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Analysing the impact of urban areas patterns on the mean annual flow of 43 urbanized catchments

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Abstract. It is often argued that urban areas play a significant role in catchment hydrology, but previous studies reported disparate results of urbanization impacts on stream flow. This might stem either from the difficulty to quantify the historical flow changes attributed to urbanization only (and not climate variability) or from the inability to decipher what type of urban planning is more critical for flows. In this study, we applied a hydrological model on 43 urban catchments in the United States to quantify the flow changes attributable to urbanization. Then, we tried to relate these flow changes to the changes of urban/impervious areas of the catchments. We argue that these spatial changes of urban areas can be more precisely characterized by landscape metrics, which enable analysing the patterns of historical urban growth. Landscape metrics combine the richness (the number) and evenness (the spatial distribution) of patch types represented on the landscape. Urbanization patterns within the framework of patch analysis have been widely studied but, to our knowledge, previous research works had not linked them to catchments hydrological behaviours. Our results showed that the catchments with larger impervious areas and larger mean patch areas are likely to have larger increase of runoff yield.

1 Introduction

There exists a wide range of past researches showing various impacts of urbanization on catchment hydrologic response, but assessing quantitatively the impact of urbanization on hydrology remains a challenge. Depending on the catchments and the chosen approaches to detect changes in hydrological behaviour, some works suggested that urbanization increases peak flow (Rose and Peters, 2001; Booth et al., 2004; Poff et al., 2006; Rozell, 2010) while other studies found opposite results (Brandt, 2000; Poff et al., 2006). Urbanization was also identified as the main cause of quite different effects on baseflow (Konrad and Booth, 2005; Kauffman et al., 2009; Rozell, 2010). However, some studies found no significant relationship between urbanization and hydrologic response (Konrad and Booth, 2005; Rozell, 2010). The diverse results obtained to assessing the impacts of urbanization on hydrograph shape may be attributed to the difficulty in (i) determining quantitatively and even qualitatively the urban patterns critical for hydrological processes and (ii) separating the effects of urbanization from these related to climate variability. Several studies used total imperviousness as a metric of urban sprawl (Rose and Peters, 2001; Burns et al., 2005; Rozell, 2010). In this study, we used landscape metrics to quantify not only the amount but also the fragmentation of urban areas of various catchments. Besides, we aimed at quantifying the direct impact of urbanization on mean flow, following the decomposition method of the Budyko framework used in the study by Wang and Hejazi (2011).

2 Method

In this section, we present first the fundamentals of the Budyko framework used to quantify the flow changes due to urbanization. Second, the spatial metrics computed to characterizing the different spatial organizations of impervious areas are presented.

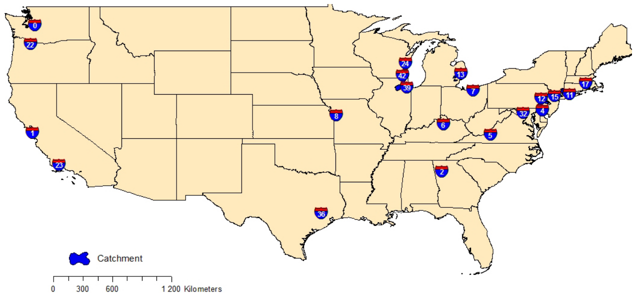

Figure 1. Location of the 43 studied catchments.

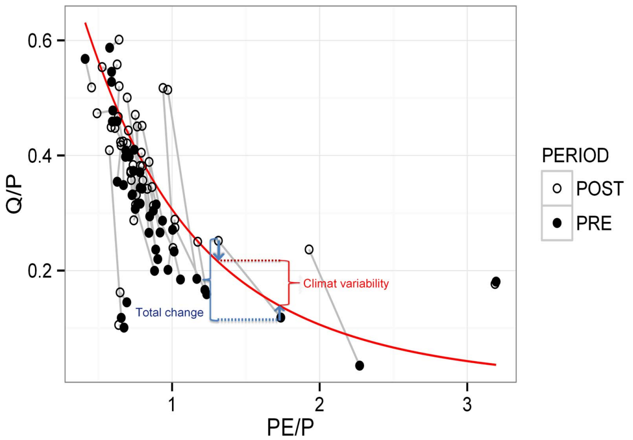

Figure 2. Budyko curve to quantify direct residual and climate impact on the flow change. Each site is described by Q, P and EP of pre and post-urbanization.

The catchment set includes 43 urban catchments in the United States for which streamflow data-series from the 30 to 70 years periods of record are available (Fig. 1). A simple conceptual hydrologic model based on the Budyko (1974) hypothesis and the decomposition method used in Wang and Hejazi (2011) were used to distinguish between the impacts of urbanization and these of climate variability on mean annual flow. In the following, we consider a catchment as urbanized if the percentage of urban area is greater than 10 %, based on the 2006 land-use (NLCD) map. The threshold of 10 % is rather arbitrary but commonly used in other studies (Schueler, 1994; Booth and Jackson, 1997). Besides, we also make the assumption that urbanized catchments were nearly not urbanized in the first 15 years of the record period, which was corroborated by a historical analysis of unit housing densities for each catchment. Thus, the decomposition method was applied on two different periods, the first and last 15 years of the record period and the 2006 urbanization were used to characteristics the urban patterns on each catchment. The runoff yields of $\frac{Q1}{P1}$ and $\frac{Q2}{P2}$ corresponding to the pre and post-urbanization periods were calculated. $Q1$, $Q2$, $P1$ and $P2$ are the averages of annual discharge and precipitation over the first and last periods respectively.

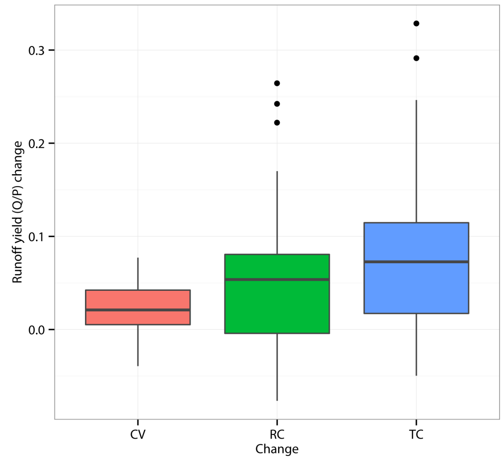

Figure 3. Boxplot of total change (TC), residual change (RC) and change due to climate variability (CV) for the 42 studied catchments. For each catchment, RC = TC-CV.

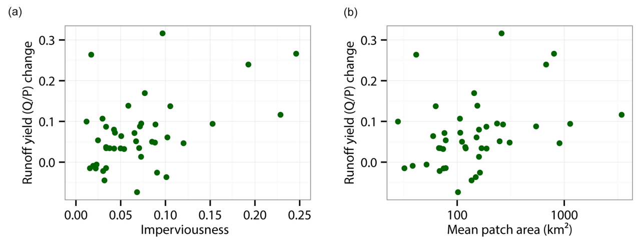

Figure 4. Residual runoff yield change versus the proportion of catchment area with more than 50 % imperviousness (left) and versus the mean patch area of catchment with more than 20 % imperviousness (right).

As described by Wang and Hejazi (2011) the catchment that moves along the Budyko-type curve had just been affected by climate variability. However, urbanization and climate variability can cause a vertical change from $\frac{Q1}{P1}$ to $\frac{Q2}{P2}$. The proposed decomposition method was applied to calculate the runoff yield change from pre-urbanization to post-urbanization periods, as the difference between the total observed change and the computed change attributable to climate variability. In the following, this residual flow change was compared to the catchment characteristics related to urbanization.

Landscape fragmentation focused on how urbanization breaks up larger land-use class (patch) into smaller ones and how the urban polygons (or patches) are concentrated in space. Therefore, the number and area of patches allow a quantitative description of urban landscape pattern (Weng, 2007). The landscape metrics widely used are: patch number (PN), mean patch area (MPA), patch density (PD) and edge density (ED). These metrics allow quantifying the fragmentation and structural complexity of each class of land-use (Jenerette and Wu, 2001; Herold et al., 2002). Urban land-

Table 1. Summary of variables used in this study.

Variable	Definition	Unit	Mean	Max	Min
Change	Urban change on the runoff yield (Q/P)	%	0.07	0.32	−0.04
FRAC22	Fraction of area with 20 to 49 % imperviousness	%	0.22	0.62	0.04
FRAC23	Fraction of area with 50 to 79 % imperviousness	%	0.07	0.25	0.01
FRAC24	Fraction of area with more than 80 % imperviousness	%	0.02	0.14	0.00
FRACTOT	Sum of all impervious fractions	%	0.31	0.88	0.06
Num.patches	Sum of urban polygons (patches) per catchments	–	687.60	6588.00	6.00
Patch.density	Density of urban patches	$\mathrm{n\,m^{-2}}$	0.002	0.005	0.0002
Edge.density	Density of urban class edge	$\mathrm{m\,m^{-2}}$	0.15	0.27	0.06
Mean.patch.area	Mean of urban class area	$\mathrm{m^2}$	282.75	3437.50	27.93

Table 2. Different p value of runoff yield change versus impervious area and landscape metrics.

	50 % imperviousness	> 80 % imperviousness	patch.density	edge.density	mean.patch.area
t value	3.115	−0.961	−0.553	−1.524	−1.898
p value	0.00282*	0.34043	0.58257	0.13284	0.0625*

* Significant linear relationships (p value < 0.1).

scape metrics were computed on the basis of land use data that were retrieved from the National Land Cover Database (NLCD) map of 2006. Besides, the NLCD land use map allowed us to compute classical urban metrics such as the impervious surface present over a given area with imperviousness of less than 20 %, between 20–49, 50–79 and 80–100 % (Fry et al., 2011). The catchments' characteristics used in this study are summarized in Table 1.

3 Results

Figure 2 shows the variation of the runoff yield (Q/P) between the pre-urbanization and the post-urbanization periods for each study catchment. Figure 3 indicated that the majority of catchments move along the Budyko-type curve but the amount of residual changes is greater than the amount of changes attributable to climate variability. This means that the change in runoff yield is mainly caused by other factors besides climate variability. Note interestingly that the residual change i.e. the change that is not due to climate might be either positive or negative but it is positive for a large majority of catchments (around 80 %, see Fig. 3). To shed more light on the causes of these changes of runoff yield on the urbanized catchments, we investigated the linear relationships between the changes and urban sprawl characteristics. Figure 4 provides examples of these relationships for the total imperviousness of the catchments and the mean patch areas, showing that catchments with high imperviousness and large mean patch areas exhibit generally greater increases of runoff yield change. Even if for these two characteristics the relationships are significant (Table 2), the coefficients of determination are pretty low, meaning that other factors should still be taken into account. Table 2 corroborates these findings since we found no significant relationships between other landscape metrics and runoff yield change (p value greater than 0.1).

4 Conclusions

This paper tried to (1) quantify the impact of urbanization on runoff yield (Q/P) on 43 catchments in the United States using a decomposition method and (2) relate this impact to urban sprawl characteristics. The Budyko framework is useful to distinguish between the effects of climate and these of urban change on streamflow characteristics (Jones et al., 2012). The flow change attributable to urban sprawl appeared heterogeneous in the United States catchments studied in this paper. The catchments with large impervious area and large mean patch areas are likely to have a larger increase of runoff yield. The other landscape metrics did not show statistically significant relationships with runoff yield changes. Further research is needed to investigate this issue by considering other hydrological behaviour characteristics such as baseflow, peak flow, flood flows for different return-periods. Besides, the landscape metrics characteristics used in this paper represented a snapshot of year 2006. For assessing rigorously the transient effect of urbanization on flow, it appears necessary to take into account the dynamics of these landscape metrics, i.e. by considering historical maps of land use.

Acknowledgements. This study utilizes data from several sources. Daily hydroclimatic data were collected from the model parameter estimation experiment (MOPEX) data set, available from the National Weather Service (available at http://www.nws.noaa.gov/oh/mopex/mo_datasets.htm). Daily streamflow data for the urbanized catchment and for some nonurbanized were collected from the USGS website (available at http://waterdata.usgs.gov/). Daily rainfall and temperature data were part of the stations from the Global Historical Climatology Network – Daily (GHCN – Daily), available from the NOAA, National Oceanic and Atmospheric Administration (http://doi.org/10.7289/V5D21VHZ). 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).

References

Booth, D. B. and Jackson, C. R.: Urbanization of aquatic systems: Degradation thresholds, stormwater detection and the limits of mitigation 1, J. Am. Water Resour. Assoc., 33, 1077–1090, 1997.

Booth, D. B., Karr, J. R., Schauman, S., Konrad, C. P., Morley, S. A., Larson, M. G., and Burges, S. J.: Reviving urban streams: Land use, hydrology, biology, and human behavior, J. Am. Water Resour. Assoc., 40, 1351–1364, 2004.

Brandt, S. A.: Classification of geomorphological effects downstream of dams, CATENA, 40, 375–401, 2000.

Budyko, M. I.: Climate and life, Academic New York, New York, 1974.

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J., and Kendall, C.: Effects of suburban development on runoff generation in the Croton River basin, New York, USA, J. Hydrol., 311, 266–281, 2005.

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J.: Completion of the 2006 National Land Cover Database for the Conterminous United States, PE&RS, 77, 858–864, 2011.

Herold, M., Scepan, J., and Clarke, K. C.: The use of remote sensing and landscape metrics to describe structures and changes in urban land uses, Environ. Plann. A, 34, 1443–1458, 2002.

Jenerette, G. D. and Wu, J.: Analysis and simulation of land-use change in the central Arizona – Phoenix region, USA, Landscape Ecol., 16, 611–626, 2001.

Jones, J. A., Creed, I. F., Hatcher, K. L., Warren, R. J., Adams, M. B., Benson, M. H., Boose, E., Brown, W. A., Campbell, J. L., Covich, A., Clow, D. W., Dahm, C. N., Elder, K., Ford, C. R., Grimm, N. B., Henshaw, D. L., Larson, K. L., Miles, E. S., Miles, K. M., Sebestyen, S. D., Spargo, A. T., Stone, A. B., Vose, J. M., and Williams, M. W.: Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites, Bioscience, 62, 390–404, 2012.

Kauffman, G., Belden, A., Vonck, K., and Homsey, A.: Link between Impervious Cover and Base Flow in the White Clay Creek Wild and Scenic Watershed in Delaware, J. Hydrol. Eng., 14, 324–334, 2009.

Konrad, C. P. and Booth, D. B.: Hydrologic changes in urban streams and their ecological significance, Am. Fish S. S., 47, 157–177, 2005.

Poff, N. L., Bledsoe, B. P., and Cuhaciyan, C. O.: Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems, Geomorphology, 79, 264–285, 2006.

Rose, S. and Peters, N. E.: Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach, Hydrol. Process., 15, 1441–1457, 2001.

Rozell, D. P. E.: Urbanization and Trends in Long Island Stream Base Flow, Seventeenth Annual Conference on Geology of Long Island and Metropolitan, New York, 12, 2010.

Schueler, T.: The importance of imperviousness, Watershed Protect. Techn., 3, 1–12, 1994.

Wang, D. and Hejazi, M.: Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States, Water Resour. Res., 47, 1–16, doi:10.1029/2010WR010283, 2011.

Weng, Y. C.: Spatiotemporal changes of landscape pattern in response to urbanization, Landscape Urban Plan., 81, 341–353, doi:10.1016/j.landurbplan.2007.01.009, 2007.