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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 INTRODUCTION

1.1 Urban transformation of river landscapes in a global context

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

1.2 Identifying and quantifying the impact of urbanization on catchment response

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

At the catchment scale (typically 10-10000 km²), due to the high spatial heterogeneity of impervious areas, the hydrological impact of urbanization is more complex. Table 1 provides an overview of previous studies that investigate the hydrological impact of urbanization at the catchment scale. This synthesis focuses on studies with observed streamflow data along spatial or temporal gradients of urbanization; therefore studies based only on simulation of hydrological models without observations (typically 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 sewered water that may either increase or decrease mean flow.

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

1.3 Relating the hydrological impact on urban landscapes

The imperviousness of the catchment has become a benchmark for urban design and zoning criteria (Arnold and Gibbons, 1996; Schueler et al., 2009). At the catchment scale, imperviousness is often calculated as the area-weighted mean of land-use categories with categorical imperviousness values. Mean catchment imperviousness, also referred to as total imperviousness area (TIA), is often suggested to explain the hydrological impact of urbanization. Diverse mean catchment imperviousness threshold values above which hydrological characteristics are modified have been put forward. Some authors reported significant effects of urbanization at a very low level (5%) of imperviousness (Booth and Jackson, 1997; Yang et al., 2010), while others observed very small changes up to 20% (Brun and Band, 2000). This wide range of imperviousness threshold values suggests that the total imperviousness of a catchment cannot explain all of the diversity of the hydrological impacts of urbanization. The total imperviousness area is probably a relevant first-order aggregated measure but might overlook other relevant explanatory factors (Alberti et al., 2007) that mitigate and in some cases offset the impact of increased imperviousness. These factors are diverse and include the location of the impervious area within the catchment (Mejía and Moglen, 2010a), in particular its interconnectedness (Mejía and Moglen, 2010b) and its proximity to the drainage network (Grove et al., 1998; Sheeder et al., 2002) as well as the development of hydraulic structures such as detention basins and natural pathway modifications (Ogden et al., 2011) in addition to the natural geomorphological settings of the catchment such as the catchment area, the hydrographic network drainage density and the presence of aquifers (Konrad et al., 2005). So far, few studies have attempted to empirically quantify the effects of these urban land patterns on hydrological catchment behavior.

1.4 Scope of the paper

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

2 DATA

2.1 Catchment selection

The catchments studied were selected among the 9067 catchments of the GAGES-II database. A preliminary selection was made according to the following criteria: (i) a relatively large fraction of urban areas compared to the total drainage area of the catchment, (ii) long-term flow measurements and (iii) a relatively small impact of upstream dams. For the first criterion, we used the National Land Cover Database (NLCD, Homer et al., 2015) and considered only the catchments presenting a percentage of areas categorized as developed (sum of classes 21, developed: open space; 22, developed: low intensity; 23, developed medium intensity and 24, developed: high intensity in the NLCD classification) greater than 10% of the total catchment drainage area. For the second criterion, we used the hydrometric stations presenting more than 30 years of data with at least 10 years of data for the 1940–1975 period and 10 years for the 1985–2010 period. For the third criterion, we used the mean annual volume of water stored in the dams collected in the GAGES-II database. We converted this volume into a mean annual runoff using the catchment area and we divided the runoff by the mean annual runoff. Finally, we considered that a ratio below 0.1 leads to a relatively small impact of dams over the catchment behavior. Based on these criteria, 430 catchments were selected for the analysis but further selection among this set of 430 catchments were made on the basis of the evolution of urbanization during the flow record periods (see Section 3.2).

2.2 Hydroclimatic data

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

2.3 Historical urbanization data

It was necessary to verify if the urban fraction had indeed evolved significantly over the flow record period. To this aim, we used the housing density (HD) maps at a 90-m resolution developed by Theobald (2005) as a proxy of urban land cover. This allows estimating long-term changes in urban areas since HD maps were available from 1940 to 2010, every 10 years, while NLCD provides only more recent maps (for the years 1992, 2001, 2006 and 2011). We considered that urban areas were defined by HD above 145 units per km^2 (Table 2), which is higher than the threshold used by Theobald (25 units per km^2) while showing better agreement with NLCD developed area classes. The HD data were reclassified to estimate mean catchment imperviousness (TIA) for each catchment and each decade. The rules of classification (Table 2) were reconsidered from previous studies (Bierwagen et al., 2010; Theobald et al., 2009) to reach better agreement with NLCD impervious surface estimates (Xian et al., 2011), considered as the land cover benchmark. The limitation of estimating urban areas and imperviousness from HD data is that areas of predominately commercial or industrial land use often have high imperviousness but low HD. However, this land use class is present in the HD maps (Urban/Built-up class) and we considered a 90% corresponding categorical value of imperviousness.

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

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

3 METHODS

3.1 Urban landscape patterns considered

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

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

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	$F.URB = \frac{S.URB}{S.URB + S.NURB}$ S.URB and S.NURB correspond to total urban area (km²) and nonurban area (km²), respectively	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.URB corresponds to the sum of the perimeters of urban areas	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.NURB corresponds to the sum of the perimeters of urban areas	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

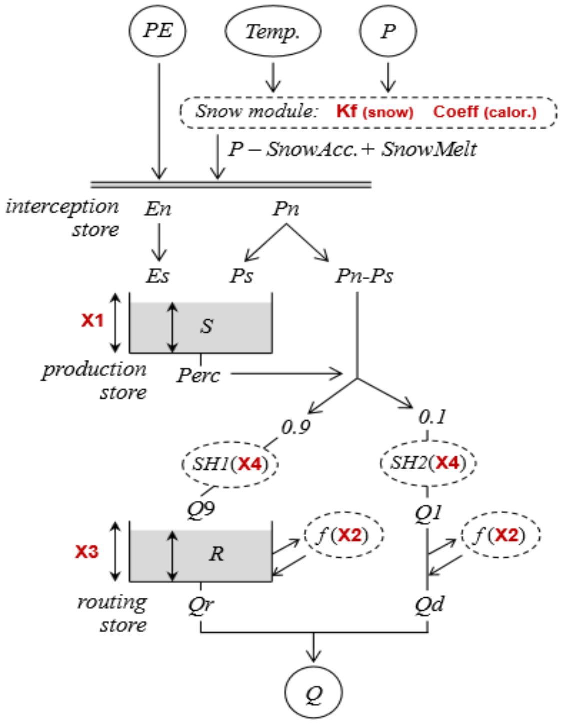
3.2 *Quantifying the hydrological impact of urbanization through hydrological modeling*

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

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

The preurbanization period was defined as the first 15 years of the streamflow record period while the last 10 years of the streamflow record period were used as the posturbanization period. The record lengths of these subperiods were chosen since they allow to reach a reasonable trade-off between two objectives: (i) the periods needed to be long enough to provide robust calibration of model parameters for the preurbanization period and significant simulation results for the posturbanization period and (ii) the periods needed to be short enough so that limited land use changes occurred during these two subperiods while important urbanization gradients existed between preurbanization and posturbanization periods. The stationarity of the preurbanization period was assessed in terms of both hydrological model parameter values and urbanization extent. Besides, we restricted the analysis on the catchments for which mean imperviousness had increased by more than 5% between the preurbanization period and the posturbanization period.

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



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	[-]

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

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

Then streamflow for the record period was simulated using the set of parameters calibrated on the preurbanization period (the first 15 years of the record period). Therefore, the simulated discharge is likely to represent the discharge that would have occurred in the urban catchment if urbanization had not expanded. Thus, the differences between the simulated and observed discharges for the posturbanization period (the last 10 years of the record period) are attributed to the effect of urbanization change on the hydrologic response.

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

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

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

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

3.3 Relating the hydrological impact of urbanization to urban landscape patterns

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

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

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

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

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

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

4 RESULTS

4.1 Catchment urbanization patterns

To assess the potential of using HD data as a proxy for imperviousness, we estimated the urban fraction and catchment imperviousness (i.e., TIA) using the lookup Table 2 for each catchment for the year 2010 and compared it to data given by NLCD database for the year 2011 since NLCD is considered as the reference database. Figure 2 shows that HD data satisfactorily estimated the fraction of urban areas and mean catchment imperviousness. The fraction of urban areas estimated by HD is generally underestimated compared to the NLCD database, while mean catchment imperviousness is slightly overestimated for those catchments presenting low TIA values. Overall, the correlation coefficients for both the fraction of urban areas and mean catchment imperviousness are above 0.96, corroborating the results of previous studies that used HD data to derive urban fractions (Over et al., 2016). The slight biases observed are probably due to the choice of the classes of the original HD dataset (Table 2) and more classes around the urban/nonurban threshold and in the upper values of HD would probably provide better agreement between HD estimates and NLCD products.

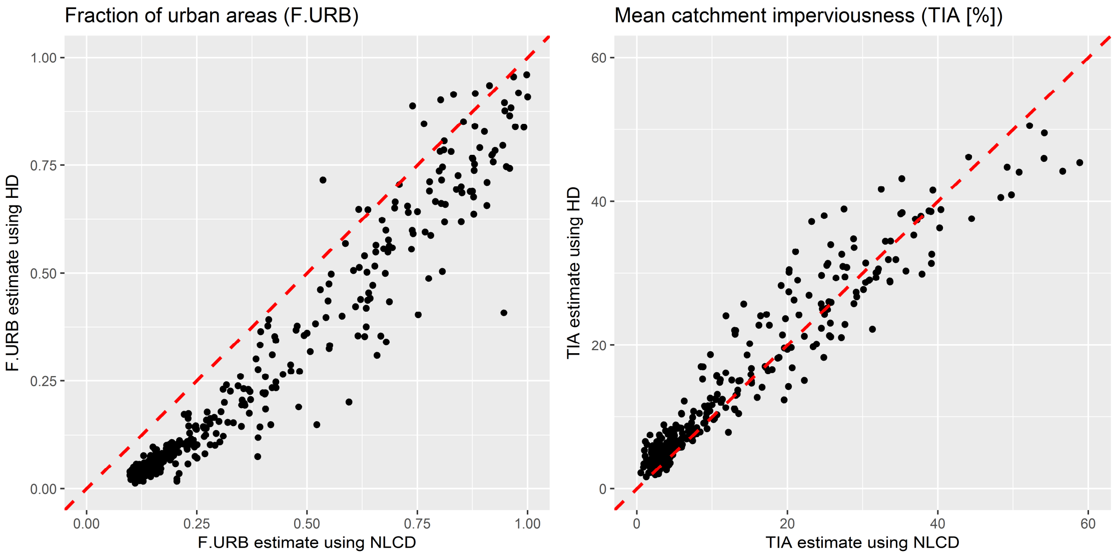


Figure 2: Fraction of urban areas and catchment imperviousness from NLCD database and HD maps on the 430 urban catchments. The NLCD data for urban areas corresponds to the sum of the developed area classes (21–24) for the year 2011, and the catchment imperviousness corresponds to the 2011 imperviousness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

To investigate whether the urban fraction had evolved significantly between the preurbanization period and the posturbanization period and among the preurbanization period, we used the HD maps that were available from 1940 to 2010, every 10 years. For each catchment, we used three HD maps representative of the preurbanization and the posturbanization periods: a map characterizing the beginning of the preurbanization period (for this map, we selected the closest decade to the beginning of the preurbanization period), a map characterizing the end of the preurbanization period (for this map, we selected the closest decade to the end of the preurbanization period) and a map characterizing the posturbanization period (for this map, we selected the closest decade to the end of the posturbanization period). The first two maps are used to investigate possible evolution of urbanization during the preurbanization period and the first and third maps are used to assess the evolution of urbanization between the preurbanization period and the posturbanization period. The urban catchment characteristics listed in were calculated for these representative maps and TIA evolution was analyzed in order to check whether the selected catchments changed significantly in terms of urbanization over the flow record period and within the preurbanization period. It is noteworthy that TIA evolution was computed as the absolute difference between TIA for the posturbanization period and TIA for the preurbanization period, i.e. a 5% increase of TIA between the two periods means that TIA had increased by 5% of the catchment area. Figure 3 notably shows that for many catchments, the increase of mean catchment imperviousness over the flow record period is low. The urban catchments were initially selected based on the fraction of urban areas given by NLCD for the year 2011 and many of the catchments selected were already urbanized at the beginning of the flow record period. Only 209 catchments presented an evolution of TIA greater than 5% between the preurbanization period and the posturbanization period. Besides, the evolution of TIA during the preurbanization period is generally low but greater than 5% for 50 catchments. Since we aimed at relating the hydrological changes to the urbanization patterns over the catchment set, we decided to focus on the catchments for which mean imperviousness had increased by more than 5% between the preurbanization and posturbanization periods while presenting low (less than 5%) evolution of TIA within the preurbanization period. This leads to a reduction of the catchment set from 430 to 142 catchments (see location on Figure 4) with drainage areas ranging from 10 to 7000 km² and a median value of 150 km².

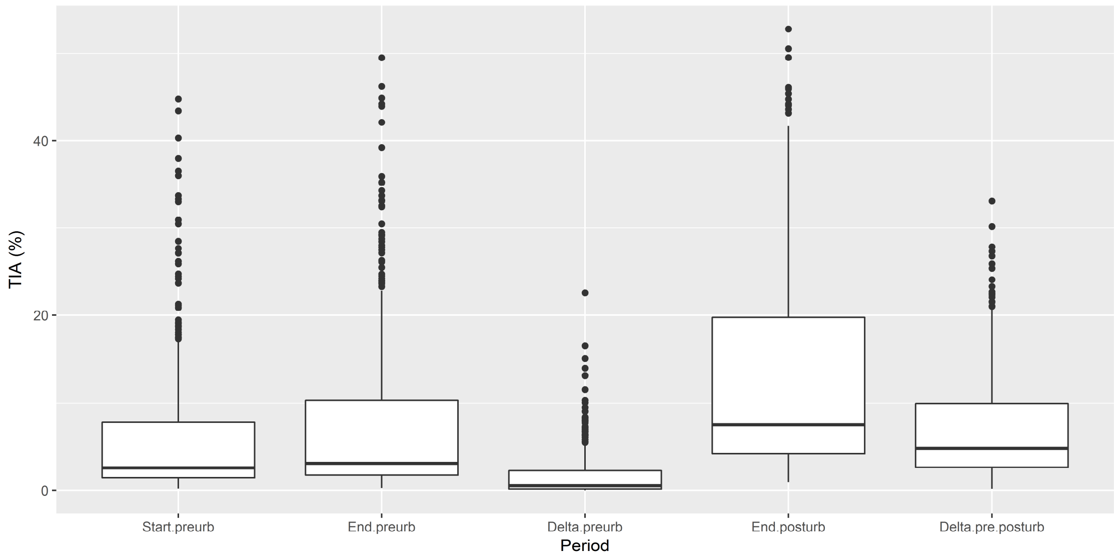


Figure 3: Distribution of the mean catchment imperviousness for the pre- and posturbanization periods and TIA evolutions.

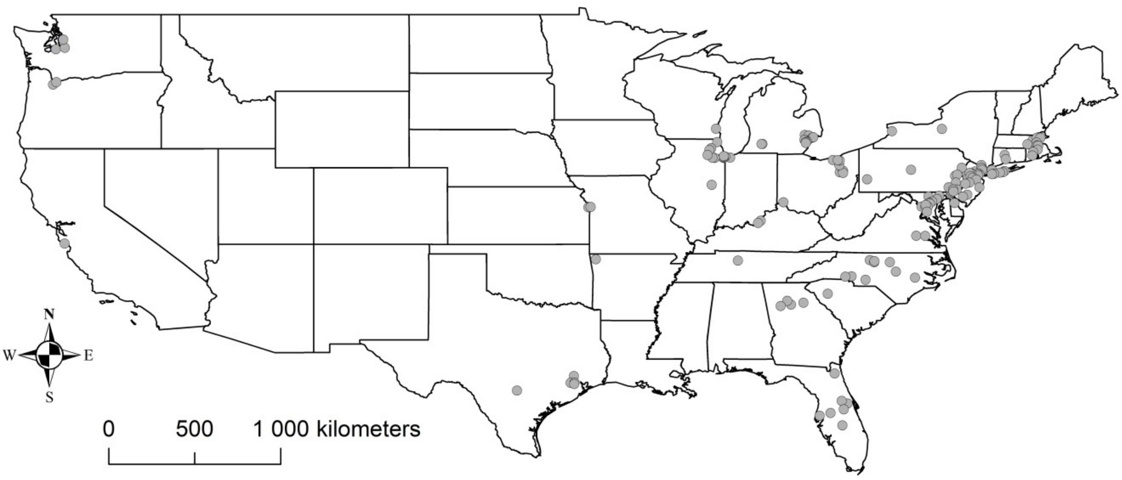


Figure 4: Location of the 142 urban catchments studied.

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

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

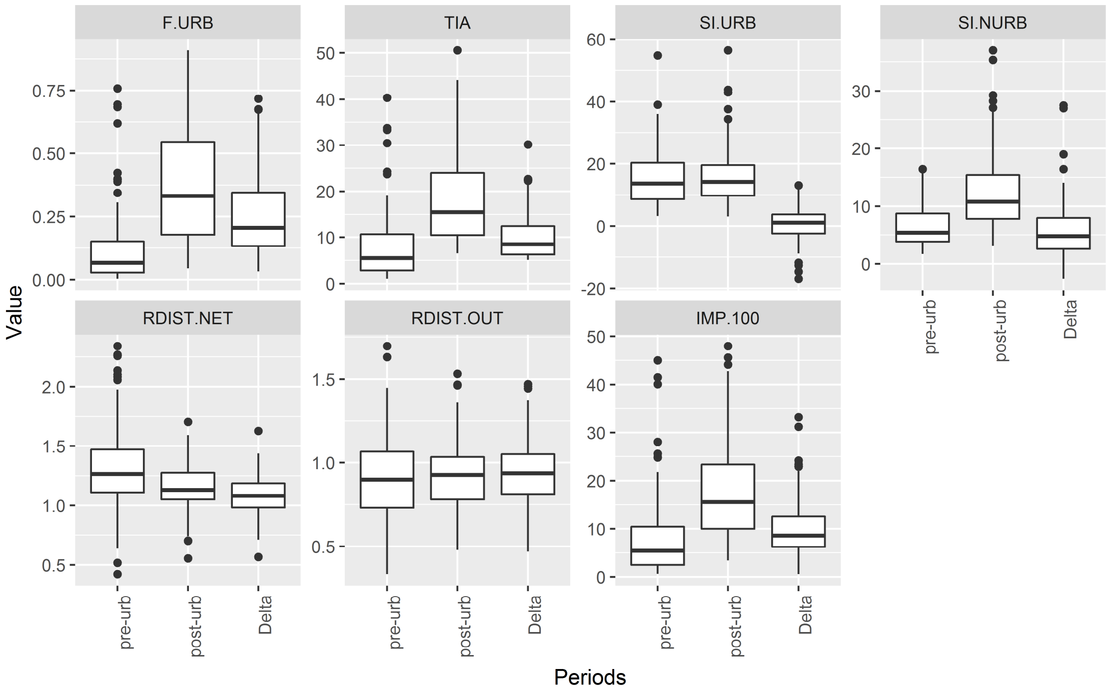


Figure 5: Catchment urbanization patterns for the preurbanization and posturbanization periods. The boxplots represent the distribution of the variables over the 142 catchments studied. The bottom and top of the boxes represent the first and third quartiles and the whiskers represent the 1.5 interquartile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

Figure 6 provides an illustration of the diversity of urbanization patterns. For a similar extent of urban areas (from around 5% of the catchment area in 1940 to around 18% in 2010), urban areas are more fragmented on the Quinnipiac River (shape index SI.URB 21 and 23 for 1940 and 2010, respectively) compared to the Whippany River (shape index SI.URB 8 and 11 for 1940 and 2010, respectively). Similarly, nonurban areas are more fragmented on the Quinnipiac River (shape index SI.NURB 6 and 12 for 1940 and 2010, respectively) compared to the Whippany River (shape index SI.NURB 3 and 6 for 1940 and 2010, respectively). The differences of these indexes for the posturbanization and preurbanization periods point out that urbanization leads to more fragmented nonurban areas over the Quinnipiac River at Wallingford.

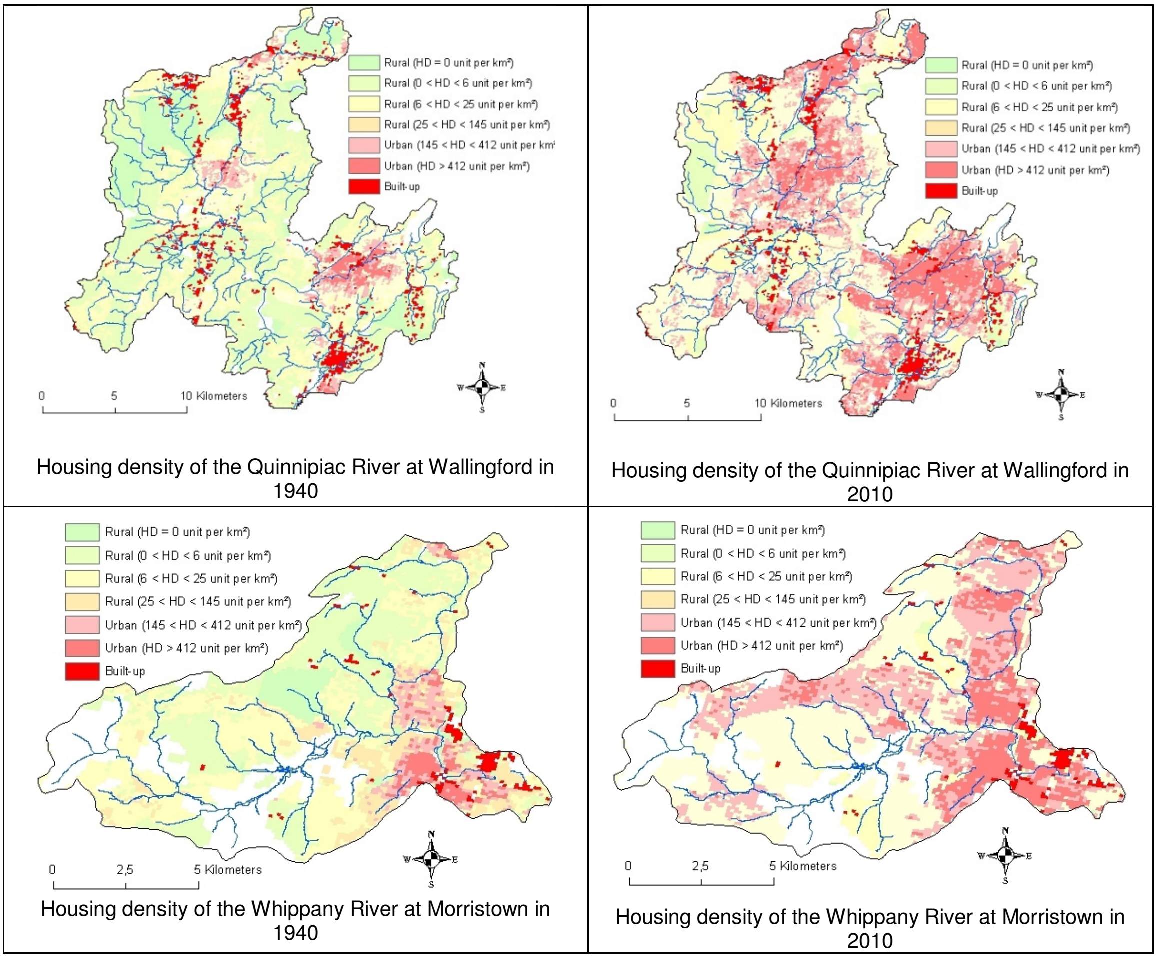


Figure 6: Two contrasted examples of catchment urbanization patterns. For a similar extent of urban area, the Quinnipiac River at Wallingford (top) presents more fragmented urban and nonurban areas than the Whippany River at Morristown (bottom) for which concentrated urban areas are located in the downstream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

4.2 Assessment of hydrological model calibration on the preurbanization period

Since the estimated flow changes are based on the model's ability to simulate the low-urbanization configuration of the catchments, we analyzed the calibration results of the hydrological model using four criteria. The first criterion is the Kling–Gupta efficiency criterion applied to root-squared streamflow, which is also used as the objective function during the optimization process of the model parameters. The three other criteria aimed at assessing the ability of the model to simulate the three streamflow characteristics (Q05, Q95 and QMA) calculated at the annual time-scale. Since the quantification of the hydrological impact of urbanization is based on the changes of the linear relationships between simulated and observed annual flow characteristics, we used the coefficients of determination (R^2) of these relationships.

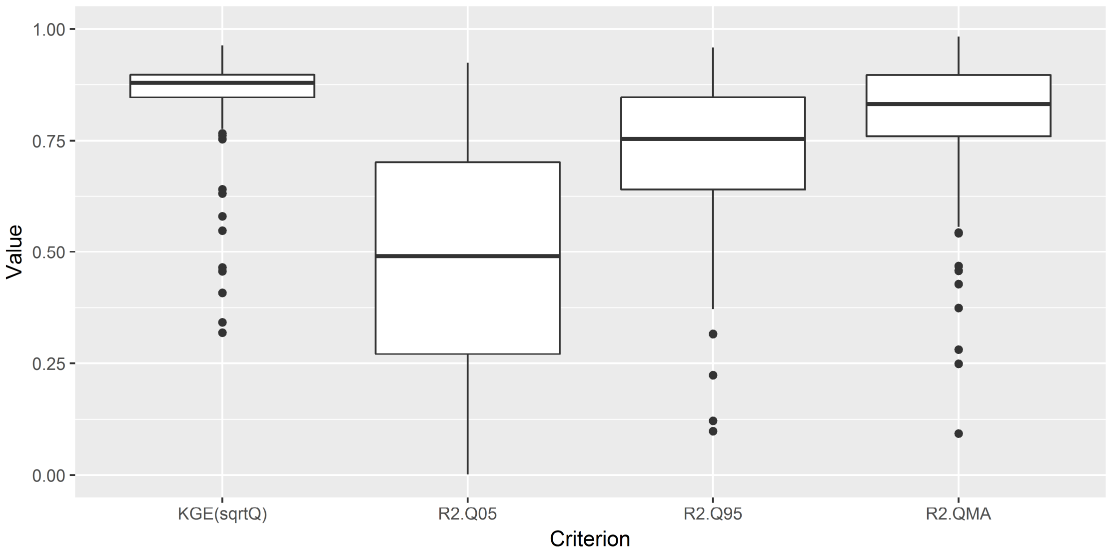


Figure 7: Model calibration efficiency over the 142 catchments studied. KGE(sqrtQ) is the Kling–Gupta efficiency criterion on root-squared transformed daily flow, R2.Q05 R2.Q95 and R2.QMA are the coefficients of determination of annual streamflow characteristics. The bottom and top of the boxes represent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

Figure 7 shows that daily streamflows are generally well simulated by the hydrological model (75% of KGE values above 0.84). Mean annual flow values are also well represented (75% of the R2.QMA above 0.76), while high- and low-flow percentiles are more difficult to reproduce (75% of the R2.Q95 above 0.64 and 75% of R2.Q05 above 0.27). One may argue that this results from the choice of the objective function, but using another objective function dedicated to low flows (e.g., KGE on log transformed flows) does not improve R2.Q05 since it mainly reduces the model's bias on low flows while only marginally improving the explained variance of the annual Q05 samples. For the sake of homogeneity of the model simulations, we kept a single objective function for simulating the three streamflow characteristics.

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

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

Figure 8: Results of the split sample test applied on the preurbanization period for the 142 studied catchments. KGE(sqrtQ) is the Kling–Gupta efficiency criterion on root-squared transformed daily flow. The bottom and top of the boxes represent the first and third quartiles and the whiskers represent the 1.5 interquartile range.

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

4.3 Analysis of the hydrological impacts of catchment imperviousness

Figure 9 provides an overview of the relative flow changes estimated over the 142 urban catchments considered, with respect to the total imperviousness increase over the flow record period. The impact of the imperviousness increase is clear for high and mean flow: an increase of TIA in most cases led to an increase of flow, which is, however, diverse over the catchment set. It is noteworthy that a relatively low TIA increase (less than around 10%) does not affect the flow characteristics considered. This result corroborates a number of previous studies pointing out a threshold value of imperviousness above which the hydrological impacts of urbanization become significant. The threshold value reported in the literature is generally between 5 (Booth and Jackson, 1997; Yang et al., 2010) and 20% (Brun and Band, 2000), and the 10% value obtained over the set of 142 catchments lies between these reported values.

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

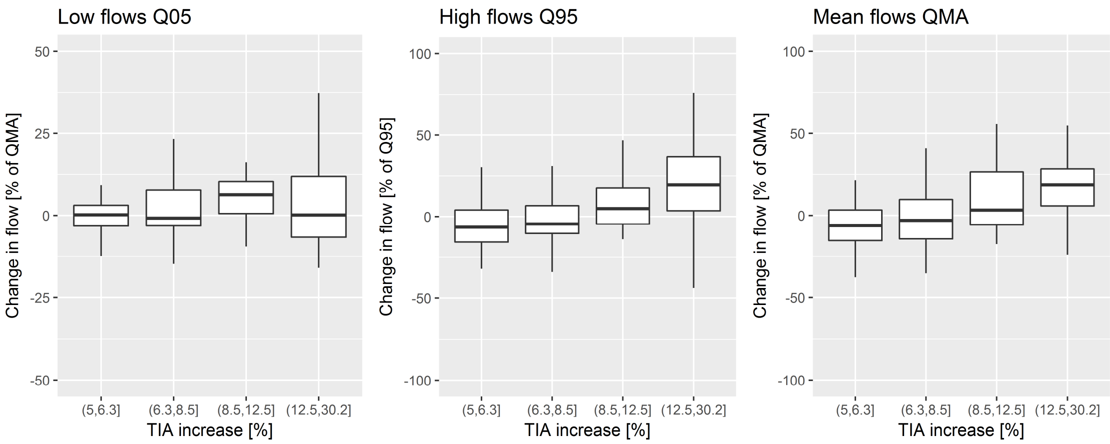


Figure 9: Relative changes for low (Q05) high (Q95) and mean (QMA) flow characteristics of the 142 catchments studied. Values are given for four TIA increase classes (5.0–6.3%, 6.3–8.5%, 8.5–12.5%, 12.5–30.2%), each class representing 35–36 catchments.

4.4 Influence of urban landscape patterns on hydrological impacts

To shed more light on the landscape patterns affecting most flow characteristics on the 142 catchments studied, this section relates the relative flow changes to the changes in urban landscape patterns. The explanatory variables tested that were used for the regression analysis were initially the absolute differences between the preurbanization and posturbanization periods of the metrics presented in Table 3. Since d.F.URB, d.TIA and d.IMP.100 presented a quite high cross correlation (above 0.95), only d.TIA is used hereafter. In addition, we used the density of major facilities WTFs extracted from the GAGE II database, for the year 2006.

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

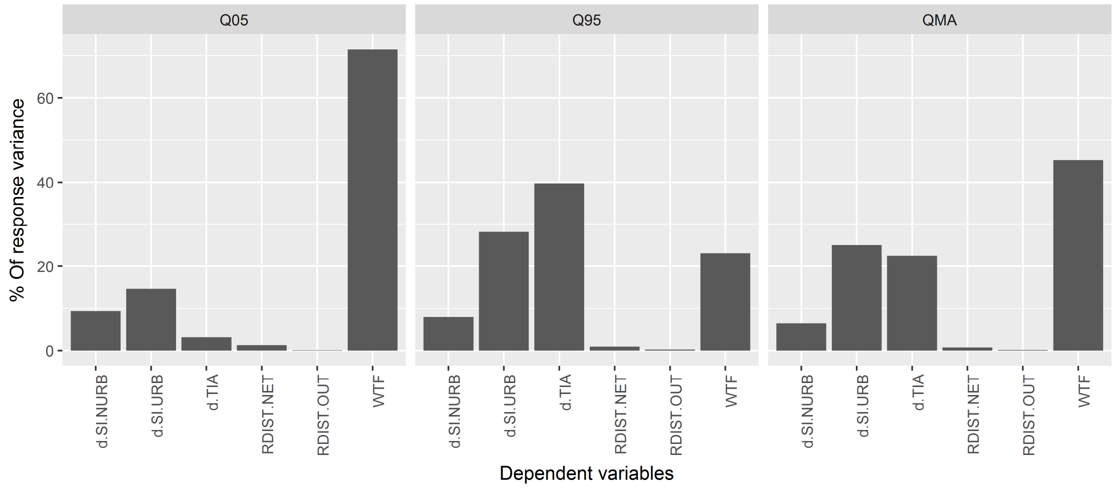


Figure 10: Hierarchical partitioning indicating the relative contribution (%) of each predictor to the variance explained by the linear models relating changes of flow characteristics and urbanization characteristics over the 142 urban catchments studied

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

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

	Independent variables (Student *t* 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

5 DISCUSSION AND CONCLUSION

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

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

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

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

Another issue addressed in this study is the role of the spatial organization of urban areas on the hydrological impact of urbanization. Over the landscape patterns analyzed in this study, mean catchment imperviousness (TIA) was indeed a key variable but other relevant metrics can help understand the variability of the impacts of urbanization. It was shown that the fragmentation of urban areas presents a negative relationship with flow changes, suggesting that the fragmentation of urban areas mitigates the impacts of urbanization. Interestingly, considering several landscape metrics better identifies the role of mean catchment imperviousness since a positive relationship was found for high and mean flow, whereas a negative one was found for low flows, suggesting that all things being equal, increased imperviousness decreases low flows and increases high flows.

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

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1/16 degree daily rainfall- and temperature-gridded data are available from ftp://ftp.hydro.washington.edu/pub/blivneh/CONUS/. Geospatial data and classifications for stream gages maintained by the U.S. Geological Survey (USGS) called Gages II are available from http://water.usgs.gov/lookup/getspatial?gagesII_Sept2011. National Land Cover Database (NLCD) data were obtained from the Multi-Resolution Land Characteristics (MRLC) Consortium website (available at http://www.mrlc.gov/about.php). Housing density data, based on David Theobald's work, were collected from the USGS. We would like to thank David Theobald and Thomas Over for their assistance with housing density data.

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FIGURE LEGENDS

TABLES