Quantifying the Spatial Configuration of Impervious Cover and its Effect on Runoff Generation in the Whiteoak Bayou Watershed in Texas

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Introduction
The capacity of a watershed to assimilate urbanization without changing its hydrologic response, and its relation to the spatial configuration of the developed areas was studied. Among the consequences of urbanization on the drainage of a watershed are the increase in runoff generation, the increase in event peak flows, and the decrease in base flows from subsurface water. The study was conducted in the Whiteoak Bayou watershed, over an analysis period from 1949 to 2010.

Study area and hydrologic data
The study area was the Whiteoak Bayou watershed of the Buffalo-San Jacinto cataloging unit 12040104, located in Harris County, Texas. The watershed is the 223-km² drainage area of the U.S. Geological Survey (USGS) flow gauging station 08074500. Because it is oriented perpendicular to the Houston outward growth rings (Figure 1), its development took place over a relatively long period. According to the area’s digital elevation model, the average slope of the watershed is 1.2 m/km; and, based on the rainfall data available for the area, its average annual precipitation depth is 1420 mm. The soils in the area are loams characterized by high clay content, moderate to very slow drainage and shallow water tables, and are classified under hydrologic soil group D.

Daily precipitation data for the analysis period was obtained from the National Climate Data Center (NCDC). The selected precipitation stations included COOPID 414317, 414321, 414323, 414327 and 414331 (Figure 1). Since the records for 414317 ended on March 31, 1954, and the one for 414331 began on April 1, 1954, and the two were located about one kilometer apart, both records were treated as a single continuous record. Annual precipitation totals are presented in Figure 2. Using the approach of Jennings and Jamigian (2002), changes in precipitation over time were analyzed by comparing the decade-averaged number of days with precipitation depth greater than given percentiles, and the decade-averaged depths for each of the percentiles. It was found that the number of days were not significantly different. However, the depths were statistically different with a level of significance of 0.05 when all events were included.

Development data
To compare development states, it is fundamental that the data be of consistent resolution and level of detail over time. Therefore, rather than using land use/cover data produced with the latest techniques, the development of a method for obtaining consistent data throughout the analysis period was preferred. Comprehensive and annually-updated land use maps and/or images – in either paper or digital format – were not available for the Whiteoak Bayou watershed for the 52-year analysis period. Even though it would have been ideal to utilize aerial photography and satellite imagery to estimate the evolution of urbanization, their use would have restricted the number of samples to only those years for which data were available. Moreover, most of the currently available land use/cover data have been produced with techniques and computer resources not existing fifty years ago, and depict relatively recent development states. For these reasons, parcel-level data collected by the Harris County Appraisal District (HCAD) were used to estimate development, both temporally and spatially. The data consisted of a digital map of the parcel boundaries (Figure 3) and a table of parcel characteristics. After processing the HCAD data, annual maps of the state of development in the watershed were obtained.

Spatial Metrics
Spatial metrics – also called landscape metrics – are measures of the spatial configuration of the different types of uses of the landscape and, although they were originally developed to study ecological processes, they are used here to assess the spatial configuration of the urban areas. As a watershed undergoes development, the spatial configuration of its urban areas changes (i.e., new developed patches are formed, others get larger, and others become connected). Because water flow is less hindered over hardcaps, interconnected developed patches are expected to increase the drainage capacity of the watershed. Thus, since spatial metrics measure some aspect of the number, size, distribution, connectivity and/or configuration of the developed patches, it is expected that they will provide valuable information to explain the watershed’s hydrologic response.

Once the development data was obtained, the 52 maps were converted into raster format and GIS applications were used to calculate spatial metrics of each of them (McGangil and Marks, 1995; Landscape Ecology Program 2005; Forest Landscape Ecology Lab, 2005). Out of the many existing metrics, particular attention was paid to those that reflected connectivity and compactness of the urban areas, with the understanding that those characteristics would bear an important effect on runoff conveyance. The following metrics were deemed the most influential on the flow regime: (1) developed area – sum of the areas of the developed patches; (2) number of patches - count of the developed patches; (3) slope of the number of patches - rate of change of the number of patches over time; and (4) edge length - sum of the lengths of the edge segments of the developed patches. Figures 4 and 5 show the evolution of these metrics over time. Note that the impervious area (Figure 4), which is known for having an important effect on runoff generation, has not been included because of its strong correlation with the developed area (i.e., linear regression coefficient of determination $r^2 = 0.997$). The number of patches, on the
other hand, was expected to capture the process of the connectivity and compactness of the urban areas. In a watershed that undergoes urbanization, a constant number of patches indicates the existing patches are being expanded; an increasing number of patches indicates new patches, separated from already-existing ones, are being developed, and a decreasing number of patches indicates the existing patches are being connected.

\[ R_s = 0.383 \times P_i - 193 \text{ for 1949-1959} \]
\[ R_s = 0.611 \times P_i - 415 \text{ for 1960-1972} \]
\[ R_s = 0.593 \times P_i + 2.05 \times D_A - 414 \text{ for 1973-2000} \]

with standard error of 54 mm. This result confirms the one just obtained for the two-interval case in that the annual runoff depth did not depend on the developed area before 1972.

The comparison of the observed values with the simulated ones when using precipitation depth and developed area as predictors, and one and three time intervals, is presented in Figure 6.

Figure 5: Evolution of the number of patches over time.

Analysis

The purpose of the analysis was to determine whether or not urbanization has caused a modification in the watershed's hydrologic conditions beyond its capacity to assimilate change, and to predict the annual runoff depth based on precipitation and the spatial metrics listed above. The standard error was used to evaluate the accuracy of the predicted values.

A multiple regression of the annual runoff based on the five selected independent variables resulted in

\[ R_s = 0.519 \times P_i - 3.03 \times D_A - 0.545 \times N\Pi - 2.28 \times S\Pi + 375 \times E_D - 363 \]

where \( P_i \) [mm] is the annual precipitation depth in year \( i \), \( D_A \) [km²] is the urban area in year \( i \), \( N\Pi \) is the number of developed patches in year \( i \), \( S\Pi \) [flyear] is the slope of the number of patches in year \( i \), and \( E_D \) [1000 km] is the edge length in year \( i \). In this multiple regression model, the standard error was 65 mm. However, the analysis of the sequential sum of squares of the regression indicated that the number of patches, the slope of the number of patches and the edge length did not explain a substantial amount of unique variance. Thus, a model with only the precipitation and developed area would be statistically equivalent and simpler. A regression equation based on these two variables was determined, which resulted in

\[ R_s = 0.539 \times P_i + 2.72 \times D_A - 435 \]

with standard error of 68 mm. In this case, both predictors were related to the independent variable with a 0.05 level of significance.

Changes in a watershed’s hydrologic conditions cause changes in its flow regime, because the runoff generation and conveyance processes adapt to the new environment. In general, the landscape can assimilate urbanization without modifying its hydrologic response within its capacity to renew, beyond which it adjusts to the new conditions. Thus, for changing hydrologic conditions, it should be expected that the relationship between the annual runoff depth, the precipitation depth and the developed area will be captured better by more than one regression equation. In other words, a new equation will be needed when the landscape is used beyond its capacity to renew. Therefore, additional regression models were developed after subdividing the 52-year timeline first into two and then into three intervals.

First, 49 regression models were developed for an equal number of three time interval combinations and, again, the one with the lowest standard error was selected. The 1949-1972 and 1973-2000 interval combination resulted in

\[ R_s = 0.458 \times P_i - 255 \text{ for 1949-1972} \]
\[ R_s = 0.593 \times P_i + 2.05 \times D_A - 255 \text{ for 1973-2000} \]

with standard error of 58 mm. Note that, in 1949-1972, changes in the developed area did not affect the response, suggesting they were assimilated by the landscape. On the contrary, in 1973-2000, after the watershed adapted to the new conditions, the developed area affected the predicted runoff depth.

Similarly, 1128 regression models were developed for an equal number of three time interval combinations and, again, the one with the lowest standard error was selected. The 1949-1969, 1960-1972 and 1973-2000 interval combination resulted in

\[ R_s = 0.383 \times P_i - 193 \text{ for 1949-1959} \]
\[ R_s = 0.611 \times P_i - 415 \text{ for 1960-1972} \]
\[ R_s = 0.593 \times P_i + 2.05 \times D_A - 414 \text{ for 1973-2000} \]

with standard error of 54 mm. This result confirms the one just obtained for the two-interval case in that the annual runoff depth did not depend on the developed area before 1972.

The comparison of the observed values with the simulated ones when using precipitation depth and developed area as predictors, and one and three time intervals, is presented in Figure 6.

Figure 6: Comparison of observed and predicted runoff depths based on precipitation depth and developed area.

Likewise, observed and simulated annual runoff depths with respect to time are plotted in Figure 7.

Figure 7: Comparison of observed and simulated runoff depths over time (in mm).

In a watershed that undergoes urbanization, the sum of the areas of the developed patches is expected to increase somewhat steadily over time; while the number of developed patches is expected to increase up to a maximum value and then decrease. Despite both metrics describe the process of urbanization, the peak value in the number of patches can be interpreted as an indicator of landscape saturation, beyond which further development connects existing patches, rather than adding new ones, and makes the urban areas more compact. This so-called landscape saturation, however, is not captured by the sum of the areas of the developed patches. It is expected that, the lower the number of patches for a given developed area, the more connected the developed areas are, the greater the chances runoff will flow over hardscape, and the less the chances it will infiltrate in undeveloped areas.

The break point in the regression equations in years 1972-1973 coincides with the early 1970s, on which, according to the development data, urbanization consisted more of connecting already existing developed patches than of creating new ones. In terms of the spatial metrics, the process of connecting the developed patches is reflected by the number of patches, which reached its maximum value in 1972. Figure 8 shows the state of urbanization in 1949, 1972 and 2000.

Figure 8: Development state in 1949, 1972 and 2000. Black refers to developed patches and gray to undeveloped patches. On average, developed patches are 40% impervious.

Conclusions

This paper discusses how urbanization affects the hydrologic conditions of a watershed when it reaches a level beyond the landscape’s capacity to assimilate change. Likewise, it presents how the number of developed patches (i.e., a metric of the spatial configuration of the urban areas) can help explain why the urbanization process caused flow regime changes.

Based on regression models, it was observed that the annual runoff depth in the watershed depended predominantly on the annual precipitation depth and the developed area. These regression models also showed that, before 1972, the developed area did not explain a substantial amount of unique variance, and that, statistically, the runoff depended exclusively on the precipitation. Starting on 1973, however, the runoff increased linearly with the developed area. It was concluded that this independence of the runoff depth from the developed area before 1972 was explained by the capacity of the watershed to assimilate urbanization without changing its flow regime; while, after 1973, the watershed’s capacity to assimilate urbanization had been exceeded. After analyzing the development data, it was also found that, starting in the early 1970s, urbanization in the watershed consisted more of connecting already developed areas than of creating new ones, which increases the watershed’s conveyance capacity and explains the change in its response. The spatial metric number of developed patches captured this urbanization pattern. The number of patches reached a maximum value in 1972, which implies that, before that year, urbanization focused predominantly on developing new patches, while after 1972, development focused on connecting existing patches. It was found that, after 1972, on average, urbanization had almost doubled the annual runoff depth.

Finally, because different cities undergo different development models, the extrapolation of these results to other watersheds with denser or less dense urbanization patterns should be done carefully. Further research on other urban watersheds with different urbanization models appears to be necessary.

References


