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Hydrological impacts of urbanization at the catchment scale

Ludovic Oudin¹, Bahar Salavati¹, Carina Furusho-Percot², Pierre Ribstein¹, Mohamed Saadi¹

⁽¹⁾ Sorbonne Université, UPMC Univ Paris 06, UMR 7619 Metis, Case 105, 4 place Jussieu, F-75005 Paris, France.

⁽²⁾ IRSTEA, Hydrosystems and Bioprocesses Research Unit, Parc de Tourvoie, BP 44, 92163 Antony Cedex, France.

Corresponding author. E-Mail: ludovic.oudin@upmc.fr

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ABSTRACT

The impacts of urbanization on floods, droughts and the overall river regime have been largely investigated in the past few decades, but the quantification and the prediction of such impacts still remain a challenge in hydrology. We gathered a sample of 142 catchments that have a documented increase in urban areas over the hydrometeorological record period in the United States. The changes in river flow regimes due to urban spread were differentiated from climate variability using the GR4J conceptual hydrological model. High, low and mean flows were impacted at a threshold of a 10% total impervious area. Moreover, the historical evolution of urban landscape spatial patterns was used to further detail the urbanization process in terms of extent and fragmentation of urban areas throughout the catchment and to help interpret the divergent impacts observed in streamflow behaviors. Regression analysis pointed out the importance of major wastewater treatment facilities that might overpass the effects of imperviousness, and therefore further research should either take them explicitly into account or select a wastewater facility-free catchment sample to clearly evaluate the impacts of urban landscape on low flows.

Keywords: rainfall-runoff modeling; urban fragmentation; total imperviousness; threshold effect; urbanization impacts.

1 **1 INTRODUCTION**

2 ***1.1 Urban transformation of river landscapes in a global context***

3 Today, 54% of the world’s population lives in urban areas, a proportion that is expected
4 to increase to 66% by 2050 (United Nations, 2014). The environmental impacts of such
5 an increase will certainly be huge, but many facets of this impact remain difficult to
6 assess. The hydrological impact of urbanization, while largely studied for more than 50
7 years (see e.g., Leopold, 1968), is very difficult to predict and even the quantification of
8 this impact for historical urban sprawl appears difficult to assess. This is quite a problem
9 since recent urban planning or mitigation strategies could be particularly useful in the
10 near future and often involve the restoration of what is assumed to be natural
11 hydrological conditions (Trinh and Chui, 2013).

12 ***1.2 Identifying and quantifying the impact of urbanization on catchment response***

13 Local hydrological processes can be deeply modified in urban settings; the development
14 of impervious areas alters surface infiltration of water, resulting in increased surface
15 runoff and decreased evapotranspiration and groundwater recharge (see the recent review
16 by Salvadore et al., 2015).

17 At the catchment scale (typically 10-10000 km²), due to the high spatial heterogeneity of
18 impervious areas, the hydrological impact of urbanization is more complex. Table 1
19 provides an overview of previous studies that investigate the hydrological impact of
20 urbanization at the catchment scale. This synthesis focuses on studies with observed
21 streamflow data along spatial or temporal gradients of urbanization; therefore studies
22 based only on simulation of hydrological models without observations (typically
23 simulations performed on land use scenario) were not included.

Table 1: Summary of studies on the hydrological impact of urbanization. Studies involving hydrological modeling are in bold.

Flow characteristic	Increased / emphasized	Decreased/ mitigated	Non significant / non systematic	Attribution of change/ main processes identified
High Flows (storm flow)	Burns et al., 2005; Choi et al., 2003 ; Diem et al., 2018; Hawley and Bledsoe, 2011; Hollis, 1977 ; H. Huang et al., 2008; S. Huang et al., 2008 ; Konrad and Booth, 2002; Mejía et al., 2015; Miller et al., 2014 ; Miller and Hess, 2017; Petchprayoon et al., 2010 ; Prosdocimi et al., 2015; Rose and Peters, 2001; Rougé and Cai, 2014; Tetzlaff et al., 2005; Tong, 1990; Yang et al., 2013			Reduced transit time and increased flashiness due to imperviousness and/or storm water conveyance systems.
Low Flows (baseflow)	Bhaskar et al., 2015; Burns et al., 2005; Diem et al., 2018; Hollis, 1977 ; Konrad et al., 2005; Rougé and Cai, 2014	Braud et al., 2013; Choi et al., 2003 ; Diem et al., 2018; Kauffman et al., 2009; Klein, 1979; Mejía et al., 2015; Rose and Peters, 2001; Simmons and Reynolds, 1982	Brandes et al., 2005; Hejazi and Moglen, 2007; Schwartz and Smith, 2014	Increased groundwater recharge due to reduced evapotranspiration; Decreased groundwater recharge due to imperviousness and less infiltration (potentially offset by presence of pervious areas within urban infrastructures); Low flows decreased due to shallow groundwater pumping but potentially increased due to deep groundwater pumping; Water supply and wastewater treatment systems may increase or decrease low flows depending on cross-basin transfer.
Mean / Total Flows	Ahn and Merwade, 2014 ; Bhaskar et al., 2015; Chen et al., 2017; Claessens et al., 2006; DeWalle et al., 2000; Diem et al., 2018; Hollis, 1977 ; Petchprayoon et al., 2010 ; Putro et al., 2016; Rose and Peters, 2001; Rougé and Cai, 2014; Tetzlaff et al., 2005		Rose and Peters, 2001; Wang and Hejazi, 2011	In addition to processes affecting low and high flows: cross-basin transfers of public water and/or sewerage water that may either increase or decrease mean flow.

25 It appears from Table 1 that diverse impacts were reported depending on the flow
26 characteristics investigated. While the increase in the peak streamflow of flood events is
27 supported by both empirical and modeling studies, the amount of change in high flows is
28 highly variable among studies. Increased catchment imperviousness reduces soil
29 infiltration and consequently baseflow, which may decrease low flows at the outlet of the
30 catchment (Kauffman et al., 2009). However, other factors might mitigate or emphasize
31 the impact on low flows: reduced evaporation from urban areas compared to other land
32 covers (Rose and Peters, 2001), modifications of soil permeability due to topographic
33 modification and soil compaction (e.g. Hibbs and Sharp, 2012). In addition, discharge
34 from wastewater treatment facilities (e.g. Göbel et al., 2004), inter-basin water transfer
35 (e.g. Barringer et al., 1994) and/or groundwater pumping (e.g. Claessens et al., 2006)
36 often occur on urban catchments and may impact the entire flow range, most particularly
37 low flows. Consequently, there is no consensus on the impact of urbanization on
38 catchment low flows that may either increase or decrease (Bhaskar et al., 2015). The
39 impact of urbanization on mean annual flows is complex as a result of the multiple
40 factors described above. Previous studies point out that mean annual flow is either
41 unimpacted (e.g., Rose and Peters, 2001) or increased (e. g. DeWalle et al., 2000).

42 ***1.3 Relating the hydrological impact on urban landscapes***

43 The imperviousness of the catchment has become a benchmark for urban design and
44 zoning criteria (Arnold and Gibbons, 1996; Schueler et al., 2009). At the catchment scale,
45 imperviousness is often calculated as the area-weighted mean of land-use categories with
46 categorical imperviousness values. Mean catchment imperviousness, also referred to as
47 total imperviousness area (TIA), is often suggested to explain the hydrological impact of

48 urbanization. Diverse mean catchment imperviousness threshold values above which
49 hydrological characteristics are modified have been put forward. Some authors reported
50 significant effects of urbanization at a very low level (5%) of imperviousness (Booth and
51 Jackson, 1997; Yang et al., 2010), while others observed very small changes up to 20%
52 (Brun and Band, 2000). This wide range of imperviousness threshold values suggests that
53 the total imperviousness of a catchment cannot explain all of the diversity of the
54 hydrological impacts of urbanization. The total imperviousness area is probably a
55 relevant first-order aggregated measure but might overlook other relevant explanatory
56 factors (Alberti et al., 2007) that mitigate and in some cases offset the impact of increased
57 imperviousness. These factors are diverse and include the location of the impervious area
58 within the catchment (Mejía and Moglen, 2010a), in particular its interconnectedness
59 (Mejía and Moglen, 2010b) and its proximity to the drainage network (Grove et al., 1998;
60 Sheeder et al., 2002) as well as the development of hydraulic structures such as detention
61 basins and natural pathway modifications (Ogden et al., 2011) in addition to the natural
62 geomorphological settings of the catchment such as the catchment area, the hydrographic
63 network drainage density and the presence of aquifers (Konrad et al., 2005). So far, few
64 studies have attempted to empirically quantify the effects of these urban land patterns on
65 hydrological catchment behavior.

66 ***1.4 Scope of the paper***

67 The objective of this study was to determine whether general conclusions can be drawn
68 on the impact of urbanization on the flow characteristics at the outlet of urbanized
69 catchments. To this aim, a hydrological model was used to quantify the historical change
70 of streamflow characteristics (mean flow, low flow and high flow) due to urbanization

71 and distinguish it from the change due to climate variability. Then the change of
72 streamflow characteristics is related to modifications of urban landscape metrics within a
73 regression framework, in order to hierarchize the impacts of land use management. To
74 determine flow changes attributable to land use changes (and not climate variability), we
75 followed in this paper the so-called model residual approach, which was found to give
76 comparable results to the paired catchment approach on a set of 24 urban catchments
77 (Salavati et al., 2016). The present study was conducted on 142 U.S. urban catchments in
78 order to reach general conclusions on several open questions: is there a threshold effect of
79 imperviousness on the impact of urbanization? Is the effect of urbanization common to
80 all catchments? Does urbanization affect low, mean and high flows differently? Does the
81 spatial organization of urban areas play a significant role on the impact of urbanization at
82 the catchment scale?

83 **2 DATA**

84 ***2.1 Catchment selection***

85 The catchments studied were selected among the 9067 catchments of the GAGES-II
86 database. A preliminary selection was made according to the following criteria: (i) a
87 relatively large fraction of urban areas compared to the total drainage area of the
88 catchment, (ii) long-term flow measurements and (iii) a relatively small impact of
89 upstream dams. For the first criterion, we used the National Land Cover Database
90 (NLCD, Homer et al., 2015) and considered only the catchments presenting a percentage
91 of areas categorized as developed (sum of classes 21, developed: open space; 22,
92 developed: low intensity; 23, developed medium intensity and 24, developed: high
93 intensity in the NLCD classification) greater than 10% of the total catchment drainage

94 area. For the second criterion, we used the hydrometric stations presenting more than 30
95 years of data with at least 10 years of data for the 1940–1975 period and 10 years for the
96 1985–2010 period. For the third criterion, we used the mean annual volume of water
97 stored in the dams collected in the GAGES-II database. We converted this volume into a
98 mean annual runoff using the catchment area and we divided the runoff by the mean
99 annual runoff. Finally, we considered that a ratio below 0.1 leads to a relatively small
100 impact of dams over the catchment behavior. Based on these criteria, 430 catchments
101 were selected for the analysis but further selection among this set of 430 catchments
102 were made on the basis of the evolution of urbanization during the flow record periods
103 (see Section 3.2).

104 **2.2 *Hydroclimatic data***

105 Daily precipitation and air temperature data for each catchment were gathered from the
106 database proposed by Livneh et al. (2013). They produced gridded meteorological
107 variables (spatial resolution, $1/16^\circ$) interpolated from ground-based measurements. This
108 dataset was created by incorporating daily observations of maximum and minimum
109 temperature as well as accumulated precipitation from National Weather Service
110 Cooperative Observer stations across the United States for the 1915–2011 period. Daily
111 potential evaporation values were estimated from air temperature data of the gridded data
112 set using the equation proposed by Oudin et al. (2005).

113 **2.3 *Historical urbanization data***

114 It was necessary to verify if the urban fraction had indeed evolved significantly over the
115 flow record period. To this aim, we used the housing density (HD) maps at a 90-m
116 resolution developed by Theobald (2005) as a proxy of urban land cover. This allows

117 estimating long-term changes in urban areas since HD maps were available from 1940 to
 118 2010, every 10 years, while NLCD provides only more recent maps (for the years 1992,
 119 2001, 2006 and 2011). We considered that urban areas were defined by HD above 145
 120 units per km² (Table 2), which is higher than the threshold used by Theobald (25 units per
 121 km²) while showing better agreement with NLCD developed area classes. The HD data
 122 were reclassified to estimate mean catchment imperviousness (TIA) for each catchment
 123 and each decade. The rules of classification (Table 2) were reconsidered from previous
 124 studies (Bierwagen et al., 2010; Theobald et al., 2009) to reach better agreement with
 125 NLCD impervious surface estimates (Xian et al., 2011), considered as the land cover
 126 benchmark. The limitation of estimating urban areas and imperviousness from HD data is
 127 that areas of predominately commercial or industrial land use often have high
 128 imperviousness but low HD. However, this land use class is present in the HD maps
 129 (Urban/Built-up class) and we considered a 90% corresponding categorical value of
 130 imperviousness.

131 **Table 2: Reclassification of housing density data to estimate urban areas and imperviousness**

Housing density (units per km ²)	Original land cover classification (Theobald, 2005)	Urban / nonurban classification used in this study	Imperviousness (%)
0	Undeveloped	Nonurban	0.0
<3	Rural I	Nonurban	0.3
[3,5]	Rural I	Nonurban	0.6
[5,6]	Rural I	Nonurban	0.7
[6,8]	Rural II	Nonurban	0.9
[8,12]	Rural II	Nonurban	1.1
[12,25]	Rural II	Nonurban	1.7
[25,145]	Exurban/urban	Nonurban	8.0
[145,412]	Exurban/urban	Urban	18.7
> 412	Exurban/urban	Urban	46.3
-	Urban/Built-up	Urban	90.0

132

133 As mentioned in the introduction, urbanization often comes along the settings of sewer
134 systems and wastewater treatment facilities that are likely to impact significantly the river
135 flow regime. Unfortunately, no historical nation-wide information exists on rain water
136 sewer system and water treatment facilities while this information should be particularly
137 complementary to imperviousness in an urban context. In this study, we used the density
138 of major Water Treatment Facilities (WTFs) extracted from the GAGE II database for the
139 year 2006. This metric is used along other landscape patterns as an explanatory variable
140 of estimated flow changes.

141 **3 METHODS**

142 ***3.1 Urban landscape patterns considered***

143 Based on reclassified HD maps, we extracted several indicators of urbanization patterns
144 for each decade to analyze the hydrological impact beyond the usual TIA estimate. Table
145 3 provides a brief description of these indicators: F.URB and TIA are basic urbanization
146 descriptors, describing only the extent and density of urbanization over the catchment;
147 SI.URB and SI.NURB are landscape fragmentation indices aimed at characterizing the
148 intrinsic structuring of urban areas within the catchment; RDIST.NET, RDIST.OUT and
149 IMP.100 (distribution of the imperviousness of areas in a 100-m buffer area from the
150 hydrographic network) aim at characterizing the location of urban areas within the
151 catchment, in particular their proximity to the drainage network and/or the outlet. All
152 these variables depend on the resolution of the data used. Since HD data are at a 90-m
153 resolution, landscape structuring metrics such as the shape indexes will not take into
154 account small parks and private gardens but they will provide an overview of urban and
155 suburban areas over the catchment. For the metrics related to the hydrographic network

156 (RDIST.NET and IMP.100), we used the high-resolution National Hydrography Dataset
157 (NHD) and considered only stream rivers flagged as perennial or intermittent, i.e.,
158 omitting ephemeral rivers. For some catchments the hydrographic network had been
159 largely modified by urbanization, and historic data are difficult to obtain at this
160 resolution. Consequently, artificial network data, pipelines and ditches that may be
161 identified by the NHD database were not considered in the RDIST.NET and IMP.100
162 estimation.

163
164

Table 3: Urban catchment characteristics used to analyze the different urbanization patterns over the catchment set

Notation	Index name	Computation	Class	Interpretation
F.URB	Fraction of urban areas over catchment drainage area	$F.URB = \frac{S.URB}{S.URB + S.NURB}$ <p>S.URB and S.NURB correspond to total urban area (km²) and nonurban area (km²), respectively</p>	Urban density	Higher values mean more urban areas
TIA	Mean catchment imperviousness	Area-weighted mean of imperviousness land use over the catchment area	Urban density	Higher values mean higher imperviousness
SI.URB	Shape index of urban areas	$SI.URB = \frac{\sum P.URB}{\sqrt{S.URB}}$ <p>P.URB corresponds to the sum of the perimeters of urban areas</p>	Landscape structuring	Higher values mean greater fragmentation of urban area
SI.NURB	Shape index of nonurban areas	$SI.NURB = \frac{\sum P.NURB}{\sqrt{S.NURB}}$ <p>P.NURB corresponds to the sum of the perimeters of nonurban areas</p>	Landscape structuring	Higher values mean greater fragmentation of nonurban areas
RDIST.NET	Ratio of distance of urban areas to hydrographic network	Mean distance of urban pixels to hydrographic network divided by the mean distance of all catchment pixels to hydrographic network	Proximity to hydrographic network	Higher values mean urban areas relatively far from hydrographic network
RDIST.OUT	Ratio of distance of urban areas to catchment outlet	Mean distance of urban pixels to catchment outlet divided by the mean distance of all catchment pixels to catchment outlet	Proximity to catchment outlet	Higher values mean urban areas relatively far from catchment outlet
IMP.100	Mean imperviousness of river corridors	Weighted mean of imperviousness land use in the 100-m riparian buffer zone	Proximity to hydrographic network	Higher values mean high imperviousness of river corridors

165

166 **3.2 *Quantifying the hydrological impact of urbanization through hydrological***
167 ***modeling***

168 In this study, we applied the model residual approach to quantify the historical impact of
169 urbanization on different flow components (Kuczera et al., 1993; Seibert and McDonnell,
170 2010). The model residual approach is a widely used approach to determine the impact of
171 land use change on hydrology (see e.g. Li et al., 2012). In the context of urbanization, it
172 was compared to the paired catchment approach and both approaches were in general in
173 good agreements (Salavati et al., 2016). The model residual approach basically consists
174 in calibrating a rainfall-runoff model on a time period before a land use change and
175 simulating flow with this set of calibrated parameters on the time period after land use
176 changes. Analysis of the model residual for the time period after land use changes allows
177 assessing the impact of land use change on streamflow at the outlet of the catchment. The
178 main advantage of the model residual approach is that it allows separating and
179 quantifying the effects of land use change and climate variability/climate change,
180 provided that the calibration of the model for the period before land use change is robust.

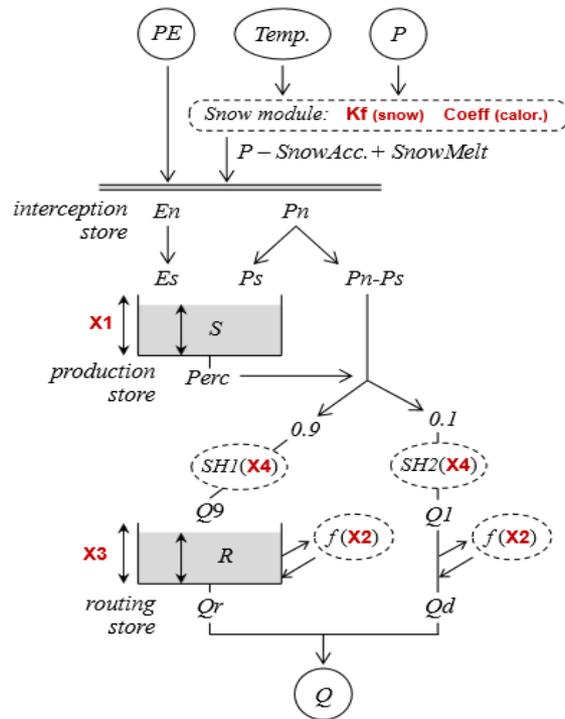
181 To apply the model residual approach, we followed the following steps for each
182 catchment: (i) determination of a preurbanization period and a posturbanization period;
183 (ii) calibration of the hydrological model on the preurbanization period, (iii) simulation of
184 streamflow on the posturbanization period using the parameter set obtained in calibration
185 on the preurbanization period, (iv) quantification of flow changes. Each of these steps are
186 detailed hereafter.

187 The preurbanization period was defined as the first 15 years of the streamflow record
188 period while the last 10 years of the streamflow record period were used as the

189 posturbanization period. The record lengths of these subperiods were chosen since they
190 allow to reach a reasonable trade-off between two objectives: (i) the periods needed to be
191 long enough to provide robust calibration of model parameters for the preurbanization
192 period and significant simulation results for the posturbanization period and (ii) the
193 periods needed to be short enough so that limited land use changes occurred during these
194 two subperiods while important urbanization gradients existed between preurbanization
195 and posturbanization periods. The stationarity of the preurbanization period was assessed
196 in terms of both hydrological model parameter values and urbanization extent. Besides,
197 we restricted the analysis on the catchments for which mean imperviousness had
198 increased by more than 5% between the preurbanization period and the posturbanization
199 period.

200 The daily rainfall-runoff model with four parameters, GR4J (Perrin et al., 2003), coupled
201 with the CemaNeige snow model (Valéry et al., 2014a, 2014b), was calibrated on the
202 preurbanization period. The association of the GR4J model with a snow module (Figure
203 1) was necessary since the influence of snow accumulation and snowmelt is not
204 negligible on many of the catchments studied.

205



Parameters		
X1	production store capacity	[mm]
X2	groundwater exchange coefficient	[-]
X3	routing store capacity	[mm]
X4	unit hydrograph time constant	[day]
Kf (snow)	degree-day melt coefficient	[mm.j ⁻¹]
Coeff (calor.)	weighting coefficient for snow pack thermal state	[-]

206

207 **Figure 1: Structure of the GR4J rainfall-runoff model used (Perrin et al., 2003) coupled with**
 208 **CemaNeige (Valéry et al., 2014a, 2014b).**

209 The model calibration was based on a local search algorithm including a steepest descent
 210 variable as used by Edijatno et al. (1999), and the objective function was the Kling–
 211 Gupta efficiency criterion (Gupta et al., 2009) applied to root-squared streamflow.

212 Then streamflow for the record period was simulated using the set of parameters
 213 calibrated on the preurbanization period (the first 15 years of the record period).
 214 Therefore, the simulated discharge is likely to represent the discharge that would have
 215 occurred in the urban catchment if urbanization had not expanded. Thus, the differences

216 between the simulated and observed discharges for the posturbanization period (the last
217 10 years of the record period) are attributed to the effect of urbanization change on the
218 hydrologic response.

219 Three flow characteristics were analyzed in this study. The mean annual flow (QMA)
220 allows investigating the impact of urbanization on the catchment's water balance. Annual
221 low flow (Q05) and high flow (Q95) characteristics were also computed to investigate the
222 impact of urbanization on extreme flow values. Q05 and Q95 represent the daily
223 discharges that were exceeded during 95% and 5% of each year of the record period,
224 respectively. To quantify the changes for the three annual flow components, we
225 computed the change based on differences between the regression equations obtained for
226 pre- and posturbanization periods at a specific flow value corresponding to the mean of
227 the observed flow characteristic over the whole record period (Salavati et al., 2016). The
228 equation used to determine the absolute flow change takes the general form of Eq. (1):

$$\text{Eq. (1)} \quad CQ = E_{POST}(Q_{obs}|_{Q_{sim}=\overline{Q_{obs}}}) - E_{PRE}(Q_{obs}|_{Q_{sim}=\overline{Q_{obs}}})$$

229 Where CQ is the absolute flow change for a given flow characteristic (Q05, Q95 or
230 QMA), E_{POST} and E_{PRE} are the linear regressed models between the annual observed
231 flow characteristic (the dependent variable) and simulated flow characteristic (the
232 explanatory variable) for the preurbanization period and the posturbanization period
233 respectively and $\overline{Q_{obs}}$ is the mean of observed annual flow characteristics over the entire
234 record period. Consequently, $E_{POST}(Q_{obs}|_{Q_{sim}=\overline{Q_{obs}}})$ and $E_{PRE}(Q_{obs}|_{Q_{sim}=\overline{Q_{obs}}})$ represent
235 the regressed values of Q_{obs} for the specific value of $\overline{Q_{obs}}$ using the linear models E_{POST}
236 and E_{PRE} respectively.

237 Since the hydroclimatic settings of the catchments are quite diverse, relative changes are
238 shown instead of absolute changes, by dividing the absolute change by the mean annual
239 flow characteristics for the preurbanization period. As the mean annual Q05 can be very
240 close to zero for some catchments, the relative Q05 change is expressed as a percentage
241 of mean annual flow, i.e., the absolute Q05 change is divided by the mean annual flow of
242 the preurbanization period.

244 ***3.3 Relating the hydrological impact of urbanization to urban landscape patterns***

245 To relate flow changes to urban landscape change, we considered absolute differences
246 between the posturbanization period and preurbanization period for all urban landscape
247 variables, except RDIST.NET and RDIST.OUT for which only the new urban pixels
248 were used to compute the metric. Therefore, the notations used hereafter to describe the
249 evolution of urban landscape patterns are d.F.URB, d.TIA, d.SI.URB, d.SI.NURB,
250 RDIST.NET, RDIST.OUT and d.IMP.100. For RDIST.NET and RDIST.OUT, the
251 differences between the metrics for the pre- and posturbanization periods were biased by
252 the differences in terms of urban extent. To focus on the locations of urban sprawl
253 between the two periods, we computed RDIST.NET and RDIST.OUT by considering
254 only the areas that were changed from rural to urban between the two periods. Besides,
255 the density of major wastewater treatment facilities for the year 2006 was used as a
256 complementary explanatory variable.

257 For each of the three flow variables Q05, Q95 and QMA, separate analyses were
258 performed. Streamflow change detections were calculated for each urban catchment for
259 the pre- and posturbanization record period. From the set of independent variables,
260 backward stepwise regression was used to identify the best linear models, using the

261 Bayesian information criterion (BIC), which was preferred to the Akaike information
262 criterion (AIC) since it tends to identify less parametrized models. The regression model
263 was fit between the dependent variables (the change of one of the three flow components)
264 and the changes of the selected urban catchment characteristics as the independent
265 variables.

266 Regression equations take the general form of Eq. (2):

$$\text{Eq. (2)} \quad CQ_i = \beta_0 + \beta_1 X_1^i + \beta_2 X_2^i + \dots + \beta_n X_n^i$$

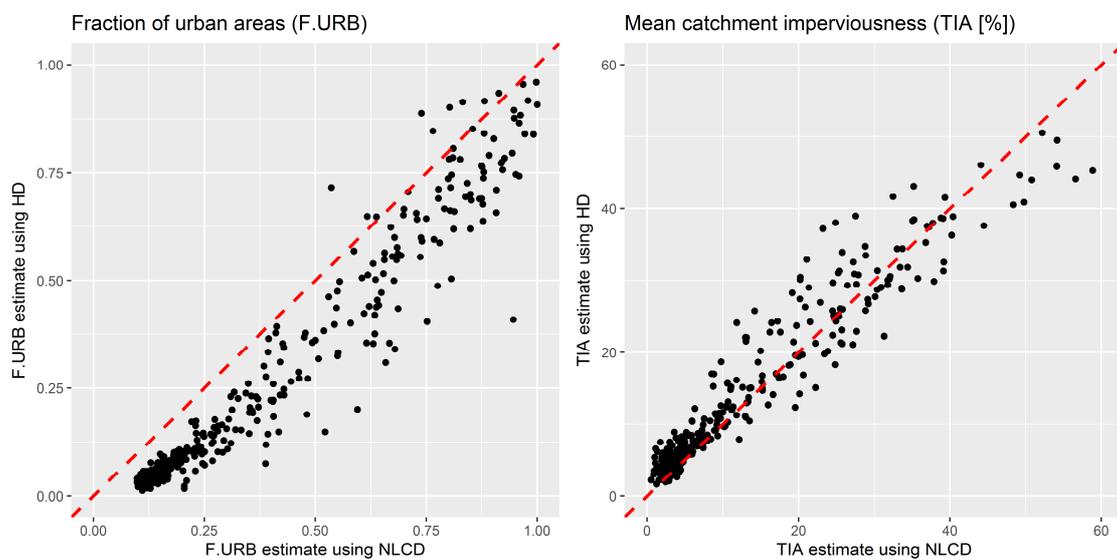
267 where CQ_i is the streamflow change for the i -th catchment, X_j^i is the change of the j -th
268 urbanization catchment characteristic of the i -th catchment and β_j are the linear model
269 coefficients. Since three flow characteristics were analyzed, three regression equations
270 were obtained. From the selected models, we performed hierarchical partitioning to
271 assess the relative contribution of each predictor within the R environment software,
272 using the hier.part package (Walsh and Mac Nally, 2003).

273 **4 RESULTS**

274 **4.1 Catchment urbanization patterns**

275 To assess the potential of using HD data as a proxy for imperviousness, we estimated the
276 urban fraction and catchment imperviousness (i.e., TIA) using the lookup Table 2 for
277 each catchment for the year 2010 and compared it to data given by NLCD database for
278 the year 2011 since NLCD is considered as the reference database. Figure 2 shows that
279 HD data satisfactorily estimated the fraction of urban areas and mean catchment
280 imperviousness. The fraction of urban areas estimated by HD is generally underestimated
281 compared to the NLCD database, while mean catchment imperviousness is slightly
282 overestimated for those catchments presenting low TIA values. Overall, the correlation

283 coefficients for both the fraction of urban areas and mean catchment imperviousness are
284 above 0.96, corroborating the results of previous studies that used HD data to derive
285 urban fractions (Over et al., 2016). The slight biases observed are probably due to the
286 choice of the classes of the original HD dataset (Table 2) and more classes around the
287 urban/nonurban threshold and in the upper values of HD would probably provide better
288 agreement between HD estimates and NLCD products.



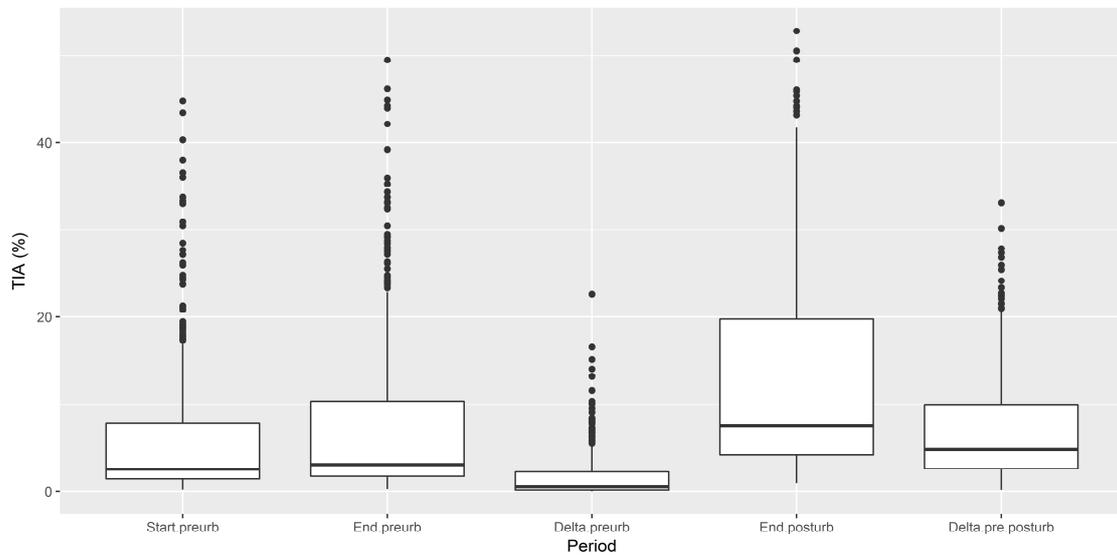
289

290 *Figure 2: Fraction of urban areas and catchment imperviousness from NLCD database and*
291 *HD maps on the 430 urban catchments. The NLCD data for urban areas corresponds to the*
292 *sum of the developed area classes (21–24) for the year 2011, and the catchment imperviousness*
293 *corresponds to the 2011 imperviousness map; HD estimates were derived from the 2010 HD*
294 *map using the reclassification proposed in Table 2.*

295 To investigate whether the urban fraction had evolved significantly between the
296 preurbanization period and the posturbanization period and among the preurbanization
297 period, we used the HD maps that were available from 1940 to 2010, every 10 years. For
298 each catchment, we used three HD maps representative of the preurbanization and the
299 posturbanization periods: a map characterizing the beginning of the preurbanization

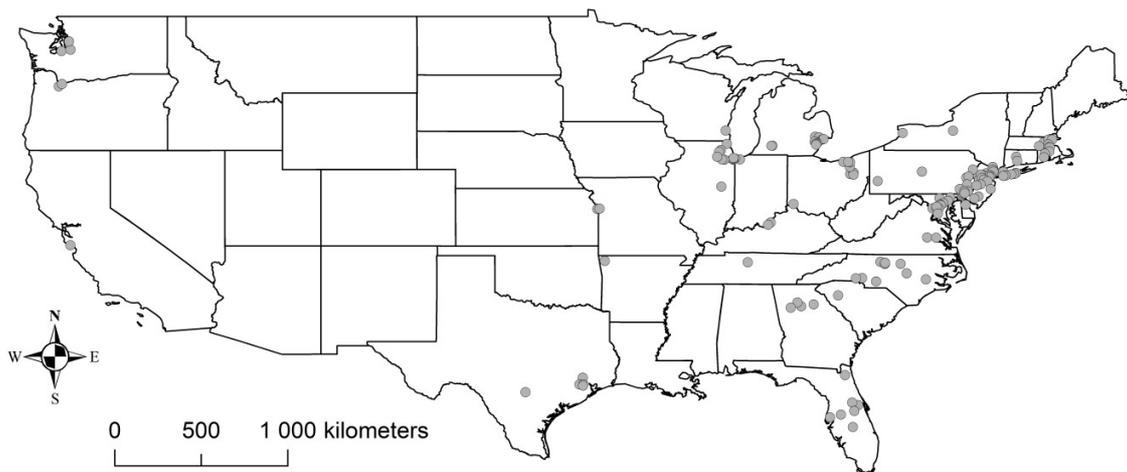
300 period (for this map, we selected the closest decade to the beginning of the
301 preurbanization period), a map characterizing the end of the preurbanization period (for
302 this map, we selected the closest decade to the end of the preurbanization period) and a
303 map characterizing the posturbanization period (for this map, we selected the closest
304 decade to the end of the posturbanization period). The first two maps are used to
305 investigate possible evolution of urbanization during the preurbanization period and the
306 first and third maps are used to assess the evolution of urbanization between the
307 preurbanization period and the posturbanization period. The urban catchment
308 characteristics listed in were calculated for these representative maps and TIA evolution
309 was analyzed in order to check whether the selected catchments changed significantly in
310 terms of urbanization over the flow record period and within the preurbanization period.
311 It is noteworthy that TIA evolution was computed as the absolute difference between TIA
312 for the posturbanization period and TIA for the preurbanization period, i.e. a 5% increase
313 of TIA between the two periods means that TIA had increased by 5% of the catchment
314 area. Figure 3 notably shows that for many catchments, the increase of mean catchment
315 imperviousness over the flow record period is low. The urban catchments were initially
316 selected based on the fraction of urban areas given by NLCD for the year 2011 and many
317 of the catchments selected were already urbanized at the beginning of the flow record
318 period. Only 209 catchments presented an evolution of TIA greater than 5% between the
319 preurbanization period and the posturbanization period. Besides, the evolution of TIA
320 during the preurbanization period is generally low but greater than 5% for 50 catchments.
321 Since we aimed at relating the hydrological changes to the urbanization patterns over the
322 catchment set, we decided to focus on the catchments for which mean imperviousness

323 had increased by more than 5% between the preurbanization and posturbanization periods
324 while presenting low (less than 5%) evolution of TIA within the preurbanization period.
325 This leads to a reduction of the catchment set from 430 to 142 catchments (see location
326 on Figure 4) with drainage areas ranging from 10 to 7000 km² and a median value of 150
327 km².



328

329 ***Figure 3: Distribution of the mean catchment imperviousness for the pre- and***
330 ***posturbanization periods and TIA evolutions.***

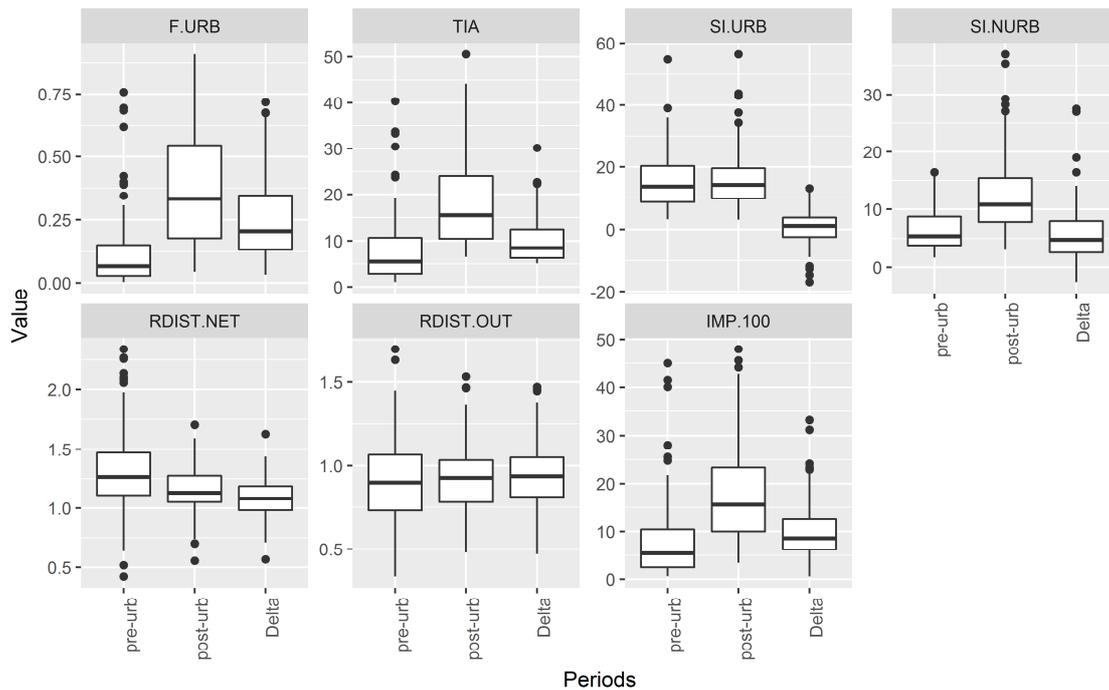


331

332 ***Figure 4: Location of the 142 urban catchments studied.***

333 The distributions of the seven urban catchment characteristics listed in Table 3 are shown
334 in Figure 5 for the 142 selected catchments. The distributions of the fraction of urban
335 areas (F.URB) and the mean catchment imperviousness (TIA) are relatively similar,
336 which is expected since the two metrics are highly correlated with each other. The
337 distributions of both F.URB and TIA are also similar to the distribution of the
338 imperviousness of areas in a 100-m buffer area from the hydrographic network
339 (IMP.100), meaning that urbanization led to increased imperviousness relatively
340 homogeneously at the catchment scale and in the vicinity of hydrographic network.
341 Fragmentation of the nonurban landscape (SI.NURB) is generally increased, but some
342 catchments present decreased nonurban fragmentation. Fragmentation of the urban
343 landscape (SI.URB) is either increased or decreased depending on the catchments
344 considered, meaning that urban development can be either concentrated or scattered over
345 the catchment area. This also stems from urban sprawl taking place in the vicinity of
346 already urban areas for some catchments while for other catchments, new urban areas
347 disconnected from urban areas already present emerged. The distributions of the distance
348 ratio of urban areas to the hydrographic network (RDIST.NET) shows that urban areas
349 are not necessarily located in the vicinity of the hydrographic network (RDIST.NET
350 generally above 1) and for a majority of the catchments, new urban areas are relatively
351 far from the hydrographic network (delta of RDIST.NET above 1 for 70% of the 142
352 catchments). The distributions of the distance ratio of urban areas to catchment outlets
353 (RDIST.OUT) show that urban areas are not preferentially located close to or far from
354 the catchment outlet, but a wide variety of situations exists.

355 To conclude on these urbanization characteristics, the set of 142 catchments present a
 356 wide variety of urbanization patterns in terms of quantity and spatial structuring within
 357 the catchment area. This diversity offers the opportunity to analyze the change of
 358 streamflow with regards to these diverse urbanization characteristics.

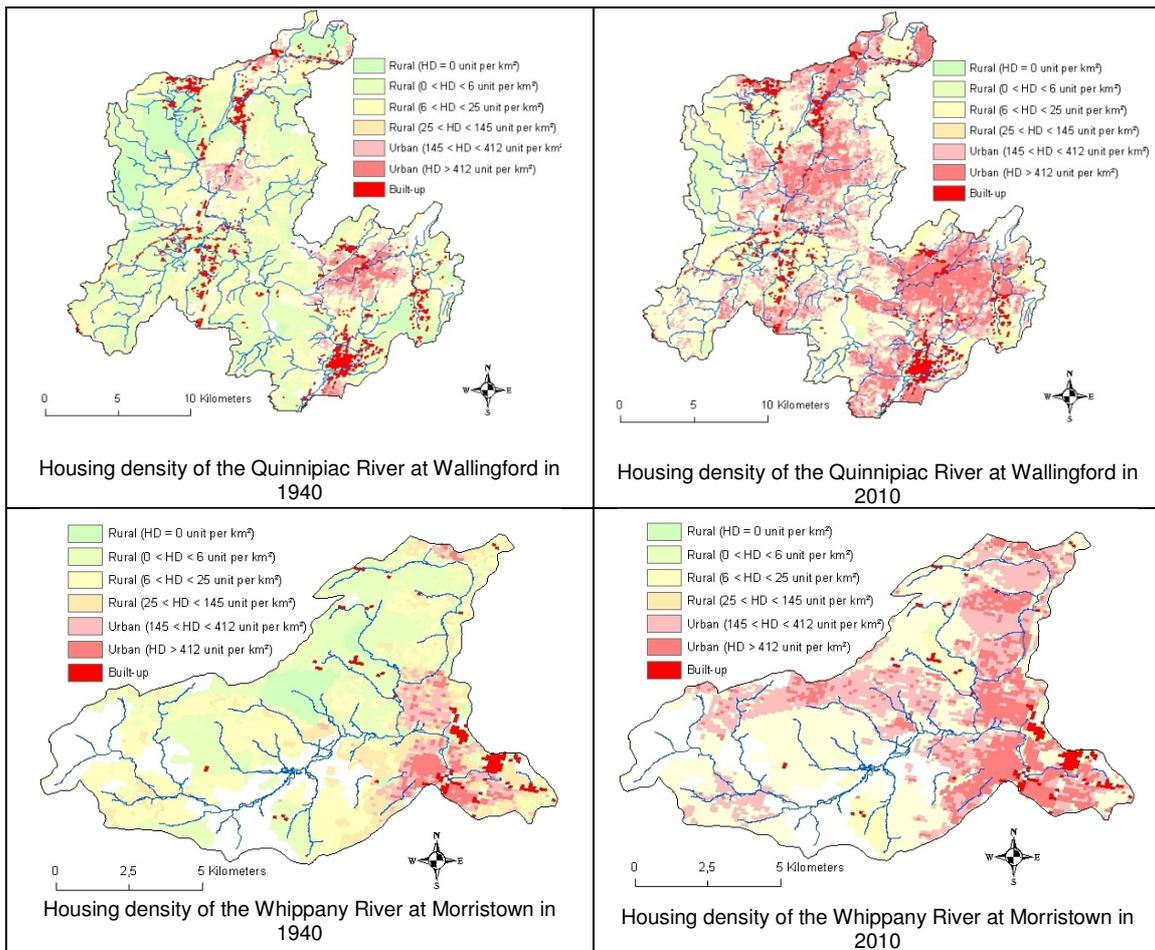


359

360 **Figure 5: Catchment urbanization patterns for the preurbanization and posturbanization**
 361 **periods. The boxplots represent the distribution of the variables over the 142 catchments**
 362 **studied. The bottom and top of the boxes represent the first and third quartiles and the**
 363 **whiskers represent the 1.5 interquartile range.**

364 Figure 6 provides an illustration of the diversity of urbanization patterns. For a similar
 365 extent of urban areas (from around 5% of the catchment area in 1940 to around 18% in
 366 2010), urban areas are more fragmented on the Quinnipiac River (shape index SI.URB 21
 367 and 23 for 1940 and 2010, respectively) compared to the Whippany River (shape index
 368 SI.URB 8 and 11 for 1940 and 2010, respectively). Similarly, nonurban areas are more
 369 fragmented on the Quinnipiac River (shape index SI.NURB 6 and 12 for 1940 and 2010,

370 respectively) compared to the Whippany River (shape index SI.NURB 3 and 6 for 1940
 371 and 2010, respectively). The differences of these indexes for the posturbanization and
 372 preurbanization periods point out that urbanization leads to more fragmented nonurban
 373 areas over the Quinnipiac River at Wallingford.

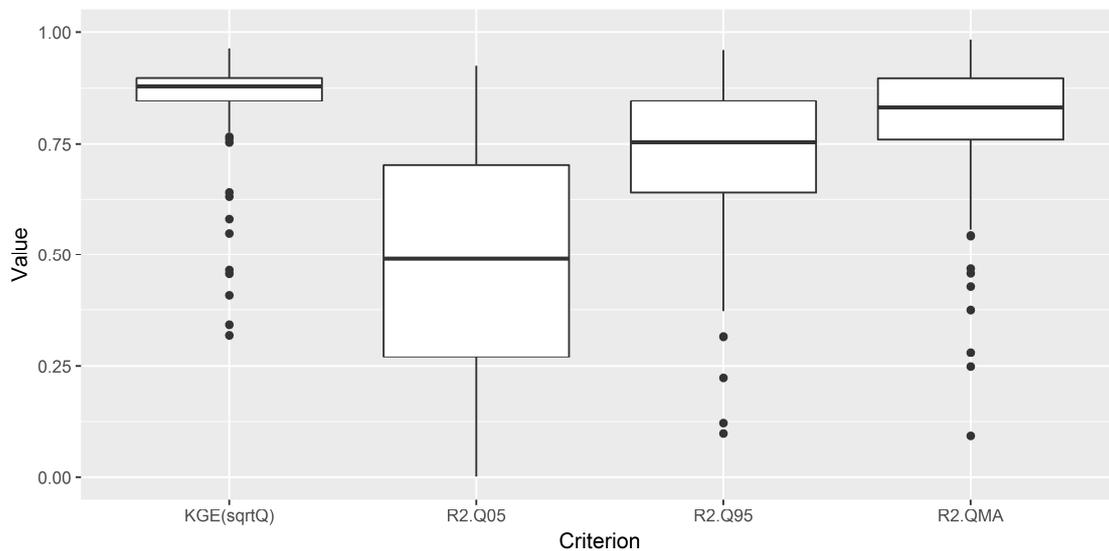


374 **Figure 6: Two contrasted examples of catchment urbanization patterns. For a similar extent of**
 375 **urban area, the Quinnipiac River at Wallingford (top) presents more fragmented urban and**
 376 **nonurban areas than the Whippany River at Morristown (bottom) for which concentrated**
 377 **urban areas are located in the downstream part of the catchment.**

378 4.2 Assessment of hydrological model calibration on the preurbanization period

379 Since the estimated flow changes are based on the model's ability to simulate the low-
 380 urbanization configuration of the catchments, we analyzed the calibration results of the

381 hydrological model using four criteria. The first criterion is the Kling–Gupta efficiency
 382 criterion applied to root-squared streamflow, which is also used as the objective function
 383 during the optimization process of the model parameters. The three other criteria aimed at
 384 assessing the ability of the model to simulate the three streamflow characteristics (Q05,
 385 Q95 and QMA) calculated at the annual time-scale. Since the quantification of the
 386 hydrological impact of urbanization is based on the changes of the linear relationships
 387 between simulated and observed annual flow characteristics, we used the coefficients of
 388 determination (R^2) of these relationships.



389

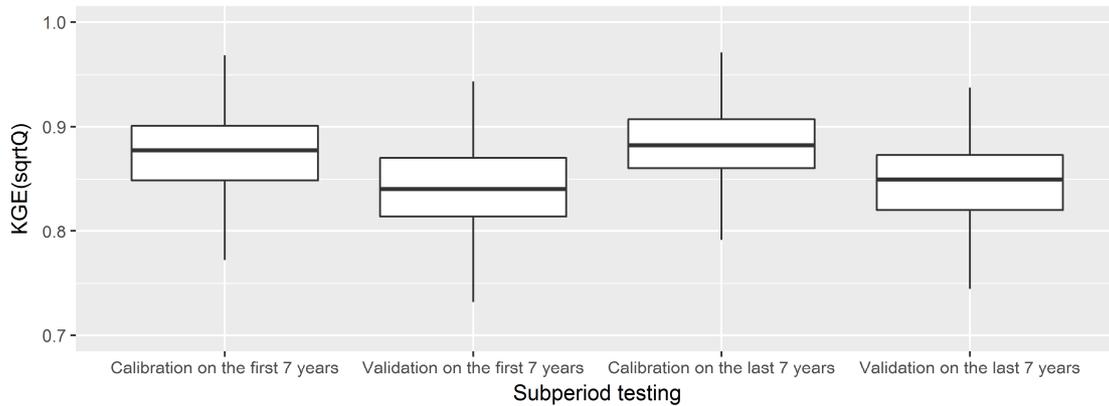
390 *Figure 7: Model calibration efficiency over the 142 catchments studied. KGE(sqrtQ) is the*
 391 *Kling–Gupta efficiency criterion on root-squared transformed daily flow, R2.Q05 R2.Q95 and*
 392 *R2.QMA are the coefficients of determination of annual streamflow characteristics. The*
 393 *bottom and top of the boxes represent the first and third quartiles and the whiskers represent*
 394 *the 1.5 interquartile range.*

395 Figure 7 shows that daily streamflows are generally well simulated by the hydrological
 396 model (75% of KGE values above 0.84). Mean annual flow values are also well
 397 represented (75% of the R2.QMA above 0.76), while high- and low-flow percentiles are

398 more difficult to reproduce (75% of the R2.Q95 above 0.64 and 75% of R2.Q05 above
399 0.27). One may argue that this results from the choice of the objective function, but using
400 another objective function dedicated to low flows (e.g., KGE on log transformed flows)
401 does not improve R2.Q05 since it mainly reduces the model's bias on low flows while
402 only marginally improving the explained variance of the annual Q05 samples. For the
403 sake of homogeneity of the model simulations, we kept a single objective function for
404 simulating the three streamflow characteristics.

405 The model's low level of efficiency in simulating low flows (and to a lesser extent high
406 flows) is inherent to hydrological model but poses the question of the reliability of model
407 simulations for the calibration period (i.e., the period before urbanization extended) and
408 for the simulation period (i.e., the period after urbanization extended). However, the
409 linear relationships obtained between annual flow characteristics are in general
410 significant at a 0.01 threshold p-value: 107 out of 142 for Q05, 139 out of 142 for Q95
411 and 140 out of 142 for QMA.

412 Another caveat of the model residual approach is the parameter uncertainty issue. To
413 address this issue, we tested the robustness of the model calibration during the
414 preurbanization by applying a split sample test over this period: the model is calibrated
415 on the first seven years and test in validation mode over the last seven years and vice-
416 versa. Figure 8 compares the model performance for the model calibration and validation
417 periods. The performance is assessed by the objective function used for calibration
418 (Kling-Gupta efficiency criterion on root-squared transformed daily flow).



419

420 **Figure 8: Results of the split sample test applied on the preurbanization period for the 142**
 421 **studied catchments. $KGE(\sqrt{Q})$ is the Kling-Gupta efficiency criterion on root-squared**
 422 **transformed daily flow. The bottom and top of the boxes represent the first and third quartiles**
 423 **and the whiskers represent the 1.5 interquartile range.**

424 Median Kling-Gupta efficiency on square-rooted streamflow over the catchment set is
 425 0.87 and 0.88 during calibration (First and last seven years respectively) and 0.83 and
 426 0.84 during validation (First and last seven years respectively). The gap between
 427 calibration and validation results is relatively small and comparable with other large-
 428 sample studies with this hydrological model (Poncelet et al., 2017). This suggests that
 429 model calibration is relatively robust in-between the preurbanization period, making the
 430 model residual approach appropriate for our study.

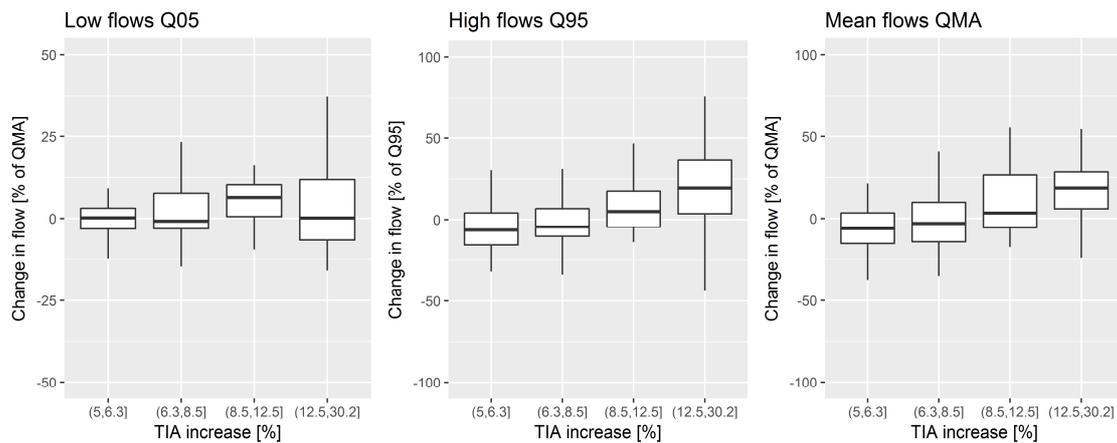
432

433 **4.3 Analysis of the hydrological impacts of catchment imperviousness**

434 Figure 9 provides an overview of the relative flow changes estimated over the 142 urban
 435 catchments considered, with respect to the total imperviousness increase over the flow
 436 record period. The impact of the imperviousness increase is clear for high and mean flow:
 437 an increase of TIA in most cases led to an increase of flow, which is, however, diverse
 438 over the catchment set. It is noteworthy that a relatively low TIA increase (less than
 439 around 10%) does not affect the flow characteristics considered. This result corroborates

440 a number of previous studies pointing out a threshold value of imperviousness above
 441 which the hydrological impacts of urbanization become significant. The threshold value
 442 reported in the literature is generally between 5 (Booth and Jackson, 1997; Yang et al.,
 443 2010) and 20% (Brun and Band, 2000), and the 10% value obtained over the set of 142
 444 catchments lies between these reported values.

445 As for the low-flow characteristic, the estimated changes also appear greater for larger
 446 TIA increases, but the sign of the changes can be either negative or positive depending on
 447 the catchment. This means that the Q05 response to urbanization is complex and the TIA
 448 increase might not be the best variable to explain alone the low-flow changes on some
 449 catchments.



450

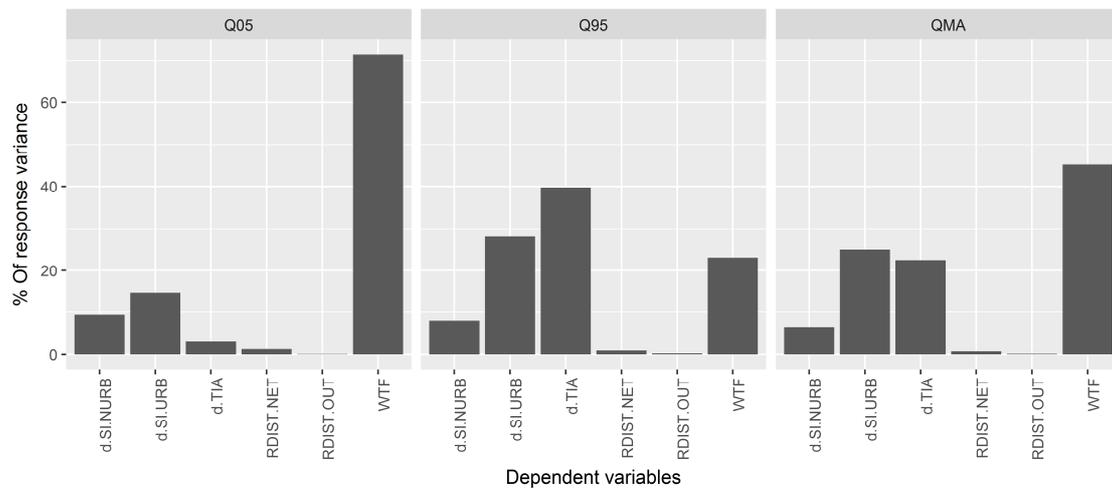
451 **Figure 9: Relative changes for low (Q05) high (Q95) and mean (QMA) flow characteristics of**
 452 **the 142 catchments studied. Values are given for four TIA increase classes (5.0–6.3%, 6.3–**
 453 **8.5%, 8.5–12.5%, 12.5–30.2%), each class representing 35–36 catchments.**

454 **4.4 Influence of urban landscape patterns on hydrological impacts**

455 To shed more light on the landscape patterns affecting most flow characteristics on the
 456 142 catchments studied, this section relates the relative flow changes to the changes in
 457 urban landscape patterns. The explanatory variables tested that were used for the

458 regression analysis were initially the absolute differences between the preurbanization
459 and posturbanization periods of the metrics presented in Table 3. Since d.F.URB, d.TIA
460 and d.IMP.100 presented a quite high cross correlation (above 0.95), only d.TIA is used
461 hereafter. In addition, we used the density of major facilities WTFs extracted from the
462 GAGE II database, for the year 2006.

463 The hierarchical partitioning (Figure 10) revealed that the density of major WTFs
464 presents the highest independent contribution in low-flow changes (71%), but also a high
465 contribution in high- and mean-flow changes (23% and 45%, respectively). The increase
466 of mean catchment imperviousness (d.TIA) presents the highest independent contribution
467 to high-flow changes (40%) and also has a high contribution to mean-flow changes
468 (22%). The evolution of the fragmentation of urban areas d.SI.URB presents a relatively
469 high contribution to high- and mean-flow changes (28% and 25%, respectively). Finally,
470 the metrics characterizing the distance of urban areas from the hydrographic network or
471 catchment outlet present a low contribution to all flow changes. This means either that
472 the location of urban areas has a second-order importance or that the metrics used are not
473 appropriate to describe the connectivity of urban areas to the hydrographic network.



474

475 **Figure 10: Hierarchical partitioning indicating the relative contribution (%) of each predictor**
 476 **to the variance explained by the linear models relating changes of flow characteristics and**
 477 **urbanization characteristics over the 142 urban catchments studied**

478 Regression modeling also demonstrated the high influence of wastewater treatment
 479 facilities on flow changes (Table 4). The models indicate that a higher number of WTFs,
 480 indicating greater density of water treatment facilities, is associated with increased flows.
 481 The catchment imperviousness variation (d.TIA) is also selected for all flow
 482 characteristics. It demonstrated a positive relationship with high and mean flow, but a
 483 negative relationship with low flow. This paradoxical effect of imperviousness on flow
 484 changes might be due to increased surface flow and decreased baseflow within the
 485 urbanized catchment, even if the presence of WTFs may offset the decreased low flow
 486 due to imperviousness for some catchments. Fragmentation metrics were also included in
 487 the best linear models. The shape index of urban areas shows a negative relationship with
 488 flow change, meaning that more fragmented (or less concentrated) urban landscapes are
 489 associated with a lower impact on flow change. Contrary to imperviousness, the variation
 490 of fragmentation is homogenously associated with flow changes. Finally, as suggested by
 491 the hierarchical analysis shown before, the metrics associated with the proximity of urban

492 areas to the hydrographic network are marginally selected. Only the distance of new
 493 urban areas is included in the best models for high and mean flow. The negative
 494 relationship indicates that a development of urban areas near the catchment outlet (i.e.,
 495 shorter distance) is associated with greater flow changes.

496 *Table 4: Results obtained from the stepwise selection procedure. The coefficients displayed in*
 497 *the table are those that were extracted from the best model (through BIC) for each flow*
 498 *characteristic. Stars represents the p-value range ‘***’ <0.001, ‘**’ <0.01, ‘*’ < 0.05.*

	Independent variables (Student <i>t</i> variable and p-values)						Goodness of fit
Flow changes	d.TIA	d.SI.URB	d.SI.NURB	RDIST.NET	RDIST.OUT	WTF	Adjusted R ²
d.Q05	-2.88 **	-3.78 ***	2.79 **	-	-	7.17 ***	0.387
d.Q95	3.82 ***	-2.49 *	-	-	-2.33 *	3.20 **	0.327
d.QMA	3.37 ***	-3.26 **	-	-	-2.71 **	6.46 ***	0.446

499

500 5 DISCUSSION AND CONCLUSION

501 This study attempted to draw general conclusions on the hydrological impact of
 502 urbanization at the catchment scale. To this aim, the derived methodology is based on a
 503 hydrological modeling framework to minimize the flow change attributed to climate
 504 variability. The choice of a relatively simple and somewhat parametrized conceptual
 505 rainfall-runoff model enabled us to apply the same methodology to a wide range of
 506 catchments with several hydroclimatic settings and with diverse levels of urban sprawl.
 507 This choice was also warranted because the model is not used to simulate the changes of
 508 hydrological processes within the catchment but to simulate the streamflow that would
 509 have occurred without urbanization. The results shed new light on several common
 510 questions on the impact of urbanization.

511 An imperviousness threshold effect on the impact of urbanization was observed. This
 512 threshold reflects an approximately 10% increase in mean catchment imperviousness

513 (TIA) and affects the three flow characteristics studied (Q05, Q95 and QMA). This
514 threshold is in agreement with other studies conducted on a more limited number of
515 catchments (e.g. Booth and Jackson, 1997; Yang et al., 2010). However, at this stage it is
516 difficult to conclude definitively on this threshold value. Does the catchment buffer
517 urbanization up to this threshold or does the lack of significant impacts detected below
518 this threshold reflect the undeniable uncertainties related to the hydrological modeling
519 framework? It is more likely that above a 10% increase in mean catchment
520 imperviousness the hydrological impacts of urbanization overtake the modeling
521 uncertainties.

522 Another question raised in the literature is the common effect of urbanization on flow
523 characteristics among urbanized catchments. The literature generally reports that
524 urbanization increases high flow, which was also observed clearly on the catchments
525 studied. The observation was similar for mean annual flow since a large majority of the
526 urbanized catchment presented positive flow changes. Concerning low flow, the results
527 obtained in this study reflect the diversity of the results reported in previous studies since
528 the catchment set studied shows both increased and decreased low flows. Therefore, the
529 effect of urbanization seems relatively common to all catchments for high and mean
530 flows but highly variable for low flows.

531 Another issue addressed in this study is the role of the spatial organization of urban areas
532 on the hydrological impact of urbanization. Over the landscape patterns analyzed in this
533 study, mean catchment imperviousness (TIA) was indeed a key variable but other
534 relevant metrics can help understand the variability of the impacts of urbanization. It was
535 shown that the fragmentation of urban areas presents a negative relationship with flow

536 changes, suggesting that the fragmentation of urban areas mitigates the impacts of
537 urbanization. Interestingly, considering several landscape metrics better identifies the role
538 of mean catchment imperviousness since a positive relationship was found for high and
539 mean flow, whereas a negative one was found for low flows, suggesting that all things
540 being equal, increased imperviousness decreases low flows and increases high flows.

541 The prominence of the density of major wastewater treatment facilities in the best linear
542 models raises the issue of compensation of the effects of imperviousness and the
543 development of water treatment facilities. To investigate the sole impact of urban
544 landscape patterns on low flow, it would be interesting to focus on urban catchments with
545 no major water treatment facilities or to take explicitly into account flow from water
546 treatment facilities. Unfortunately, the catchment set used here did not allow this further
547 analysis and a study focusing on a smaller catchment set would probably be more
548 appropriate to obtain the data to perform this analysis. Another hypothesis of this study
549 that was not verified given the large catchment set is that urbanization may be the
550 dominant change over the catchment during the record period. The results obtained
551 suggest that this hypothesis might be valid for a majority of catchments, but a more
552 detailed assessment of historical changes over the catchments in terms of land use and
553 land cover as well as in terms of hydrographic and sewer networks should ideally be
554 examined.

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559 1/16 degree daily rainfall- and temperature-gridded data are available from
560 <ftp://ftp.hydro.washington.edu/pub/blivneh/CONUS/>. Geospatial data and classifications
561 for stream gages maintained by the U.S. Geological Survey (USGS) called Gages II are
562 available from http://water.usgs.gov/lookup/getspatial?gagesII_Sept2011. National Land
563 Cover Database (NLCD) data were obtained from the Multi-Resolution Land
564 Characteristics (MRLC) Consortium website (available at
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FIGURE LEGENDS

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