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Urbanization and Runoff in the Whiteoak Bayou Watershed

Francisco Olivera
Department of Civil Engineering
Texas A&M University
3136 TAMU
College Station, TX 77843
Email: <folivera@civil.tamu.edu>

Buren B. DeFee
School of Forest Resources
University of Arkansas at Monticello
110 University Court
Monticello, Arkansas 71656
Email: <defee@uamont.edu>

In this paper, 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 2000.

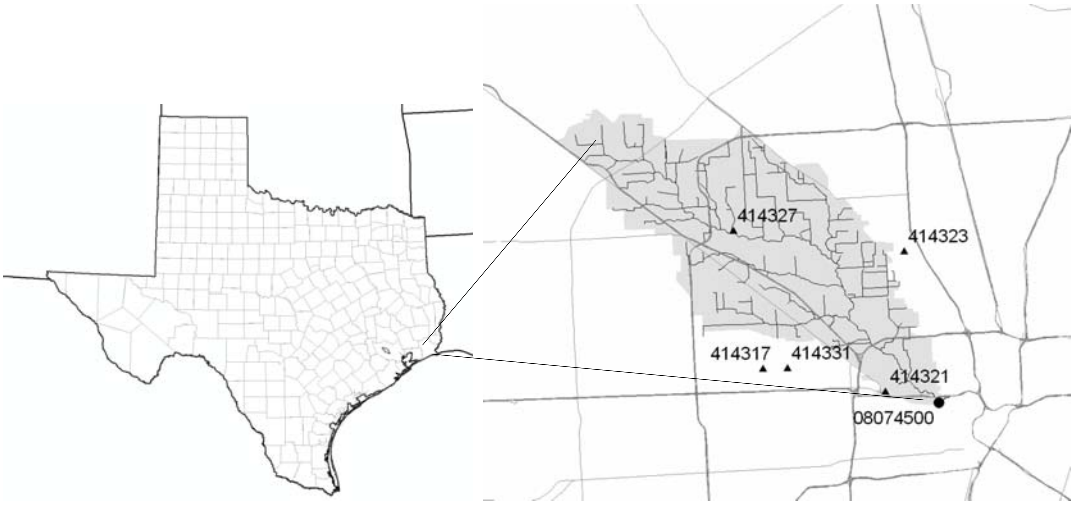

Figure 1: The Whiteoak Bayou watershed is located in Texas, northwest of downtown Houston

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-km^2 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 (USGS, 2005a), the average slope of the watershed is 1.2 m/km; and, based on the rainfall data available for the area (NCDC, 2005), 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 (NRCS, 2005).

Daily precipitation data for the analysis period was obtained from the National Climate Data Center (NCDC, 2005). 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 Jarnigan (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.

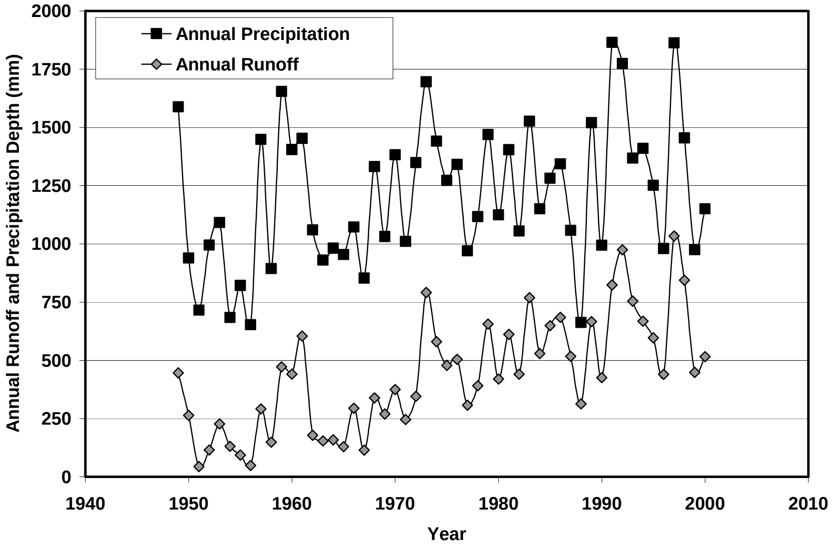

Figure 2: Runoff and precipitation depth over time

Daily mean flows at USGS flow gauging station number 08074500 were obtained from the National Water Information System (NWIS) (USGS, 2005b). The selected gage has collected flow data continuously at the mouth of Whiteoak Bayou since June 1, 1936. Annual runoff depth totals are presented in Figure 2. Changes in flow over time were studied with the same method used for the analysis of changes in precipitation over time. It was found that the decade mean flows were statistically different with a level of significance of 0.05.

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 the 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 and a table of parcel characteristics. After processing the HCAD data, annual maps of the state of development in the watershed were obtained.

For quality control purposes, development data was contrasted with on-site observations, not with the intention of correcting the data (which would have made it inconsistent over time), but of assessing the applicability of the method for obtaining development data. No instances of disagreement between the year - 2000 data and the observations were found, other than those caused by construction that took place after 2000. It was not possible to conduct an equivalent quality control for the development data of previous years.

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 hardscape, 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 (McGarigal and Marks, 1995; Landscape Ecology Program 2005; Forest Landscape Ecology Lab, 2005) were used to calculate spatial metrics of each of them. 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 3 and 4 show the evolution of these metrics over time. Note that the *impervious area* (i.e., the sum of the impervious areas of the developed patches) (Figure 3), 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 progress 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.

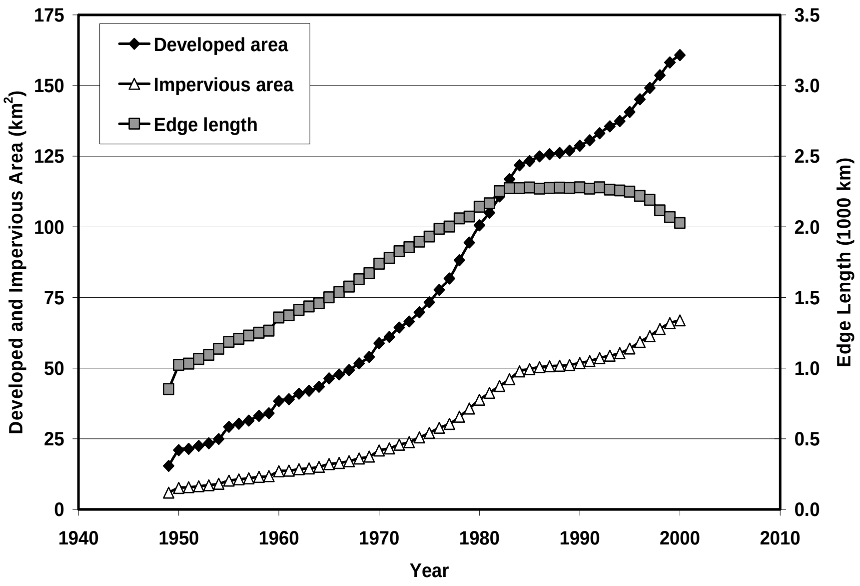

Figure 3: Evolution of the developed area, impervious area and edge length over time

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 (Figure 4). The standard error was used to evaluate the accuracy of the predicted values.

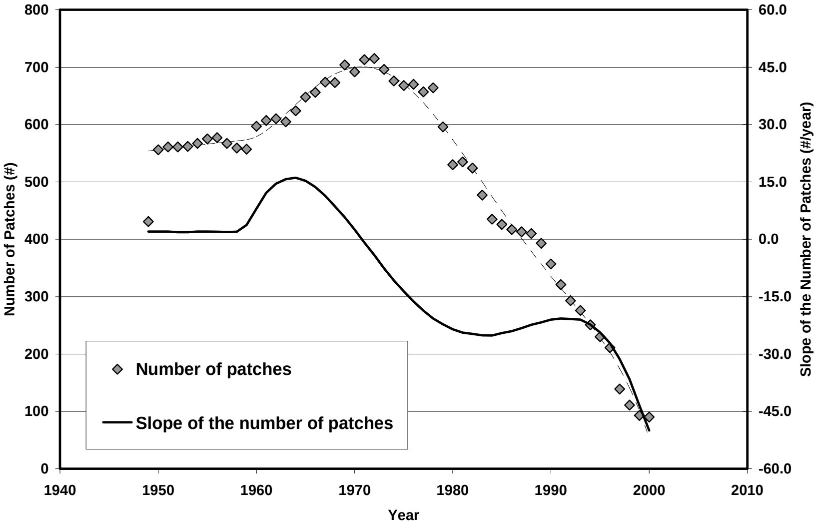

Figure 4: Evolution of the number of patches over time

A multiple regression of the annual runoff based on the five selected independent variables resulted in $R_{S-i} = 0.519\,P_i - 3.03\,DA_i - 0.545\,NP_i - 2.28\,SNP_i + 375\,EL_i - 363$, where P_i [mm] is the annual precipitation depth in year i, DA_i [km^2] is the urban area in year i, NP_i [#] is the number of developed patches in year i, SNP_i [#/year] is the slope of the number of patches in year i, and EL_i [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 $R_{S-i} = 0.539\,P_i + 2.72\,DA_i - 435$ 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 two time interval combinations, and the one with the lowest standard error was selected. The 1949-1972 and 1973-2000 interval combination resulted in $R_{S-i} = 0.458\,P_i - 255$ for 1949-1972 and $R_{S-i} = 0.593\,P_i + 2.05\,DA_i - 414$ 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 1949-1959, 1960-1972 and 1973-2000 interval combination resulted in $R_{S-i} = 0.383\,P_i - 193$ for 1949-1959, $R_{S-i} = 0.611\,P_i - 415$ for 1960-1972, and $R_{S-i} = 0.593\,P_i + 2.05\,DA_i - 414$ 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.

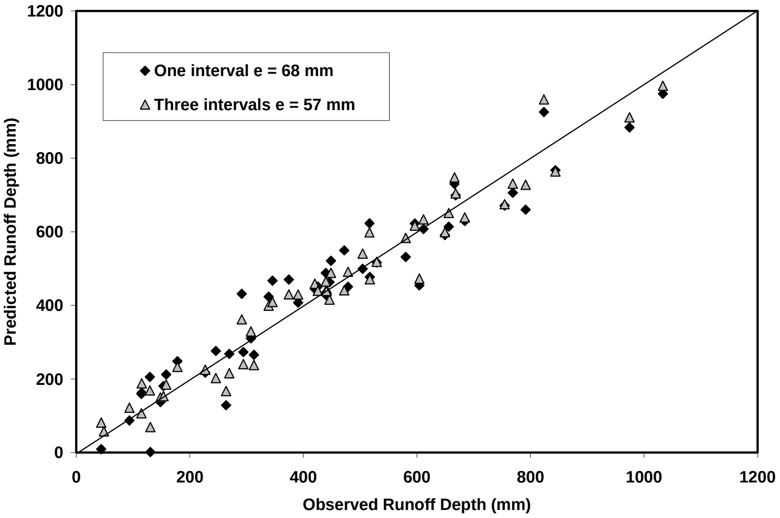

Figure 5: Comparison of observed and predicted runoff depths based on precipitation depth and developed area

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 5. Likewise, observed and simulated runoff depths with respect to time are plotted in Figure 6. Figure 7, additionally, shows the observed and simulated responses, but without accounting for the adjustment in 1972 because of urbanization. In other words, it shows what the annual runoff depth would have been if it had not been modified by urbanization. Note that from 1973 to 2000 the annual runoff depth ranged from 310 mm to 1030 mm with an average of 600 mm; while, had the before-1973 conditions been kept and equation $R_{S-i} = 0.458\,P_i - 255$ applied, it would have ranged from 50 mm to 600 mm with an average of 340 mm. That is, on average, urbanization has almost doubled the annual runoff depth. It is important to stress, however, that doubling the annual runoff volume does not imply doubling each individual storm runoff volume, because most of the increment takes place during small events.

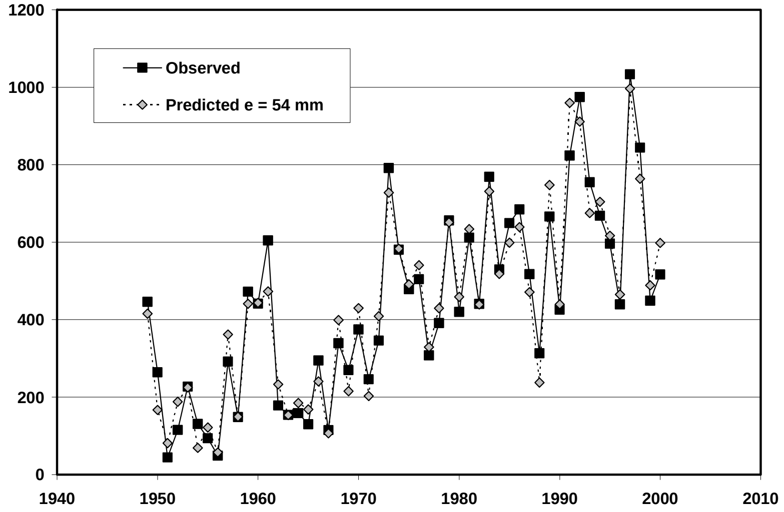

Figure 6: Comparison of observed and predicted runoff depths over time

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.

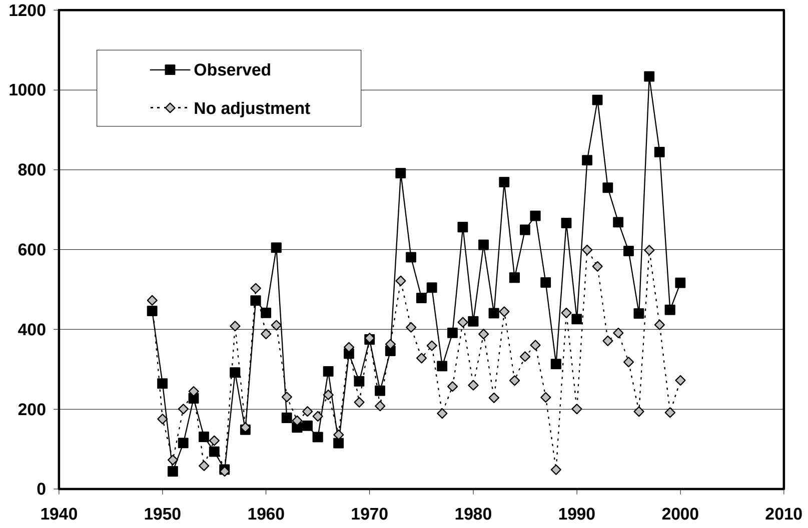

Figure 7: Comparison of observed and predicted runoff depths over time without accounting for the hydrologic response adjustment in 1972

The break point in the regression equations in years 1972-1973 coincides with the early 1970s in 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: From left to right, 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 has 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.

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