mediterranean climate, where extreme rainfall intensities strengthen the transfer of contaminants into the receiving environment (Rio et al., 2017).

Urban storm water modelling is an increasing field of interest aiming to support decision makers in managing water quantity and quality in urban areas. Semi-distributed models such as CANOE, MIKE URBAN or the Storm Water Management Model (SWMM) are widely used (Niazi et al., 2017; Zoppou, 2001). These models allow the user to represent a collection of subcatchments which generate runoff and contaminant loads into a drainage system. The land use within each subcatchment is defined as a fraction of impervious area. Conceptual models such as non-linear reservoirs are used for runoff generation from precipitation data and the transfer of runoff to the outlet is performed by solving the Saint Venant equations.

Build-up and wash-off of contaminants are complex processes influenced by numerous factors such as storm event characteristics, particle size distribution and catchment features (Hong et al., 2016; Liu et al., 2012; Wijesiri et al., 2016). In semi-distributed hydrological models, wash-off processes are generally represented by three empirical models: exponential wash-off, rating curve wash-off and event mean concentration wash-off (Rossman, 2010). Several researchers performed small-scale experiments and showed that the exponential equation can be used to describe the wash-off of Total Suspended Solids (TSS) and heavy metals on roof and road surfaces (Egodawatta et al., 2009; Hossain et al., 2010; Luo et al., 2018; Wicke et al., 2012). Many authors attempted to calibrate the parameters associated to the exponential wash-off at catchment scale (Barco et al., 2004; Di Modugno et al., 2015; Temprano et al., 2006). However, more recent research emphasized the difficulty to reproduce the spatial and temporal variability of contaminant concentrations when calibrating the model over a long-time period within a heterogeneous catchment (Bonhomme and Petrucci, 2017; Sandoval et al., 2018).

To better represent the spatial variability of wash-off processes at catchment scale, the exponential wash-off model must be applied on homogeneous land cover types. It is commonly accepted to distinguish land cover as the biophysical conditions of the earth from land use that links land cover to human activities. The convention is to define land use as urban landscapes (eg. residential, commercial areas) and land cover as land use components (eg., roof, vegetation,...). Previous works showed that storm water pollutant concentrations can't be directly related to land use classification (Fletcher et al., 2013). In their study, Liu et al. (2013) showed that the land use classification as "industrial", "commercial" and "residential" areas isn't appropriate for water quality modelling. They found that site specific characteristics such as the type of urban surface (roof, road or garden) have an important influence on both build-up and wash-off processes and therefore should be taken into account into the modelling process. Moreover, Petrucci and Bonhomme (2014) tested the influence of geographical data on the modelling of TSS concentration. The predictive capability of the model was increased when the subcatchments were represented as homogeneous units of land cover such as green areas, roads and roofs. Consequently, a deep analysis of urban land cover at catchment scale is currently identified as a major concern among water quality modellers. Besides, decision makers increasingly need water quality models based on an appropriate description of urban land cover as supporting tools to assess the impacts of land use planning scenarios and effectively implement Best Management Practices (BMPs).

Recent research focused on improving hydrological models by discretizing a catchment at the scale of a land cover type. Tuomela et al. (2019) discretized an 11.4 ha catchment into 600 subcatchments representing vegetation, roofs, asphalt, sand/gravel, stone/tile pavers or open rock. Similarly, Niemi et al. (2019) developed an automated tool to delineate adaptive subcatchments with homogeneous land cover. High resolution land cover and topography data are required for such catchment discretization. However, in large urban areas the delineation of homogeneous land cover types is rarely available. Various digital remote sensing approaches can be undertaken to analyse urban land cover. From satellite imagery, automated extraction methods are complex to implement and their accuracy is affected by shadow and image distortion (Weng, 2012). Manual photointerpretation of large urban areas is laborious and highly time-consuming. Consequently, simple and reliable tools are needed to analyse land cover in large urban areas for water quality modelling purposes.

The purpose of this work is to open opportunities to represent urban land cover into water quality models at catchment scale and further allow the assessment of the impacts of BMPs on runoff volumes and TSS loads. This paper develops a reliable and transposable methodology to analyse and integrate land cover data in the modelling of discharges and TSS concentrations. Firstly, a time-effective original method is presented to classify the urban land cover accordingly to runoff generation and contaminant wash-off processes. Secondly, the sensitivity of model outputs to the representation of land cover is investigated. The particularity of the model structure is that homogeneous land cover surfaces are aggregated into Water Quality Response Units (WQRUs). The method is exemplified within a Mediterranean urban catchment.

2. MATERIALS AND METHODS

There are two main stages to the analysis. Firstly, urban land cover types are identified according to a relevant nomenclature in terms of hydrological and build-up/wash-off processes. By adapting classical rules of remote sensing, a sampling strategy is developed from an existing land-use map. Secondly, two representations of land cover are integrated into the modelling process and compared by hydrological and water quality outputs. The application of the method to a mediterranean urban catchment illustrates its performances. The limitations and uncertainties associated to the modelling approach are discussed in the next section.

2.1. Land cover classification according to hydrological and build-up/wash-off processes

2.1.1. Relevant nomenclature

It has been showed that pollutant build-up and wash-off are highly influenced by the types of urban land cover (Fraga et al., 2016). However, numerous nomenclatures of existing land use maps don't reflect the hydrological and build-up/wash-off processes occurring on urban surfaces. Consequently, the first step of this study is to classify the land cover according to a relevant nomenclature in terms of both water quantity and quality modelling. The level 1 of the proposed nomenclature is based on the two hydrological covers generally defined to describe runoff processes; (i) the pervious surfaces, where infiltration takes place, and (ii) the impervious surfaces, with no infiltration. These surfaces are considered in this study as Hydrological Response Unit (HRUs), a common concept used in hydrological modelling to combine areas of uniform soil and land use type (Salvadore et al., 2015). From this classification, the level 2 of the nomenclature is developed based on contaminant build-up and wash-off on the different urban surfaces, forming Water Quality Response Units (WQRUs). First of all, the types and levels of released contaminants differ among several impervious surfaces. Roof surfaces are shown to release significant quantities of Total Suspended Solids (TSS) and trace metals (Charters et al., 2016). Road traffic is responsible for the transfer of TSS, but also trace metals and polycyclic aromatic hydrocarbons, due to direct deposition of abrasion particles and fuel and lubricant leakages from vehicles on roads and car parks (Egodawatta et al., 2007). Further to the nature of the released contaminants, build-up and wash-off are influenced by the processes leading to runoff generation that differs from a surface to another. For example, flat roofs can have a significant water storage capacity, while no depression storage can be associated with sloped roofs. Moreover, the average slope of roads is significantly different from the car parks that are generally flat to avoid accidents. As no infiltration take place in swimming pools, they can also be considered as impervious areas with important initial losses. The remaining impervious surfaces with no road traffic and no particular hydrological characteristics can be called “pedestrian areas”. Finally, the surfaces where infiltration can occur are clustered into “pervious surfaces”. They represent natural areas such as forests, grassed areas, shrubs and hedgerow, bare soils and banks, as well as gardens, squares, parks and cemeteries. Although these surfaces present different runoff coefficients, they are aggregated into one class in this study that focuses on the contributions of impervious surfaces to surface water contamination. The resulting nomenclature is presented in Table 1.

Table 1

2.1.2. Time effective method of land cover analysis

To further develop a hydrological model based on the previous nomenclature, the surfaces of each class within a given catchment need to be known. Numerous remote sensing approaches are available for the identification of WQRUs within urban areas (Chankon et al., 2015; Jacqueminet et al., 2013). Unless the area of interest is very small, an aerial photo interpretation over a whole catchment would be highly time consuming. Besides, automated extraction methods such as pixel based and object-based image analysis are difficult to implement and associated with errors arising from shadow and image distortion (Weng, 2012). Consequently, existing urban maps can be an interesting basis for land cover analysis. In one hand, high resolution land cover mappings classify vegetation (tree or grass), water, shade, and impervious area (bright or dark) (Weng 2012). In other hand, existing land use maps classes correspond to homogeneous landscape units. Both are not directly useable for SWMM because of classification and/or spatial resolution. The definition of a universal relationship between land use classes and impervious cover is very difficult (Ackerman and Stein, 2008). Indeed, this relationship is influenced by the different photointerpretation rules adopted to create land use maps and the specific features of urban areas. Consequently, the method developed here consists in identifying WQRUs from an existing land use map by defining on-site sampled areas, also called training sites, within which the urban surfaces can be manually delineated by aerial photo interpretation. As land use maps are generally produced by combining remote sensing technics, surveys and expert rules, it is acceptable as a consequence of an hypothesis of homogeneity in each land use class (i.e landscape), that sampled areas for a given class, have comparable metrics such as build surfaces percentage, diversity index, or main surface percentage. The purpose isn’t to find the initial rules but the initial spatial units that compose a given land use class. The surface fractions obtained in the training sites are finally extended to the entire catchment.

For the analysis, general rules of remote sensing are used. A stratified sampling strategy is employed by defining a number of sampled areas associated to the classes of an existing nomenclature. The number of training sites per land use class is defined proportionally to the size of each class. The total surface of the sampled areas represents more than 4% of the catchment surface. Within each of the land use classes, the sampled areas are defined as circles of 1 ha surface. The shape and the surface of the training sites are defined to fit into the polygons corresponding to the land use classes of the existing map. The sampled areas are randomly distributed within the land use classes although the delineation of the polygons associated to the existing nomenclature constrains their localizations. Regarding the classes scarcely represented, the analysis is directly performed within the associated polygons. Then, within each of the sampled areas, the identification of the urban surfaces is completed by photo-interpretation from available aerial photography. Finally, the results obtained within the sampled areas are extended to the land use classes and eventually to the entire catchment. When the land use classes are associated with only one training site, the results of the photointerpretation performed within the training site are directly applied to the entire land use class. When several training sites are associated to a land use class of the existing nomenclature, the surfaces of each land cover types are summed over the total surface encompassed by the sampled areas within the considered land use class. The proportions of land cover are then computed over the total surface represented by the training sites. For example, five 1-ha training sites are defined into a land use class called "Discontinuous mixed housing". The surfaces of car parks obtained by photointerpretation are 0.08, 0.11, 0.06, 0.04, and 0.08 ha within these 5 sampling sites. Consequently, the proportion of car parks associated to the class "Discontinuous mixed housing" is 100*(0.08+0.11+0.06+0.04+0.08)/5 = 7.4%. The method of land cover analysis is illustrated in Figure 1.

Figure 1

2.2. Land cover representation in modelling TSS concentrations

In this paper, the influence of land cover representation on simulated TSS concentrations is investigated using the Storm Water Management Model (SWMM). SWMM is a dynamic rainfall-runoff-routing simulation model used to simulate runoff quantity and quality in urban areas. A catchment is conceptualized as a rectangular surface with a uniform slope and width that drains to a single outlet (Rossman, 2010). For runoff generation, the principle of mass conservation is applied on three hydrological covers: pervious (characterized by infiltration parameters), impervious and impervious with no depression storage.

Concentrations of contaminants are computed using the water quality module divided into build-up and wash-off sub-modules. The build-up and wash-off models are associated to land cover categories, defined within the catchment as percentages of the total area, independently of the hydrological covering. Consequently, the land cover defined in the water quality module doesn't impact the runoff generation but only the concentrations of pollutants that are computed for the whole catchment. Although previous studies showed good performances in terms of water quantity modelling when the catchments were defined by their hydrological covering, some others emphasized the need of a more detailed description of the land cover in water quality modelling (Liu et al., 2012; Niazi et al., 2017). Consequently, the method further developed consists in discretizing a catchment into water quality response units in order to improve the representation of wash-off processes in the modelling process.

2.2.1. Discretization of a catchment into HRUs and WQRUs

To illustrate the two model approaches investigated in this paper, a schematic representation of a catchment is presented in Figure 2. On the one hand, Figure 2a represents the catchment as one rectangle with geometrical dimensions (surface, width) representative of the catchment characteristics. This representation corresponds to the standard description of a catchment within the SWMM. The width is computed from the surface and the flow path length, measured as the longest flow pathway across the catchment. The three hydrological covers corresponding to the hydrological response units are represented. The impervious surface corresponds to the sum of the flat roofs, pedestrian areas, car parks, swimming pools, and road surfaces. The impervious surface with no depression storage is the area of sloped roofs, whereas the pervious surface contains all the areas where infiltration occurs. The runoff generated by each of the hydrological covers flows directly to the outlet. On the other hand, Figure 2b illustrates the representation of the same catchment as water quality response units. The flow path lengths are estimated specifically for each unit. Regarding the pedestrian areas, car parks, flat roofs and pervious areas, no geometrical feature can be defined for these classes, thus the ratio of the flow path length and width is conserved from the value computed for the entire catchment. The sloped roofs are associated to the maximum length allowed by the legislation. The flow path length of the catchment is chosen for the roads, and a value of 10m is defined for the swimming pools, which don't contribute to runoff generation unless overflows occur.

Figure 2

The hydrologic parameters of the model are pre-estimated according to physical considerations. The links between the parameters associated to the HRUs and the WQRUs are presented in Table 2. Whereas the average slope of the subcatchment is chosen to characterize the roads, pedestrian areas and natural fields, a high value is attributed to the sloped roof as it is imposed by the regulation. On the contrary, the flat roofs are associated to a very low slope of 0.01%. The car parks are generally flat to avoid accidents when it is possible according to the topography, hence the slope is taken as one tenth of the average slope of the subcatchment. Regarding the Manning coefficients attributed to the WQRUs, they are computed from estimates of materials roughness and the Nikuradze, Darcy-Weisbach and Manning-Strickler formulas. The depression storage of the roads, car parks and pedestrian areas are defined according to the roughness and degradation of the materials of the different land cover types. In recently urbanized areas where integrated account of runoff issue concerns, the flat roofs can be designed to store rainwater. In this case a part of the rainfall is lost by evaporation while the other part is restituted to the drainage network. Consequently, the associated depression storage is high. In this study, it is chosen as being 20 mm. Finally, the widely used Curve Number method from the Soil Conservation Service is chosen to model runoff generation. The Curve Number (CN) varies with soil type and antecedent conditions. Within the application catchment, the hydrologic soil group is C. A unique value of 50 is attributed to all pervious areas, according to available literature (Rossman, 2010).

Table 2

2.2.2. Validation and comparative analysis of hydrological outputs

To assess the performances of the two modelling approaches, hydrological outputs are compared with observed data. An event-based validation is undertaken by computing Nash values from observed hydrographs. Widely used in urban hydrology, the Nash-Sutcliffe efficiency (NSE) is calculated as following (Equation 1) (Nash and Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{t=1}^{N}(q_{obs}(t) - q_{sim}(t))^2}{\sum_{t=1}^{N}(q_{obs}(t) - \bar{q}_{obs})^2} \tag{1}$$

Where $q_{obs}(t)$ is the observed flow at time t, $q_{sim}(t)$ is the simulated flow, $\bar{q}_{obs}$ is the mean observed flow value over the simulation period of length N. In addition, the simulated runoff volume, flow peak and time to peak are compared between the two model representations.

2.2.3. Exponential wash-off model applied to HRUs and WQRUs

The water quality model focuses on Total Suspended Solids (TSS) concentrations. Event-based simulations are performed and the initial amount of TSS is considered to reach its maximum between each rainfall event. The mediterranean climate is characterized by intense rainfall events interspersed with long dry periods. The initial amount of TSS is chosen to be the same at the beginning of each event, and its value is fixed according to the available literature (Chow et al., 2012; Fallah Shorshani et al., 2014; Wicke et al., 2012). Only the wash-off module sensitivity is tested for the simulations. In the case of the HRUs, the wash-off is computed at each time-step from the runoff rate at the outlet of the catchment following the Equation 2 given hereafter:

$$w(t) = K_w * q(t)^2 * m_b(t) \tag{2}$$

Where *w(t)* ($kg.h^{-1}$) is the rate of wash-off at time t, K_w ($h.mm^{-2}$) is a wash-off coefficient, *q(t)* ($mm.h^{-1}$) is the runoff rate over the sub-catchment at time t, and $m_b(t)$ (kg) is the amount of build-up remaining on the surface at time t. When the catchment is discretized into WQRUs, the wash-off is the sum of the wash-off at the outlets of the WQRUs, according to the following Equation 3:

$$w(t) = \sum_{i=1}^{7} K_{wi} * q_i(t)^2 * m_{bi}(t) \tag{3}$$

Where *w(t)* ($kg.h^{-1}$) is the rate of wash-off at time t, *i* is the summation index ranging from 1 to 7, corresponding to the 7 WQRUs, K_{wi} ($h.mm^{-2}$) is a wash-off coefficient associated to the i-th WQRU, $q_i(t)$ ($mm.h^{-1}$) is the runoff rate over the i-th WQRU at time t, and $m_{bi}(t)$ (kg) is the amount of build-up remaining on the i-th WQRU at time t.

In this study, the computation time step is 1 second. $q(t)^2$ represents the kinetic energy of the runoff. The wash-off coefficient K_{wi} is identical among the WQRUs and to the value of K_w associated to the HRUs. The simulations are run with values of the wash-off coefficient (Kw) being [0.0001; 0.001; 0.01; 0.1]. The range of Kw values is chosen according to the available literature (Chow et al., 2012; Fallah Shorshani et al., 2014; Rossman, 2010; Wicke et al., 2012). The wide range of Kw values doesn't aim at calibrating the model but assessing the sensitivity of model outputs to the representation of land cover independently of the value assigned to the wash-off coefficient Kw.

2.3. Application site and available data

The Verdanson canal is a 7.5 km long watercourse flowing across the city of Montpellier, located in the south of France. The climate is Mediterranean, presenting semi-arid conditions with average rainfall of 676 mm/year. The majority of rainfall is recorded in autumn and flash floods are observed during intense and local storms that occur after long dry periods (Perrin and Tournoud, 2009). The catchment, presented in Figure 3, is entirely urbanized and its surface is 16.02 km². The land use is mainly shared between residential areas (48%) and major infrastructures (16%) such as hospitals and universities. The existing land use map presented in Figure 3 is provided by Montpellier Méditerranée Métropole. The map layer was produced in 2015, based on the SPOT THEMA nomenclature (with a multi spatial resolution from 1/25000 to 1/5000). Other GIS data used in the analysis come from the BD ORTHO®, which notably contains aerial photographies with a 0.5m resolution, and the BD TOPO®, which provides the delineations of buildings (produced in 2015) and roads (produced from 2012 to 2017).

Figure 3

In this study, the land cover analysis is performed over the 23 subcatchments of the Verdanson catchment. Their delineation and geographical characteristics are determined using the 5m resolution digital elevation model (produced from 2008 to 2015) provided by the RGE ALTI® database. Among them, the Chateau d'O subcatchment is chosen to perform the comparative analysis of the two land cover representations in water quality modelling. With a surface of 1.25 km², this catchment is an entirely separate storm water sewer system. As showed in Figure 4, five subcatchments are delineated within this catchment which includes two large retention ponds.

Figure 4

Rainfall measurements are produced by an acoustic rain gauge (Vaisala RAINCAP® Sensor) at the outlet of the Chateau d'O catchment. Based on the detection of individual raindrop impacts, the uncertainty associated to this technology mostly arises from the variation in the shape and vertical velocity of raindrops (Salmi and Ikonen, 2005) and raindrop size distributions (Krajewski et al., 2006). Rainfall data are available from June 2012 to February

2019 with a 5 min time step. Over the same period, water level measurements were produced by a water level radar sensor with a 5 min time interval at the outlet of the Chateau d'O subcatchment. Numerous anomalies are identified in the water level dataset, thus the analysis of rainfall events is performed over a discontinuous period of 2.5 years of consistent data. To compute flow values, a rating curve is defined from flow measurements performed under different hydrological conditions. The uncertainties associated to the flow measurements range from 10 to 20%.

From this dataset, 39 rainfall-runoff events are identified. These events cover a large range of rainfall amounts, from 10.1 mm to 94 mm and runoff coefficient, ranging from 6 to 80%. No observation is available for extreme events, so-called "Cévenol" events, as the hydrological section is overflooded. Otherwise, the sample represents a wide range of durations and intensities observed during the four seasons. The Verdanson river is a small watercourse as the peak flow at the outlet of the Chateau d'O catchment is measured between 0.52 and 3.10 m^3/s. The catchment response is generally rapid, as the median time to peak is 1h33min.

3. RESULTS AND DISCUSSION

3.1. Land cover analysis

3.1.1. Application of the land cover analysis to the Verdanson catchment

Table 3 gives the number of training sites associated to the classes of the SPOT THEMA nomenclature in proportion to their surface within the Verdanson catchment. Five classes are not associated with sampled area. Regarding the main road network and the car parks, they can be directly transferred into corresponding water quality response unit. The railway network in the study area is the tramway, which is half on pavements and roads (impervious surfaces), half on grass areas (pervious surfaces). Finally, the green areas are directly associated to pervious areas, as well as the water bodies which relate to the location of the watercourses. In total, 4.45% of the surface of the Verdanson catchment is represented by the sampled areas. The photo-interpretation performed within each of the training sites is based on aerial photography provided by the BD ORTHO® database, which is commonly used to assess the impervious cover in France (Jacqueminet et al., 2013).

Table 3

The stratified sampling approach used for the land cover analysis gives the repartition of the water quality response units (WQRUs) in a given area. The results of the application to the Verdanson catchment are presented in Figure 5. With an imperviousness of 57.9%, the surface is mainly represented by roofs, with 13.4% of flat roofs and 7.1% of sloped roofs, and roads and car parks, which encompass 14.7 and 12.9% of the total surface respectively (Figure 5a). At a smaller scale, the Chateau d'O catchment presents a lower imperviousness (50.9%) and a slightly different repartition of the roof surfaces (Figure 5b). As the urbanization is recent in this catchment and characterized by flat roofed buildings, the fraction of sloped roofs is very low (1.9%). Within the Chateau d'O catchment, the land cover of the five subcatchments is heterogeneous (Figure 5c). The urbanization of the upstream "Gimel" subcatchment is limited, with 85.9% of pervious areas. The two subcatchments called "Malbosc 3" and "Malbosc 2" are characterized by a recent urbanization of residential and commercial surfaces, with an imperviousness higher than 70%. Although the "Malbosc" subcatchment is also recent and residential, the lower imperviousness is explained by a part of the catchment that is not urbanized yet. Finally, the "Domaine d'O" subcatchment has 61.6% of pervious surfaces, due to a 23ha landscaped park.

Figure 5

3.1.2. Analysis of the robustness of the land cover analysis

A validation of the methodology is undertaken by comparing the estimated surfaces with reference surfaces from the BD TOPO® database (Figure 6). The latter is the French large scale geographic referential and contains the delineations of roofs, roads, car parks and green areas. As no distinction is made in the BD TOPO® between flat and sloped roofs, they are joined to perform the validation. The roads are directly compared between the reference data and the estimated surfaces. Regarding the car parks, no validation can be undertaken as the BD TOPO® only considers the car parks bigger than 0.5 ha. Similarly, natural fields identified in the analysis can't be associated to the green areas of the BD TOPO® because they only represent wooded areas bigger than 500 m^2. Furthermore, no data from the BD TOPO® corresponds to the pedestrian areas nor the swimming pools. Consequently, the validation is undertaken on roofs and roads, which are the main impervious surfaces represented in the study area. Indeed, within the 23 subcatchments delineated in the Verdanson catchment, the surfaces of roads and roofs combined represent between 21 and 58% of the subcatchments areas. The validation is performed from existing data rather than field observation as several surfaces like roofs may not be accessible in urban areas.

A satisfactory correlation between estimated and reference surfaces of roads and roofs is observed in Figure 6a, as the distribution follows the 1:1 sloped straight line. The performance of the methodology is illustrated by Pearson coefficients computed for roads and roofs surfaces that are respectively 0.97 and 0.98. Absolute values of the relative error associated to estimated surfaces are represented in Figure 6b. The median error value is 14.1% and 11% for roads and roofs respectively. Considering the total surface of the Verdanson catchment, the error associated to the road surfaces is 10.2% whereas it is 10.0% for roof areas. Moreover, Figure 4b shows that 70% of the errors are lower than 20%. An extreme error value is observed in roads surfaces, which corresponds to the smallest subcatchment of the area (3.5 ha). This error should be put into perspective as it corresponds to small road areas, the estimated surface being 0.19 ha against a reference surface of 0.72 ha.

Figure 6

The errors observed between estimated and reference surfaces of the BD TOPO® highlight the difficulty of comparing maps with different nomenclatures and photo-interpretation rules. For example, in the sampled areas the roads are directly delineated by photo-interpretation whereas they are defined as lines associated with widths in the BD TOPO®. Also, the identification of buildings may differ because of uncertainties induced by shadow and image distortion, as explained by Weng (2012). Although a large number of training sites were analyzed in this study, some uncertainties also arise from the variability of the different land cover types within the classes of the SPOT THEMA nomenclature. In an attempt to assess this variability, Ackerman and Stein (2008) highlighted the difficulty of describing the relationship between impervious cover and uniform classes of land use such as “residential” or “commercial”. Nevertheless, the results presented in this paper are consistent with the rules adopted to define the SPOT THEMA nomenclature. As an example, the continuous urban fabric represents areas where buildings and artificial surfaces cover the near totality of the soil, and the associated imperviousness is found to reach 92%, with 53% of roofs, 26% of pedestrian areas and 13% of roads. Furthermore, 43% of pervious areas are found in discontinuous housing, where the soil is shared between buildings and green areas or bare soils. Finally, the discontinuous collective housing mostly corresponds to apartment blocks and towers, hence there is a high percentage of flat roofs (25%).

Conclusively, the stratified sampling method of land cover analysis gives satisfactory results in regards to their use in the modelling process. The performance assessed through the comparison between estimated surfaces and the BD TOPO® is consistent with other studies employing various methods. In Thailand, an accuracy of 75.21% and 88.30% was reached by Chankon et al. (2015) when delineating roads and buildings respectively by using the object-based image analysis method. In France, Jacqueminet et al. (2013) obtained similar performances when using three semi-automatic mapping procedures to delineate roofs and roads in a large urban catchment. When analyzing urban land cover, the results systematically depend upon the available data and the chosen method, being either manual photo-interpretation, semi-automatic or automatic procedures (Weng, 2012). In hydrological modelling, it has to be noted that uncertainties related to land cover data might have an impact on the simulated runoff volume and peak discharge, even though it can be muted by the parametrization of the model (Beighley et al., 2009). In this paper, the method of land cover analysis is time-saving by using an existing land use map, and can be applied elsewhere when land-use data are available.

3.2. Impact of land cover representation on hydrological outputs

The two representations of the catchment as HRUs and WQRUs give comparable performances when modelling water quantity. As showed in Figure 7a, some rainfall events are associated to low Nash values in the two representations whereas some others are well simulated in both cases. It is noteworthy that in 85% of the simulations, the Nash criterion is higher within the WQRUs than the HRUs. Indeed over the 39 rainfall events, the Nash value is equal or above 0.6 for 21 simulations within the WQRUs against 11 within the HRUs. This finding is consistent with the study of Petrucci and Bonhomme (2014), who observed a significant improvement in Nash values when the catchment was discretized into homogeneous units. They highlighted that the performances of the homogeneous units, being roofs, roads, green areas and other, are similar when the model is either calibrated or uncalibrated. In this study, the pre-estimation of the parameters associated to the WQRUs leads to a satisfactory representation of a large part of observed events.

The simulated runoff volume, peak flow and time to peak are also compared between the two model representations (Figure 7b, c & d). The results are similar between the two modelling approaches, as for the majority of simulated events, runoff volume and time to peak are identical while peak flow values are close to the 1:1 sloped straight line. The differences observable in several cases are mainly induced by the spatial distribution of depression storage during small events. Indeed, as the flat roofs are associated to a high value of depression storage, the average computed at the catchment scale is highly influenced, particularly if the flat roofs encompass a large area. Consequently, the shape of the hydrograph slightly differs from the HRUs to the WQRUs, as well as the storage capacity of the catchment when the rainfall amount is lower than the depression storage associated to the flat roofs. For such rainfall events, the simulated runoff volume and the peak flow are higher within the WQRUs, while the time to peak is shorter. Contrarily to Skotnicki and Sowiński (2013) who studied small variations of depression storage, this study shows that computing an average depression storage for impervious surfaces is not appropriate when a significant part of the catchment presents high storage capacity. When rainfall amounts are higher than the depression storage associated to the flat roofs, runoff volumes are equal between the two representations, as showed in Figure 7b. However for such events, the simulated peak flow is slightly lower from the WQRUs than from the HRUs. This can be explained by the differences of width and longest flow path between the WQRUs and the HRUs. As the flow pathways vary among the WQRUs, the resulting combination of peak flows differs from the peak flow simulated at the outlet of the HRUs.

Figure 7

To illustrate the dynamics of the hydrographs within the Chateau d'O subcatchment, Figure 8 presents the simulated and observed hydrographs obtained for 6 rainfall events with various runoff coefficients. It is noticeable that the highest Nash values are obtained for runoff coefficients higher than 22%, whereas poor performances are achieved for lower runoff coefficients. Figure 8a & b illustrates the good fitting achieved for runoff coefficients ranging from 22 to 50%. The results corresponding to the highest runoff coefficients are represented in Figure 8c & d. The abnormally high flow values observed during these two events could be explained by log jams that could have distorted the measurement of water level or the lack of knowledge of rainfall over the whole catchment. Finally, Figure 8e & f give examples of simulated and observed hydrographs for low runoff coefficients. Regarding the majority of these events, a very low response is observed at the outlet of the catchment even though rainfall amounts are recorded at the raingauge. Consequently, the reliability of water level measurement during such events might be questioned as well as the spatial rainfall distribution that could not be assessed by a single raingauge.

Figure 8

3.3. Impact of land cover representation on simulated TSS concentrations

Figure 9 shows the sensitivity of simulated pollutographs to urban land cover representation. The results are highly contrasted between the HRUs and the WQRUs. Figure 9a presents the normalized mass of TSS exported, defined as the total mass of TSS exported divided by the initial mass of TSS available over the catchment. Although the normalized mass exported increases with the wash-off coefficient Kw in both cases, no linear correlation can be established between the normalized mass exported by two model representations. While at the outlet of the HRUs the ratio between the exported mass and the initial amount of TSS reaches 1, a maximum threshold appears at the outlet of the WQRUs. This can be explained by the very low contribution of the pervious areas, as very little or no runoff is generated within these surfaces during the considered events. Figure 9b presents the normalized time to maximum concentration, defined as the duration between the beginning of the rainfall event and the maximum concentration divided by the event duration. The HRUs systematically presents a higher time to maximum concentration compared to the WQRUs. No link exists between the wash-off coefficient and the normalized time to maximum concentration. The maximum concentration from the WQRUs and the HRUs are compared on Figure 9c, showing that the maximum concentration increases with Kw and is globally higher within the WQRUs. The two models are highly sensitive to the parameter Kw. The dynamic of the pollutograph is significantly different from one representation to the other, with quicker and higher maximum concentration from the WQRUs.

Figure 9

The pollutographs generated by the HRUs and the WQRUs on the 15/10/2018 are presented in Figure 10. Even though the parameters of the wash-off equation are the same in both cases, significant differences in the dynamics are due to the representation of the land cover.

Figure 10

3.4. Perspectives for water quality modelling

In this paper, an accurate identification of the different land cover types associated to contaminant wash-off is achieved. The modelling results show that the representation of land cover as WQRUs keeps its ability to reproduce observed hydrographs as the hydrological outputs are similar between the two representations of land cover. From these findings, interesting perspectives are open.

Firstly, the main perspective of this work is to estimate the potential reduction of TSS loads induced by several scenarios of BMPs implemented within the WQRUs. Such an analysis could bring some knowledge to support decision makers in effectively implementing BMPs in the current need of transforming urban areas into resilient cities. Even if no calibration of the water quality model can be performed from observed TSS data, the relative change of TSS loads generated by different configurations of BMPs can still be assessed and bring useful information. The reliability of such results would depend on the analysis of their sensitivity to hydrological and wash-off parameters. A variation range of TSS load reduction could be estimated, which magnitude will depend on model parameters.

Secondly, the calibration of simulated TSS concentrations from observed data would validate the use of the WQRUs to model real-time TSS concentrations. The representation of land cover as WQRUs provide great flexibility for calibrating the wash-off coefficients, as they can be independently parametrized for the WQRUs as proposed by Fraga et al. (2016) on roofs, roads and car parks. Also, the maximum build-up can be specified for each WQRU and the pervious areas can be divided according to vegetation and soils to improve the modelling of runoff generation from these surfaces. A better simulation of TSS concentrations can be expected from WQRU land cover representation as recent research emphasized the difficulty to reproduce the spatial variability of contaminant concentrations when calibrating hydrological models within HRU heterogeneous catchments. Besides, in their study Petrucci and Bonhomme (2014) simulated TSS concentrations with the SWMM and obtained equal or better Nash values when the catchment was discretized as homogeneous units like roofs, roads, green areas and others. They showed that the discretization of a catchment as homogeneous land cover units increases the predictive capability of the water quality model.

Notwithstanding, the exponential wash-off model presents some limitations. Although it has been widely used within SWMM to model water quality (Barco et al., 2004; Chow et al., 2012; Di Modugno et al., 2015; Fallah Shorshani et al., 2014; Gorgoglione et al., 2016; Temprano et al., 2005; Wicke et al., 2012), some authors recently highlighted the difficulty to maintain its physical meaning when calibrating the model within heterogeneous catchments (Bonhomme and Petrucci, 2017; Sandoval et al., 2018). Other water quality models have been developed, such as the conceptual runoff quality simulation model described by Crobeddu and Bennis (2011), however the performances are similar to the rating curve and exponential models. Also, Fraga et al. (2016) developed a modelling framework to improve the predictive ability of the exponential model by taking into account meteorological data, such as rainfall pH, duration, intensity and the number of antecedent dry days, and geometric features, such as the materials of the different impervious surfaces. Nevertheless, this approach requires a large amount of data that can be difficult to obtain, especially in large urban catchments. Moreover, to be effective an increase of the spatial resolution of the model should coincide with a refined spatial description of the rainfall (Cristiano et al., 2019).

The method described in this paper affords the advantage of being applicable elsewhere from an existing land use map and a limited amount of hydrological data. Although the TSS are the only water quality variable considered into the modelling process, it gives information on various other pollutants. Even though no link can be established between TSS concentrations and other contaminants, it is known that minimizing the transfer of TSS also minimize the transfer of other pollutants such as PAHs and trace metals (Gasperi et al., 2014; Zgheib et al., 2012).

4. CONCLUSIONS

One of the major challenges related to water quality modelling is the representation of the spatial heterogeneity of urban land cover within hydrologic models. This paper pursues two objectives; (i) developing a time effective method of identifying homogeneous urban land cover types from an existing land use map and (ii) integrating these data into the modelling process by discretizing a catchment into Water Quality Response Units (WQRUs). In an attempt of opening opportunities to improve the modelling of TSS concentrations, the proposed method was developed to be easy to implement with a limited amount of data, time effective and transposable elsewhere. Firstly, the identification of WQRUs is performed through a stratified sampling method of land cover analysis developed from an openly available land use map. Secondly, the sensitivity of simulated discharges and TSS concentrations to land cover representation is assessed by comparing the discretization into WQRUs with a standard representation of a catchment as pervious and impervious surfaces. In the modelling process, the hydrologic parameters are pre-estimated according to physical considerations and a unique set of wash-off parameters is used in the two approaches. The methodology is tested within a mediterranean urban catchment.

The results are promising. They indicate that the performance of the land cover analysis is satisfactory in regards to the modelling requirements. The estimated roads and roof surfaces are associated to a relative error lower than 11% when compared a large scale geographic referential. Compared to numerous remote sensing approaches, the proposed method affords the advantage of being robust, time saving and easily applicable elsewhere with a minimum of resources. The comparative analysis of hydrological modelling shows that the discretization of a catchment as WQRUs enhances the hydrological outputs compared to the representation as pervious and impervious surfaces. The satisfactory representation of several observed events show that the pre-estimation of hydrologic parameters would be satisfactory and can be reproduced in other catchments, evenly ungauged catchments. Besides, the aggregation of similar homogeneous land cover types into WQRUs prevents unmanageable high level of catchment discretization. Regarding TSS simulations, the WQRUs provide higher flexibility for the calibration of the wash-off coefficients, as the dynamics of the pollutograph is sensitive to this parameter. Moreover, the wash-off parameters can be specified for each WQRU according to the properties of the considered urban surfaces.

A perspective of this work is a deep investigation of the uncertainties arising from the land cover analysis to assess their impacts on modelling outputs. Further research could also investigate the representation of urban land cover as WQRUs using other wash-off functions, infiltration methods or hydrologic models. Although this study focuses on TSS, dissolved pollutants could also be simulated using the WQRU representation. In such analysis, the types of pollutants accumulated within the WQRUs can be specified. Moreover, the pervious areas can be divided according to vegetation, soil and maintenance practices. Finally, the main future outlook of this work is the implementation of urban land use planning scenarios in the modelling process. Estimating ranges of runoff volume and TSS load reductions under several scenarios of best management practices could support urban runoff management.

Acknowledgments

This work was supported by funding provided by a doctoral fellowship (Marlène Rio) from the Labex DRIIHM, French programme "Investissements d'Avenir" (ANR-11-LABX-0010) which is managed by the ANR. We also acknowledge Montpellier Méditerranée Métropole for the support and provided data.

References

Ackerman, D., Stein, E.D., 2008. Estimating the Variability and Confidence of Land Use and Imperviousness Relationships at a Regional Scale. Journal of the American Water Resources Association, 44 (4), 996–1008. https://doi.org/10.1111/j.1752-1688.2008.00215.x

Barco, O.J., Ciaponi, C., Papiri, S., 2004. Pollution in Storm Water Runoff. Two Cases: An Urban Catchment and a Highway Toll Gate Area. NOVATECH, 5th International Conference on Sustainable Techniques and Strategies in Urban Water Management. Lyon, France, June, 6-10.

Beighley, R.E., Kargar, M., He, Y., 2009. Effects of Impervious Area Estimation Methods on Simulated Peak Discharges. Journal of Hydrologic Engineering, 14 (4), 388–98. https://doi.org/10.1061/(ASCE)1084-0699(2009)14:4(388)

Bonhomme, C., Petrucci, G., 2017. Should We Trust Build-up/Wash-off Water Quality Models at the Scale of Urban Catchments? Water Research, 108(January), 422-31. https://doi.org/10.1016/j.watres.2016.11.027

Chankon, K., Iabchoon, S., Wongsai, S., 2015. Urban land use mapping based on object-based image analysis using worldview-3 satellite imagery. Proceedings of the 36th Asian Conference on Remote Sensing. Metro Manila, Philippines, October, 19-23.

Charters, F.J., Cochrane, T.A., O'Sullivan A.D., 2016. Untreated Runoff Quality from Roof and Road Surfaces in a Low Intensity Rainfall Climate. Science of The Total Environment, 550 (April), 265–72. https://doi.org/10.1016/j.scitotenv.2016.01.093

Chow, M.F., Yusop, Z., Toriman, M.E., 2012. Modelling Runoff Quantity and Quality in Tropical Urban Catchments Using Storm Water Management Model. International Journal of Environmental Science and Technology, 9 (4), 737-48. https://doi.org/10.1007/s13762-012-0092-0

Cristiano, E., Veldhuis, M.C., Wright, D.B., Smith, J.A., Giesen, N., 2019. The Influence of Rainfall and Catchment Critical Scales on Urban Hydrological Response Sensitivity. Water Resour. Res, 55 (4), 3375–3390. https://doi.org/10.1029/2018WR024143

Crobeddu, E., Bennis, S., 2011. A New Model for Simulating TSS Washoff in Urban Areas. Applied and Environmental Soil Science, 2011, 1–9. https://doi.org/10.1155/2011/318765

Di Modugno, M., Gioia, A., Gorgoglione, A., Iacobellis, V., la Forgia, G., Piccinni, A.F., Ranieri, E., 2015. Build-Up/Wash-Off Monitoring and Assessement for Sustainable Management of First Flush in an Urban Area. Sustainability, 7 (5), 5050-5070. https://doi.org/10.3390/su7055050

Egodawatta, P., Thomas, E., Goonetilleke, A., 2007. Mathematical Interpretation of Pollutant Wash-off from Urban Road Surfaces Using Simulated Rainfall. Water Research, 41 (13), 3025–31. https://doi.org/10.1016/j.watres.2007.03.037

Egodawatta, P., Thomas, E., Goonetilleke, A., 2009. Understanding the Physical Processes of Pollutant Build-up and Wash-off on Roof Surfaces. Science of The Total Environment, 407 (6), 1834-41. https://doi.org/10.1016/j.scitotenv.2008.12.027

Einstein, H.A., 1934. Der hydraulische oder profil radius. Scherizer-isch Bauzeitung, 103 (8) (in German)

Fallah Shorshani, M., Bonhomme, C., Petrucci, G., André, M., Seigneur, C., 2014. Road Traffic Impact on Urban Water Quality: A Step towards Integrated Traffic, Air and Stormwater Modelling. Environmental Science and Pollution Research, 21 (8), 5297-5310. https://doi.org/10.1007/s11356-013-2370-x

Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, Management and Modelling of Urban Hydrology and Its Consequences for Receiving Waters: A State of the Art. Advances in Water Resources, 51 (January), 261–79. https://doi.org/10.1016/j.advwatres.2012.09.001.

Fraga, I., Charters, F.J., O'Sullivan, A.D., Cochrane, T.A., 2016. A Novel Modelling Framework to Prioritize Estimation of Non-Point Source Pollution Parameters for Quantifying Pollutant Origin and Discharge in Urban Catchments. Journal of Environmental Management, 167 (February), 75–84. https://doi.org/10.1016/j.jenvman.2015.11.003

Gasperi, J., Sebastian, C., Ruban, V., Delamain, M., Percot, S., Wiest, L., Mirande, C., Caupos, E., Demare, D., Diallo Kessoo Kessoo, M., Saad, M., Schwartz, J.J., Dubois, P., Fratta, C., Wolff, H., Moilleron, R., Chebbo, G., Cren, C., Millet, M., Barraud, S., Gromaire, M.C., 2014. Micropollutants in Urban Stormwater: Occurrence, Concentrations, and Atmospheric Contributions for a Wide Range of Contaminants in Three French Catchments. Environmental Science and Pollution Research, 21 (8), 5267–5281. https://doi.org/10.1007/s11356-013-2396-0

Gorgoglione, A., Gioia, A., Iacobellis, V., Ferruccio Piccinni, A., Ranieri, E., 2016. A Rationale for Pollutograph Evaluation in Ungauged Areas, Using Daily Rainfall Patterns: Case Studies of the Apulian Region in Southern Italy. Applied and Environmental Soil Science, 2016, 1–16. https://doi.org/10.1155/2016/9327614

Hong, Y., Bonhomme, C., Le, M-H., Chebbo, G., 2016. New Insights into the Urban Washoff Process with Detailed Physical Modelling. Science of The Total Environment 573 (December), 924–36. https://doi.org/10.1016/j.scitotenv.2016.08.193

Hossain, I., Imteaz, M., Gato-Trinidad, S., Shanableh, A., 2010. Development of a Catchment Water Quality Model for Continuous Simulations of Pollutants Build-up and Wash-Off. International Journal of Environmental and Ecological Engineering, 4 (1), 11-18. https://doi.org/10.1007/s11270-018-3777-2

Jacqueminet, C., Kermadi, S., Michel, K., Béal, D., Gagnage, M., Branger, F., Jankowfsky, S., Braud, I., 2013. Land Cover Mapping Using Aerial and VHR Satellite Images for Distributed Hydrological Modelling of Periurban Catchments: Application to the Yzeron

Catchment (Lyon, France). Journal of Hydrology, 485 (April), 68–83. https://doi.org/10.1016/j.jhydrol.2013.01.028

Krajewski, W.F., Kruger, A., Caracciolo, C., Golé, P., Barthes, L., Creutin, J.D., Delahaye, J.Y., Nikolopoulos, E.I., Ogden, F., Vinson, J.P., 2006. DEVEX-disdrometer evaluation experiment: Basic results and implications for hydrologic studies. Adv. Water Resour., 29, 807–814. https://doi.10.1016/j.advwatres.2005.03.018

Liu, A., Goonetilleke, A., Egodawatta, P., 2012. Inherent Errors in Pollutant Build-up Estimation in Considering Urban Land Use as a Lumped Parameter. Journal of Environmental Quality, 41 (5), 1690-94. https://doi.10.2134/jeq2011.0419

Liu, A., Egodawatta, P., Guan, Y., Goonetilleke, A., 2013. Influence of Rainfall and Catchment Characteristics on Urban Stormwater Quality. Science of The Total Environment, 444 (February), 255–62. https://doi.org/10.1016/j.scitotenv.2012.11.053

Luo, X., Zhao, H., Liao, Y., Li, X., 2018. Evaluation of the Methods for Quantifying Particle Wash-off Loadings in Urban Impervious Surfaces at Small Scales. Environmental Science and Pollution Research 25 (7), 6969–79. https://doi.org/10.1007/s11356-017-1018-7

Mancini, L., Formichetti, P., D'Angelo, A.M., Pierdominici, E., Sorace, A., Bottoni, P., Laconelli, M., Ferrari, C., Tancioni, L., Rossi, N., Rossi, A., 2005. Freshwater Quality in Urban Areas: A Case Study from Rome, Italy. Microchemical Journal, 79 (1–2), 177-83. https://doi.org/10.1016/j.microc.2004.08.009

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I. A discussion of principles. Journal of Hydrology, 10 (3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B.R., Tryby, M., Massoudieh, A., 2017. Storm Water Management Model: Performance Review and Gap Analysis. Journal of Sustainable Water in the Built Environment 3 (2), 04017002. https://doi.org/10.1061/JSWBAY.0000817

Niemi, T.J., Kokkonen, T., Sillanpää, N., Setälä, H., Koivusalo, H., 2019. Automated Urban Rainfall–Runoff Model Generation with Detailed Land Cover and Flow Routing. Journal of Hydrologic Engineering 24 (5), 04019011. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001784

Perrin, J.L., Tournoud, M.G., 2009. Hydrological Processes Controlling Flow Generation in a Small Mediterranean Catchment under Karstic Influence. Hydrological Sciences Journal, 54 (6), 1125-40. https://doi.org/10.1623/hysj.54.6.1125

Petrucci, G., Bonhomme, C. 2014. The Dilemma of Spatial Representation for Urban Hydrology Semi-Distributed Modelling: Trade-Offs among Complexity, Calibration and Geographical Data. Journal of Hydrology, 517 (September), 997–1007. https://doi.org/10.1016/j.jhydrol.2014.06.019

Rio, M., Salles, C., Rodier, C., Cantet, F., Marchand, P., Mosser, T., Cernesson, F., Monfort, P., Tournoud, M-G., 2017. An empirical model to quantify fecal bacterial loadings to coastal areas: application in a Mediterranean context. CR Geosciences, 349, 299-309. http://dx.doi.org/10.1016/j.crte.2017.09.005

Rossman, L.A., 2010. Storm water management model user's manual, version 5.0. National Risk Management Research Laboratory, Office of Research and Development, U.S. EPA, Cincinnati, OH.

Salmi, A., Ikonen, J., 2005. Piezoelectric precipitation sensor from Vaisala. In WMO Technical Conference on Instruments and Methods of Observation, Bucharest, Romania, 4-7.

Salvadore, E., Bronders, J., Batelaan, O. 2015. Hydrological Modelling of Urbanized Catchments: A Review and Future Directions. Journal of Hydrology, 529 (October), 62–81. https://doi.org/10.1016/j.jhydrol.2015.06.028

Sandoval, S., Vezzaro, L., Bertrand-Krajewski, J-L., 2018. Revisiting Conceptual Stormwater Quality Models by Reconstructing Virtual State Variables. Water Science and Technology, 78 (3), 655-63. https://doi.org/10.2166/wst.2018.337

Skotnicki, M., Sowiński, M., 2015. The Influence of Depression Storage on Runoff from Impervious Surface of Urban Catchment. Urban Water Journal, 12 (3), 207–18. https://doi.org/10.1080/1573062X.2013.839717

Temprano, J., Arango, Ó., Cagiao, J., Suárez, J., Tejero, I., 2005. Stormwater Quality Calibration by SWMM: A Case Study in Northern Spain. Water SA, 32 (1), 55-63. https://doi.org/10.4314/wsa.v32i1.5240

Tuomela, C., Sillanpää, N., Koivusalo, H., 2019. Assessment of Stormwater Pollutant Loads and Source Area Contributions with Storm Water Management Model (SWMM). Journal of Environmental Management 233 (March), 719–27. https://doi.org/10.1016/j.jenvman.2018.12.061

Weng, Q., 2012. Remote Sensing of Impervious Surfaces in the Urban Areas: Requirements, Methods, and Trends. Remote Sensing of Environment, 117 (February), 34–49. https://doi.org/10.1016/j.rse.2011.02.030

Wicke, D., Cochrane, T.A., O'Sullivan, A., 2012. Build-up Dynamics of Heavy Metals Deposited on Impermeable Urban Surfaces. Journal of Environmental Management, 113 (December), 347-54. https://doi.org/10.1016/j.jenvman.2012.09.005

Wijesiri, B., Egodawatta, P., McGree, J., Goonetilleke, A., 2016. Assessing Uncertainty in Stormwater Quality Modelling. Water Research, 103 (October), 10-20. https://doi.org/10.1016/j.watres.2016.07.011

Zgheib, S., Moilleron, R., Chebbo, G., 2012. Priority Pollutants in Urban Stormwater: Part 1 – Case of Separate Storm Sewers. Water Research, 46 (20), 6683–92. https://doi.org/10.1016/j.watres.2011.12.012

Zoppou, C., 2001. Review of Urban Storm Water Models. Environmental Modelling & Software, 16 (3), 195-231. https://doi.org/10.1016/S1364-8152(00)00084-0

Figure and table captions

Figure 1. Illustration of the stratified sampling strategy used for land cover analysis. (a) Random location of the training sites within a study catchment; (b) Location of training sites within an existing land use map (here, land use map from Montpellier Méditerranée Métropole); (c) Aerial photography in one training site (here, BD ORTHO®); (d) Results of the photo-interpretation

Figure 2. (a) Representation of the subcatchment as hydrological response units; (b) Representation of the subcatchment divided into water quality response units

Figure 3. Description of the Verdanson catchment, France. The land use map is provided by Montpellier Méditerranée Métropole (level 3 2015)

Figure 4. Description of the Chateau d'O catchment divided into 5 subcatchments

Figure 5. Repartition of the water quality response units within the study area. (a) Verdanson catchment; (b) Chateau d'O catchment; (c) Subcatchments within the Chateau d'O catchment

Figure 6. Validation of the methodology used for the land cover analysis in 23 subcatchments of the Verdanson catchment. (a) Comparison between the estimated and reference surfaces of roads and roofs. The slope of the dotted line is 1:1; (b) Boxplot of the errors computed from the BDTOPO® database

Figure 7. Comparison of water quantity outputs in the two model approaches; (a) Nash values; (b) Runoff volume; (c) Peak flow; (d) Time to peak

Figure 8. Examples of observed and simulated hydrographs. The envelope curve represents the uncertainties associated with flow measurements. The computation time step of the model is 1 second.

Figure 9. Comparison of simulated pollutographs in the two model approaches; (a) Total mass of TSS exported divided by the initial amount of TSS (%); (b) Time between the beginning of the rainfall event and the maximum concentration divided by the event duration (%); (c) Maximum concentration

Figure 10. Examples of simulated pollutographs corresponding to the event that occurred on October 15th 2018

Table 1. Nomenclature used for land cover classification

Table 2. Hydraulic parameters defined for the two representations of land cover within a catchment

Table 3. Number of training sites associated to the SPOT THEMA nomenclature in the Verdanson catchment

Table 1

Level 1 (Hydrological Response Units)	Level 2 (Water Quality Response Units)
Impervious surfaces	Sloped roofs
	Flat roofs
	Roads
	Car parks
	Pedestrian areas
	Swimming pools
Pervious surfaces	Pervious surfaces

Table 2

	Hydrological response units (Pervious and impervious surfaces)	Water quality response units						
		Roads	**Sloped roofs**	**Flat roofs**	**Car parks**	**Pedestrian areas**	**Pervious areas**	**Swimming pools**
Surface (ha)	Defined from the stratified sampling method of land cover analysis							
Longest flow path (m)	Longest flow path of the catchment	Longest flow path of the catchment	assessed from local legislation (12)	Same length-width ratio as the whole catchment				10
Slope (%)	Average slope of the catchment	Average slope of the catchment	Assessed from local regulation (30)	0.01	One tenth of the average slope of the catchment	Average slope of the catchment	Average slope of the catchment	-
Impervious surfaces (%)	Corresponds to the surfaces of the flat roofs, roads, sloped roofs, car parks, pedestrian areas and swimming pools	100	100	100	100	100	-	100
Manning coefficient for impervious surfaces	Computed from the Manning coefficients of the WQRUs according to the Einstein formula (1934) : $n = (\frac{1}{l} * \sum_{i} l_i * n_i^{\frac{3}{2}})^{\frac{2}{3}}$ Where *n* is the Manning coefficient and *l* is the width of the considered catchment	0.033	0.017	0.05	0.033	0.025	-	-
Manning coefficient for pervious surfaces		-	-	-	-	-	0.05	-
Depression storage on impervious surfaces (mm)	Calculated as the weighted average of the depression storage on the WQRUs	1	0	20	1	0.5	-	150
Depression storage on pervious surfaces (mm)		-	-	-	-	-	8	-
Impervious surfaces with no depression storage (%)	Corresponds to the surface of the sloped roofs	-	100	-	-	-	-	-

Table 3

Classes of the SPOT THEMA nomenclature	Surface (ha)	Number of training sites
Continuous urban fabric	59.3	3
Discontinuous high-density housing	217.3	8
Discontinuous low-density housing	73.7	3
Discontinuous collective housing	293.0	11
Discontinuous mixed housing	127.2	5
Isolated housing	6.3	1
Major infrastructures	260.1	9
Car parks	83.2	0
Industrial areas	5.2	1
Commercial areas	3.8	1
Technology parks and tertiary activities areas	43.5	3
Mixed activities areas	34.3	3
Main road network and associated lands	82.4	0
Railway network	18.0	0
Construction sites	12.6	1
Urban green spaces	47.8	3
Other parks and gardens	20.0	1
Sports facilities	36.9	2
Urban open spaces	39.0	2
Green areas	138.5	0
Water bodies	0.46	0