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### ► **To cite this version:**

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. *Journal of Hydrology*, 2020, 586, pp.124865. 10.1016/j.jhydrol.2020.124865 . hal-02995391

**HAL Id: hal-02995391**

**<https://hal.science/hal-02995391>**

Submitted on 12 Apr 2022

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

3

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12

13 **Abstract**

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

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

32 **Highlights**

- 33 - Water quality response unit vs hydrological response unit to model wash-off processes
- 34
- 35 - Time efficient method of land cover analysis in urban catchments
- 36
- 37 - Water quality response unit-based model more flexible for calibration process
- 38
- 39 - Methodology easily transposable elsewhere
- 40
- 41 - Supporting tool for urban land use planning impacts on water quality

## 42 1. INTRODUCTION

43  
44 Urban areas have been widely shown to impact the water quality of urban rivers during  
45 rainfall events, by transferring a wide range of contaminants accumulated on impervious  
46 surfaces and released into drainage and sewage networks (Gasperi et al., 2014; Mancini et  
47 al., 2005). Since cities are unceasingly expanding, as in the European Union where 75% of  
48 the population live in urban areas, aquatic ecosystems are increasingly threatened.  
49 Consequently, decision makers need clear and effective tools to manage water quality in  
50 urban areas and reach the objectives set by the Water Framework Directive. Such supporting  
51 tools must be adapted to climatic conditions, particularly under a Mediterranean climate, where  
52 extreme rainfall intensities strengthen the transfer of contaminants into the receiving  
53 environment (Rio et al., 2017).

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

62 Build-up and wash-off of contaminants are complex processes influenced by numerous factors  
63 such as storm event characteristics, particle size distribution and catchment features (Hong et  
64 al., 2016; Liu et al., 2012; Wijesiri et al., 2016). In semi-distributed hydrological models, wash-  
65 off processes are generally represented by three empirical models: exponential wash-off, rating  
66 curve wash-off and event mean concentration wash-off (Rossman, 2010). Several researchers  
67 performed small-scale experiments and showed that the exponential equation can be used to  
68 describe the wash-off of Total Suspended Solids (TSS) and heavy metals on roof and road  
69 surfaces (Egodawatta et al., 2009; Hossain et al., 2010; Luo et al., 2018; Wicke et al., 2012).  
70 Many authors attempted to calibrate the parameters associated to the exponential wash-off at  
71 catchment scale (Barco et al., 2004; Di Modugno et al., 2015; Temprano et al., 2006).  
72 However, more recent research emphasized the difficulty to reproduce the spatial and  
73 temporal variability of contaminant concentrations when calibrating the model over a long-time  
74 period within a heterogeneous catchment (Bonhomme and Petrucci, 2017; Sandoval et al.,  
75 2018).

76 To better represent the spatial variability of wash-off processes at catchment scale, the  
77 exponential wash-off model must be applied on homogeneous land cover types. It is  
78 commonly accepted to distinguish land cover as the biophysical conditions of the earth from  
79 land use that links land cover to human activities. The convention is to define land use as  
80 urban landscapes (eg. residential, commercial areas) and land cover as land use components

81 (eg., roof, vegetation,...). Previous works showed that storm water pollutant concentrations  
82 can't be directly related to land use classification (Fletcher et al., 2013). In their study, Liu et  
83 al. (2013) showed that the land use classification as "industrial", "commercial" and "residential"  
84 areas isn't appropriate for water quality modelling. They found that site specific characteristics  
85 such as the type of urban surface (roof, road or garden) have an important influence on both  
86 build-up and wash-off processes and therefore should be taken into account into the  
87 modelling process. Moreover, Petrucci and Bonhomme (2014) tested the influence of  
88 geographical data on the modelling of TSS concentration. The predictive capability of the  
89 model was increased when the subcatchments were represented as homogeneous units of  
90 land cover such as green areas, roads and roofs. Consequently, a deep analysis of urban  
91 land cover at catchment scale is currently identified as a major concern among water quality  
92 modellers. Besides, decision makers increasingly need water quality models based on an  
93 appropriate description of urban land cover as supporting tools to assess the impacts of land  
94 use planning scenarios and effectively implement Best Management Practices (BMPs).

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

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

## 117 **2. MATERIALS AND METHODS**

118 There are two main stages to the analysis. Firstly, urban land cover types are identified  
119 according to a relevant nomenclature in terms of hydrological and build-up/wash-off processes.  
120 By adapting classical rules of remote sensing, a sampling strategy is developed from an  
121 existing land-use map. Secondly, two representations of land cover are integrated into the  
122 modelling process and compared by hydrological and water quality outputs. The application of  
123 the method to a mediterranean urban catchment illustrates its performances. The limitations  
124 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**

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

154 contributions of impervious surfaces to surface water contamination. The resulting nomenclature  
155 is presented in Table 1.

156 Table 1

### 2.1.2. Time effective method of land cover analysis

157 To further develop a hydrological model based on the previous nomenclature, the surfaces of  
158 each class within a given catchment need to be known. Numerous remote sensing  
159 approaches are available for the identification of WQRUs within urban areas (Chankon et al.,  
160 2015; Jacqueminet et al., 2013). Unless the area of interest is very small, an aerial photo  
161 interpretation over a whole catchment would be highly time consuming. Besides, automated  
162 extraction methods such as pixel based and object-based image analysis are difficult to  
163 implement and associated with errors arising from shadow and image distortion (Weng, 2012).  
164 Consequently, existing urban maps can be an interesting basis for land cover analysis. In one  
165 hand, high resolution land cover mappings classify vegetation (tree or grass), water, shade,  
166 and impervious area (bright or dark) (Weng 2012). In other hand, existing land use maps  
167 classes correspond to homogeneous landscape units. Both are not directly useable for SWMM  
168 because of classification and/or spatial resolution. The definition of a universal relationship  
169 between land use classes and impervious cover is very difficult (Ackerman and Stein, 2008).  
170 Indeed, this relationship is influenced by the different photointerpretation rules adopted to  
171 create land use maps and the specific features of urban areas. Consequently, the method  
172 developed here consists in identifying WQRUs from an existing land use map by defining on-  
173 site sampled areas, also called training sites, within which the urban surfaces can be  
174 manually delineated by aerial photo interpretation. As land use maps are generally produced  
175 by combining remote sensing technics, surveys and expert rules, it is acceptable as a  
176 consequence of an hypothesis of homogeneity in each land use class (i.e landscape), that  
177 sampled areas for a given class, have comparable metrics such as build surfaces percentage,  
178 diversity index, or main surface percentage. The purpose isn't to find the initial rules but the  
179 initial spatial units that compose a given land use class. The surface fractions obtained in the  
180 training sites are finally extended to the entire catchment.

181 For the analysis, general rules of remote sensing are used. A stratified sampling strategy is  
182 employed by defining a number of sampled areas associated to the classes of an existing  
183 nomenclature. The number of training sites per land use class is defined proportionally to the  
184 size of each class. The total surface of the sampled areas represents more than 4% of the  
185 catchment surface. Within each of the land use classes, the sampled areas are defined as  
186 circles of 1 ha surface. The shape and the surface of the training sites are defined to fit into  
187 the polygons corresponding to the land use classes of the existing map. The sampled areas  
188 are randomly distributed within the land use classes although the delineation of the polygons  
189 associated to the existing nomenclature constrains their localizations. Regarding the classes  
190 scarcely represented, the analysis is directly performed within the associated polygons. Then,

191 within each of the sampled areas, the identification of the urban surfaces is completed by  
192 photo-interpretation from available aerial photography. Finally, the results obtained within the  
193 sampled areas are extended to the land use classes and eventually to the entire catchment.  
194 When the land use classes are associated with only one training site, the results of the  
195 photointerpretation performed within the training site are directly applied to the entire land use  
196 class. When several training sites are associated to a land use class of the existing  
197 nomenclature, the surfaces of each land cover types are summed over the total surface  
198 encompassed by the sampled areas within the considered land use class. The proportions of  
199 land cover are then computed over the total surface represented by the training sites. For  
200 example, five 1-ha training sites are defined into a land use class called “Discontinuous mixed  
201 housing”. The surfaces of car parks obtained by photointerpretation are 0.08, 0.11, 0.06, 0.04,  
202 and 0.08 ha within these 5 sampling sites. Consequently, the proportion of car parks  
203 associated to the class “Discontinuous mixed housing” is  $100 \times (0.08 + 0.11 + 0.06 + 0.04 + 0.08) / 5 =$   
204 7.4%. The method of land cover analysis is illustrated in Figure 1.

205

Figure 1

## 2.2. Land cover representation in modelling TSS concentrations

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

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

224

### 2.2.1. Discretization of a catchment into HRUs and WQRUs

225 To illustrate the two model approaches investigated in this paper, a schematic representation  
226 of a catchment is presented in Figure 2. On the one hand, Figure 2a represents the



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

244 Figure 2

245 The hydrologic parameters of the model are pre-estimated according to physical  
246 considerations. The links between the parameters associated to the HRUs and the WQRUs  
247 are presented in Table 2. Whereas the average slope of the subcatchment is chosen to  
248 characterize the roads, pedestrian areas and natural fields, a high value is attributed to the  
249 sloped roof as it is imposed by the regulation. On the contrary, the flat roofs are associated  
250 to a very low slope of 0.01%. The car parks are generally flat to avoid accidents when it is  
251 possible according to the topography, hence the slope is taken as one tenth of the average  
252 slope of the subcatchment. Regarding the Manning coefficients attributed to the WQRUs, they  
253 are computed from estimates of materials roughness and the Nikuradze, Darcy-Weisbach and  
254 Manning-Strickler formulas. The depression storage of the roads, car parks and pedestrian  
255 areas are defined according to the roughness and degradation of the materials of the different  
256 land cover types. In recently urbanized areas where integrated account of runoff issue  
257 concerns, the flat roofs can be designed to store rainwater. In this case a part of the rainfall  
258 is lost by evaporation while the other part is restituted to the drainage network. Consequently,  
259 the associated depression storage is high. In this study, it is chosen as being 20 mm.  
260 Finally, the widely used Curve Number method from the Soil Conservation Service is chosen  
261 to model runoff generation. The Curve Number (CN) varies with soil type and antecedent  
262 conditions. Within the application catchment, the hydrologic soil group is C. A unique value of  
263 50 is attributed to all pervious areas, according to available literature (Rossman, 2010).

264 Table 2

265 **2.2.2. Validation and comparative analysis of hydrological outputs**

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

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

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

273 **2.2.3. Exponential wash-off model applied to HRUs and WQRUs**

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

$$w(t) = K_w * q(t)^2 * m_b(t) \quad (2)$$

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

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

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

292 In this study, the computation time step is 1 second.  $q(t)^2$  represents the kinetic energy of  
293 the runoff. The wash-off coefficient  $K_{wi}$  is identical among the WQRUs and to the value of  $K_w$   
294 associated to the HRUs. The simulations are run with values of the wash-off coefficient ( $K_w$ )  
295 being [0.0001; 0.001; 0.01; 0.1]. The range of  $K_w$  values is chosen according to the available  
296 literature (Chow et al., 2012; Fallah Shorshani et al., 2014; Rossman, 2010; Wicke et al.,  
297 2012). The wide range of  $K_w$  values doesn't aim at calibrating the model but assessing the  
298 sensitivity of model outputs to the representation of land cover independently of the value  
299 assigned to the wash-off coefficient  $K_w$ .

### 2.3. Application site and available data

300 The Verdanson canal is a 7.5 km long watercourse flowing across the city of Montpellier,  
301 located in the south of France. The climate is Mediterranean, presenting semi-arid conditions  
302 with average rainfall of 676 mm/year. The majority of rainfall is recorded in autumn and flash  
303 floods are observed during intense and local storms that occur after long dry periods (Perrin  
304 and Tournoud, 2009). The catchment, presented in Figure 3, is entirely urbanized and its  
305 surface is 16.02 km<sup>2</sup>. The land use is mainly shared between residential areas (48%) and  
306 major infrastructures (16%) such as hospitals and universities. The existing land use map  
307 presented in Figure 3 is provided by Montpellier Méditerranée Métropole. The map layer was  
308 produced in 2015, based on the SPOT THEMA nomenclature (with a multi spatial resolution  
309 from 1/25000 to 1/5000). Other GIS data used in the analysis come from the BD ORTHO®,  
310 which notably contains aerial photographs with a 0.5m resolution, and the BD TOPO®,  
311 which provides the delineations of buildings (produced in 2015) and roads (produced from  
312 2012 to 2017).

313 Figure 3

314 In this study, the land cover analysis is performed over the 23 subcatchments of the  
315 Verdanson catchment. Their delineation and geographical characteristics are determined using  
316 the 5m resolution digital elevation model (produced from 2008 to 2015) provided by the RGE  
317 ALTI® database. Among them, the Chateau d'O subcatchment is chosen to perform the  
318 comparative analysis of the two land cover representations in water quality modelling. With a  
319 surface of 1.25 km<sup>2</sup>, this catchment is an entirely separate storm water sewer system. As  
320 showed in Figure 4, five subcatchments are delineated within this catchment which includes  
321 two large retention ponds.

322 Figure 4

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

328 2019 with a 5 min time step. Over the same period, water level measurements were  
329 produced by a water level radar sensor with a 5 min time interval at the outlet of the  
330 Chateau d'O subcatchment. Numerous anomalies are identified in the water level dataset, thus  
331 the analysis of rainfall events is performed over a discontinuous period of 2.5 years of  
332 consistent data. To compute flow values, a rating curve is defined from flow measurements  
333 performed under different hydrological conditions. The uncertainties associated to the flow  
334 measurements range from 10 to 20%.

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

### 342 **3. RESULTS AND DISCUSSION**

#### **3.1. Land cover analysis**

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

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

354 Table 3

355 The stratified sampling approach used for the land cover analysis gives the repartition of the  
356 water quality response units (WQRUs) in a given area. The results of the application to the  
357 Verdanson catchment are presented in Figure 5. With an imperviousness of 57.9%, the  
358 surface is mainly represented by roofs, with 13.4% of flat roofs and 7.1% of sloped roofs,  
359 and roads and car parks, which encompass 14.7 and 12.9% of the total surface respectively  
360 (Figure 5a). At a smaller scale, the Chateau d'O catchment presents a lower imperviousness  
361 (50.9%) and a slightly different repartition of the roof surfaces (Figure 5b). As the urbanization  
362 is recent in this catchment and characterized by flat roofed buildings, the fraction of sloped

363 roofs is very low (1.9%). Within the Chateau d'O catchment, the land cover of the five  
364 subcatchments is heterogeneous (Figure 5c). The urbanization of the upstream "Gimel"  
365 subcatchment is limited, with 85.9% of pervious areas. The two subcatchments called  
366 "Malbosc 3" and "Malbosc 2" are characterized by a recent urbanization of residential and  
367 commercial surfaces, with an imperviousness higher than 70%. Although the "Malbosc"  
368 subcatchment is also recent and residential, the lower imperviousness is explained by a part  
369 of the catchment that is not urbanized yet. Finally, the "Domaine d'O" subcatchment has  
370 61.6% of pervious surfaces, due to a 23ha landscaped park.

371 Figure 5

### 3.1.2. Analysis of the robustness of the land cover analysis

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

387 A satisfactory correlation between estimated and reference surfaces of roads and roofs is  
388 observed in Figure 6a, as the distribution follows the 1:1 sloped straight line. The  
389 performance of the methodology is illustrated by Pearson coefficients computed for roads and  
390 roofs surfaces that are respectively 0.97 and 0.98. Absolute values of the relative error  
391 associated to estimated surfaces are represented in Figure 6b. The median error value is  
392 14.1% and 11% for roads and roofs respectively. Considering the total surface of the  
393 Verdanson catchment, the error associated to the road surfaces is 10.2% whereas it is 10.0%  
394 for roof areas. Moreover, Figure 4b shows that 70% of the errors are lower than 20%. An  
395 extreme error value is observed in roads surfaces, which corresponds to the smallest  
396 subcatchment of the area (3.5 ha). This error should be put into perspective as it  
397 corresponds to small road areas, the estimated surface being 0.19 ha against a reference  
398 surface of 0.72 ha.

399 Figure 6

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

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

### **3.2. Impact of land cover representation on hydrological outputs**

433 The two representations of the catchment as HRUs and WQRUs give comparable  
434 performances when modelling water quantity. As showed in Figure 7a, some rainfall events  
435 are associated to low Nash values in the two representations whereas some others are well  
436 simulated in both cases. It is noteworthy that in 85% of the simulations, the Nash criterion is  
437 higher within the WQRUs than the HRUs. Indeed over the 39 rainfall events, the Nash value

438 is equal or above 0.6 for 21 simulations within the WQRUs against 11 within the HRUs. This  
439 finding is consistent with the study of Petrucci and Bonhomme (2014), who observed a  
440 significant improvement in Nash values when the catchment was discretized into homogeneous  
441 units. They highlighted that the performances of the homogeneous units, being roofs, roads,  
442 green areas and other, are similar when the model is either calibrated or uncalibrated. In this  
443 study, the pre-estimation of the parameters associated to the WQRUs leads to a satisfactory  
444 representation of a large part of observed events.

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

466 Figure 7

467 To illustrate the dynamics of the hydrographs within the Chateau d'O subcatchment, Figure 8  
468 presents the simulated and observed hydrographs obtained for 6 rainfall events with various  
469 runoff coefficients. It is noticeable that the highest Nash values are obtained for runoff  
470 coefficients higher than 22%, whereas poor performances are achieved for lower runoff  
471 coefficients. Figure 8a & b illustrates the good fitting achieved for runoff coefficients ranging  
472 from 22 to 50%. The results corresponding to the highest runoff coefficients are represented  
473 in Figure 8c & d. The abnormally high flow values observed during these two events could  
474 be explained by log jams that could have distorted the measurement of water level or the  
475 lack of knowledge of rainfall over the whole catchment. Finally, Figure 8e & f give examples

476 of simulated and observed hydrographs for low runoff coefficients. Regarding the majority of  
477 these events, a very low response is observed at the outlet of the catchment even though  
478 rainfall amounts are recorded at the raingauge. Consequently, the reliability of water level  
479 measurement during such events might be questioned as well as the spatial rainfall  
480 distribution that could not be assessed by a single raingauge.

481 Figure 8

### 3.3. Impact of land cover representation on simulated TSS concentrations

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

501 Figure 9

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

505 Figure 10

### 3.4. Perspectives for water quality modelling

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



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

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

534 Notwithstanding, the exponential wash-off model presents some limitations. Although it has  
535 been widely used within SWMM to model water quality (Barco et al., 2004; Chow et al.,  
536 2012; Di Modugno et al., 2015; Fallah Shorshani et al., 2014; Gorgoglione et al., 2016;  
537 Temprano et al., 2005; Wicke et al., 2012), some authors recently highlighted the difficulty to  
538 maintain its physical meaning when calibrating the model within heterogeneous catchments  
539 (Bonhomme and Petrucci, 2017; Sandoval et al., 2018). Other water quality models have been  
540 developed, such as the conceptual runoff quality simulation model described by Crobeddu and  
541 Bennis (2011), however the performances are similar to the rating curve and exponential  
542 models. Also, Fraga et al. (2016) developed a modelling framework to improve the predictive  
543 ability of the exponential model by taking into account meteorological data, such as rainfall  
544 pH, duration, intensity and the number of antecedent dry days, and geometric features, such  
545 as the materials of the different impervious surfaces. Nevertheless, this approach requires a  
546 large amount of data that can be difficult to obtain, especially in large urban catchments.  
547 Moreover, to be effective an increase of the spatial resolution of the model should coincide  
548 with a refined spatial description of the rainfall (Cristiano et al., 2019).

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

#### 555 **4. CONCLUSIONS**

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

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

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

## 596 **Acknowledgments**

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

## 601 **References**

- 602 Ackerman, D., Stein, E.D., 2008. Estimating the Variability and Confidence of Land Use and  
603 Imperviousness Relationships at a Regional Scale. *Journal of the American Water*  
604 *Resources Association*, 44 (4), 996–1008. [https://doi.org/10.1111/j.1752-](https://doi.org/10.1111/j.1752-1688.2008.00215.x)  
605 [1688.2008.00215.x](https://doi.org/10.1111/j.1752-1688.2008.00215.x)
- 606 Barco, O.J., Ciaponi, C., Papiri, S., 2004. Pollution in Storm Water Runoff. Two Cases: An  
607 Urban Catchment and a Highway Toll Gate Area. NOVATECH, 5th International  
608 Conference on Sustainable Techniques and Strategies in Urban Water Management.  
609 Lyon, France, June, 6-10.
- 610 Beighley, R.E., Kargar, M., He, Y., 2009. Effects of Impervious Area Estimation Methods on  
611 Simulated Peak Discharges. *Journal of Hydrologic Engineering*, 14 (4), 388–98.  
612 [https://doi.org/10.1061/\(ASCE\)1084-0699\(2009\)14:4\(388\)](https://doi.org/10.1061/(ASCE)1084-0699(2009)14:4(388))
- 613 Bonhomme, C., Petrucci, G., 2017. Should We Trust Build-up/Wash-off Water Quality Models  
614 at the Scale of Urban Catchments? *Water Research*, 108(January), 422-31.  
615 <https://doi.org/10.1016/j.watres.2016.11.027>
- 616 Chankon, K., labchoon, S., Wongsai, S., 2015. Urban land use mapping based on object-  
617 based image analysis using worldview-3 satellite imagery. *Proceedings of the 36th*  
618 *Asian Conference on Remote Sensing*. Metro Manila, Philippines, October, 19-23.
- 619 Charters, F.J., Cochrane, T.A., O'Sullivan A.D., 2016. Untreated Runoff Quality from Roof and  
620 Road Surfaces in a Low Intensity Rainfall Climate. *Science of The Total Environment*,  
621 550 (April), 265–72. <https://doi.org/10.1016/j.scitotenv.2016.01.093>
- 622 Chow, M.F., Yusop, Z., Toriman, M.E., 2012. Modelling Runoff Quantity and Quality in  
623 Tropical Urban Catchments Using Storm Water Management Model. *International*  
624 *Journal of Environmental Science and Technology*, 9 (4), 737-48.  
625 <https://doi.org/10.1007/s13762-012-0092-0>
- 626 Cristiano, E., Veldhuis, M.C., Wright, D.B., Smith, J.A., Giesen, N., 2019. The Influence of  
627 Rainfall and Catchment Critical Scales on Urban Hydrological Response Sensitivity.  
628 *Water Resour. Res.*, 55 (4), 3375–3390. <https://doi.org/10.1029/2018WR024143>

- 629 Crobbeddu, E., Bennis, S., 2011. A New Model for Simulating TSS Washoff in Urban Areas.  
630 Applied and Environmental Soil Science, 2011, 1–9. <https://doi.org/10.1155/2011/318765>
- 631 Di Modugno, M., Gioia, A., Gorgoglione, A., Iacobellis, V., la Forgia, G., Piccinni, A.F.,  
632 Ranieri, E., 2015. Build-Up/Wash-Off Monitoring and Assessment for Sustainable  
633 Management of First Flush in an Urban Area. Sustainability, 7 (5), 5050-5070.  
634 <https://doi.org/10.3390/su7055050>
- 635 Egodawatta, P., Thomas, E., Goonetilleke, A., 2007. Mathematical Interpretation of Pollutant  
636 Wash-off from Urban Road Surfaces Using Simulated Rainfall. Water Research, 41  
637 (13), 3025–31. <https://doi.org/10.1016/j.watres.2007.03.037>
- 638 Egodawatta, P., Thomas, E., Goonetilleke, A., 2009. Understanding the Physical Processes of  
639 Pollutant Build-up and Wash-off on Roof Surfaces. Science of The Total Environment,  
640 407 (6), 1834-41. <https://doi.org/10.1016/j.scitotenv.2008.12.027>
- 641 Einstein, H.A., 1934. Der hydraulische oder profil radius. Scherizer-isch Bauzeitung, 103 (8) (in  
642 German)
- 643 Fallah Shorshani, M., Bonhomme, C., Petrucci, G., André, M., Seigneur, C., 2014. Road  
644 Traffic Impact on Urban Water Quality: A Step towards Integrated Traffic, Air and  
645 Stormwater Modelling. Environmental Science and Pollution Research, 21 (8), 5297-  
646 5310. <https://doi.org/10.1007/s11356-013-2370-x>
- 647 Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, Management and Modelling of  
648 Urban Hydrology and Its Consequences for Receiving Waters: A State of the Art.  
649 Advances in Water Resources, 51 (January), 261–79.  
650 <https://doi.org/10.1016/j.advwatres.2012.09.001>.
- 651 Fraga, I., Charters, F.J., O’Sullivan, A.D., Cochrane, T.A., 2016. A Novel Modelling Framework  
652 to Prioritize Estimation of Non-Point Source Pollution Parameters for Quantifying  
653 Pollutant Origin and Discharge in Urban Catchments. Journal of Environmental  
654 Management, 167 (February), 75–84. <https://doi.org/10.1016/j.jenvman.2015.11.003>
- 655 Gasperi, J., Sebastian, C., Ruban, V., Delamain, M., Percot, S., Wiest, L., Mirande, C.,  
656 Caupos, E., Demare, D., Diallo Kessoo Kessoo, M., Saad, M., Schwartz, J.J., Dubois,  
657 P., Fratta, C., Wolff, H., Moilleron, R., Chebbo, G., Cren, C., Millet, M., Barraud, S.,  
658 Gromaire, M.C., 2014. Micropollutants in Urban Stormwater: Occurrence,  
659 Concentrations, and Atmospheric Contributions for a Wide Range of Contaminants in  
660 Three French Catchments. Environmental Science and Pollution Research, 21 (8),  
661 5267–5281. <https://doi.org/10.1007/s11356-013-2396-0>
- 662 Gorgoglione, A., Gioia, A., Iacobellis, V., Ferruccio Piccinni, A., Ranieri, E., 2016. A Rationale  
663 for Pollutograph Evaluation in Ungauged Areas, Using Daily Rainfall Patterns: Case  
664 Studies of the Apulian Region in Southern Italy. Applied and Environmental Soil  
665 Science, 2016, 1–16. <https://doi.org/10.1155/2016/9327614>
- 666 Hong, Y., Bonhomme, C., Le, M-H., Chebbo, G., 2016. New Insights into the Urban Washoff  
667 Process with Detailed Physical Modelling. Science of The Total Environment 573  
668 (December), 924–36. <https://doi.org/10.1016/j.scitotenv.2016.08.193>
- 669 Hossain, I., Imteaz, M., Gato-Trinidad, S., Shanableh, A., 2010. Development of a Catchment  
670 Water Quality Model for Continuous Simulations of Pollutants Build-up and Wash-Off.  
671 International Journal of Environmental and Ecological Engineering, 4 (1), 11-18.  
672 <https://doi.org/10.1007/s11270-018-3777-2>
- 673 Jacqueminet, C., Kermadi, S., Michel, K., Béal, D., Gagnage, M., Branger, F., Jankowsky, S.,  
674 Braud, I., 2013. Land Cover Mapping Using Aerial and VHR Satellite Images for  
675 Distributed Hydrological Modelling of Periurban Catchments: Application to the Yzeron

- 676 Catchment (Lyon, France). *Journal of Hydrology*, 485 (April), 68–83.  
677 <https://doi.org/10.1016/j.jhydrol.2013.01.028>
- 678 Krajewski, W.F., Kruger, A., Caracciolo, C., Golé, P., Barthes, L., Creutin, J.D., Delahaye,  
679 J.Y., Nikolopoulos, E.I., Ogden, F., Vinson, J.P., 2006. DEVEX-disdrometer evaluation  
680 experiment: Basic results and implications for hydrologic studies. *Adv. Water Resour.*,  
681 29, 807–814. <https://doi.10.1016/j.advwatres.2005.03.018>
- 682 Liu, A., Goonetilleke, A., Egodawatta, P., 2012. Inherent Errors in Pollutant Build-up Estimation  
683 in Considering Urban Land Use as a Lumped Parameter. *Journal of Environmental*  
684 *Quality*, 41 (5), 1690-94. <https://doi.10.2134/jeq2011.0419>
- 685 Liu, A., Egodawatta, P., Guan, Y., Goonetilleke, A., 2013. Influence of Rainfall and Catchment  
686 Characteristics on Urban Stormwater Quality. *Science of The Total Environment*, 444  
687 (February), 255–62. <https://doi.org/10.1016/j.scitotenv.2012.11.053>
- 688 Luo, X., Zhao, H., Liao, Y., Li, X., 2018. Evaluation of the Methods for Quantifying Particle  
689 Wash-off Loadings in Urban Impervious Surfaces at Small Scales. *Environmental*  
690 *Science and Pollution Research* 25 (7), 6969–79. [https://doi.org/10.1007/s11356-017-](https://doi.org/10.1007/s11356-017-1018-7)  
691 [1018-7](https://doi.org/10.1007/s11356-017-1018-7)
- 692 Mancini, L., Formichetti, P., D'Angelo, A.M., Pierdominici, E., Sorace, A., Bottoni, P., Laconelli,  
693 M., Ferrari, C., Tancioni, L., Rossi, N., Rossi, A., 2005. Freshwater Quality in Urban  
694 Areas: A Case Study from Rome, Italy. *Microchemical Journal*, 79 (1–2), 177-83.  
695 <https://doi.org/10.1016/j.microc.2004.08.009>
- 696 Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I. A  
697 discussion of principles. *Journal of Hydrology*, 10 (3), 282–290.  
698 [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6)
- 699 Niazi, M., Nietch, C., Maghrebi, M., Jackson, N., Bennett, B.R., Tryby, M., Massoudieh, A.,  
700 2017. Storm Water Management Model: Performance Review and Gap Analysis.  
701 *Journal of Sustainable Water in the Built Environment* 3 (2), 04017002.  
702 <https://doi.org/10.1061/JSWBAY.0000817>
- 703 Niemi, T.J., Kokkonen, T., Sillanpää, N., Setälä, H., Koivusalo, H., 2019. Automated Urban  
704 Rainfall–Runoff Model Generation with Detailed Land Cover and Flow Routing. *Journal*  
705 *of Hydrologic Engineering* 24 (5), 04019011. [https://doi.org/10.1061/\(ASCE\)HE.1943-](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001784)  
706 [5584.0001784](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001784)
- 707 Perrin, J.L., Tournoud, M.G., 2009. Hydrological Processes Controlling Flow Generation in a  
708 Small Mediterranean Catchment under Karstic Influence. *Hydrological Sciences Journal*,  
709 54 (6), 1125-40. <https://doi.org/10.1623/hysj.54.6.1125>
- 710 Petrucci, G., Bonhomme, C. 2014. The Dilemma of Spatial Representation for Urban  
711 Hydrology Semi-Distributed Modelling: Trade-Offs among Complexity, Calibration and  
712 Geographical Data. *Journal of Hydrology*, 517 (September), 997–1007.  
713 <https://doi.org/10.1016/j.jhydrol.2014.06.019>
- 714 Rio, M., Salles, C., Rodier, C., Cantet, F., Marchand, P., Mosser, T., Cernesson, F., Monfort,  
715 P., Tournoud, M-G., 2017. An empirical model to quantify fecal bacterial loadings to  
716 coastal areas: application in a Mediterranean context. *CR Geosciences*, 349, 299-309.  
717 <http://dx.doi.org/10.1016/j.crte.2017.09.005>
- 718 Rossman, L.A., 2010. Storm water management model user's manual, version 5.0. National  
719 Risk Management Research Laboratory, Office of Research and Development, U.S.  
720 EPA, Cincinnati, OH.
- 721 Salmi, A., Ikonen, J., 2005. Piezoelectric precipitation sensor from Vaisala. In WMO Technical  
722 Conference on Instruments and Methods of Observation, Bucharest, Romania, 4-7.

- 723 Salvadore, E., Bronders, J., Batelaan, O. 2015. Hydrological Modelling of Urbanized  
724 Catchments: A Review and Future Directions. *Journal of Hydrology*, 529 (October), 62–  
725 81. <https://doi.org/10.1016/j.jhydrol.2015.06.028>
- 726 Sandoval, S., Vezzaro, L., Bertrand-Krajewski, J-L., 2018. Revisiting Conceptual Stormwater  
727 Quality Models by Reconstructing Virtual State Variables. *Water Science and*  
728 *Technology*, 78 (3), 655-63. <https://doi.org/10.2166/wst.2018.337>
- 729 Skotnicki, M., Sowiński, M., 2015. The Influence of Depression Storage on Runoff from  
730 Impervious Surface of Urban Catchment. *Urban Water Journal*, 12 (3), 207–18.  
731 <https://doi.org/10.1080/1573062X.2013.839717>
- 732 Temprano, J., Arango, Ó., Cagiao, J., Suárez, J., Tejero, I., 2005. Stormwater Quality  
733 Calibration by SWMM: A Case Study in Northern Spain. *Water SA*, 32 (1), 55-63.  
734 <https://doi.org/10.4314/wsa.v32i1.5240>
- 735 Tuomela, C., Sillanpää, N., Koivusalo, H., 2019. Assessment of Stormwater Pollutant Loads  
736 and Source Area Contributions with Storm Water Management Model (SWMM). *Journal*  
737 *of Environmental Management* 233 (March), 719–27.  
738 <https://doi.org/10.1016/j.jenvman.2018.12.061>
- 739 Weng, Q., 2012. Remote Sensing of Impervious Surfaces in the Urban Areas: Requirements,  
740 Methods, and Trends. *Remote Sensing of Environment*, 117 (February), 34–49.  
741 <https://doi.org/10.1016/j.rse.2011.02.030>
- 742 Wicke, D., Cochrane, T.A., O'Sullivan, A., 2012. Build-up Dynamics of Heavy Metals Deposited  
743 on Impermeable Urban Surfaces. *Journal of Environmental Management*, 113  
744 (December), 347-54. <https://doi.org/10.1016/j.jenvman.2012.09.005>
- 745 Wijesiri, B., Egodawatta, P., McGree, J., Goonetilleke, A., 2016. Assessing Uncertainty in  
746 Stormwater Quality Modelling. *Water Research*, 103 (October), 10-20.  
747 <https://doi.org/10.1016/j.watres.2016.07.011>
- 748 Zgheib, S., Moillon, R., Chebbo, G., 2012. Priority Pollutants in Urban Stormwater: Part 1 –  
749 Case of Separate Storm Sewers. *Water Research*, 46 (20), 6683–92.  
750 <https://doi.org/10.1016/j.watres.2011.12.012>
- 751 Zoppou, C., 2001. Review of Urban Storm Water Models. *Environmental Modelling & Software*,  
752 16 (3), 195-231. [https://doi.org/10.1016/S1364-8152\(00\)00084-0](https://doi.org/10.1016/S1364-8152(00)00084-0)
- 753

754 **Figure and table captions**

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

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

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

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

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

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

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

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

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

780 **Figure 10.** Examples of simulated pollutographs corresponding to the event that occurred on  
781 October 15<sup>th</sup> 2018

782 **Table 1.** Nomenclature used for land cover classification

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

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



787 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

788

789

790 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
<b>Surface (ha)</b>		Defined from the stratified sampling method of land cover analysis						
<b>Longest flow path (m)</b>	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
<b>Slope (%)</b>	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	-
<b>Impervious surfaces (%)</b>	Corresponds to the surfaces of the flat roofs, roads, sloped roofs, car parks, pedestrian areas and swimming pools	100	100	100	100	100	-	100
<b>Manning coefficient for impervious surfaces</b>	Computed from the Manning coefficients of the WQRUs according to the Einstein formula (1934) :	0.033	0.017	0.05	0.033	0.025	-	-
<b>Manning coefficient for pervious surfaces</b>	$n = \frac{1}{l} * \sum_i l_i * n_i^{\frac{3}{2}}$ Where $n$ is the Manning coefficient and $l$ is the width of the considered catchment	-	-	-	-	-	0.05	-
<b>Depression storage on impervious surfaces (mm)</b>	Calculated as the weighted average of the depression storage on the WQRUs	1	0	20	1	0.5	-	150
<b>Depression storage on pervious surfaces (mm)</b>		-	-	-	-	-	8	-
<b>Impervious surfaces with no depression storage (%)</b>	Corresponds to the surface of the sloped roofs	-	100	-	-	-	-	-

791

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