Alterations to Natural Catchments due to Urbanization, a Morphologic Approach

Approche morphologique: modifications des bassins naturels dues à l'urbanisation

Jorge Gironás[1], Hervé Andrieu[2], Larry Roesner[3]

[1] Colorado State University, Department of Civil Engineering
Fort Collins, Colorado, 80523, USA.
jorge.gironas@colostate.edu

[2] Laboratoire Central des Ponts et Chaussées, division Eau et Environnement
Route de Bouaye BP 4129, 44341 Bouguenais cedex, France.
herve.andrieu@lcpc.fr

[3] Colorado State University, Department of Civil Engineering
Fort Collins, Colorado, 80523, USA.
larry.roesner@colostate.edu

RESUME

La comparaison entre les bassins versants urbains et les bassins versants naturels est le plus souvent abordée en mettant en avant l'influence de l'urbanisation sur l'infiltration ou la capacité de rétention du bassin versant. Cette comparaison peut être complétée en prenant également en compte les propriétés morphologiques et topologiques des bassins versants urbains, et la façon dont ces propriétés diffèrent de celles des bassins versants naturels. Cette communication traite donc de la caractérisation des bassins versants urbains au moyen d'une approche morphologique et topologique, et illustre les modifications que l'urbanisation apporte aux bassins versants naturels selon les critères de cette approche. Les résultats obtenus montrent que l'urbanisation altère sévèrement la morphologie des réseaux de drainage. Cet effet doit être pris en compte pour mieux comprendre la réponse hydrologique des zones urbanisées, en améliorer la modélisation et la planification et conception des systèmes de drainage urbains. Une discussion des avantages de cette approche conclut la communication.

ABSTRACT

Currently, the characterization of urban watersheds and their differences with respect to natural basins is based on the description of the infiltration and storage capacity and how these processes are modified once urbanization takes place. This characterization can be improved by also considering morphological and topological features of urban catchments and how they differ from the ones observed in natural watersheds. This paper discusses the study and the morphologic and topologic characterization of urban watersheds, and exemplifies the changes caused to natural catchments by urban development using this approach. Results obtained here show that there are major alterations to the morphology of drainage systems. They need to be taken into account to better understand the hydrologic response of anthropogenic basins, and to improve the modeling, planning and design of sub-urban and urban areas. Finally, a series of advantages of this approach are also discussed.

KEYWORDS

Drainage system, Effects of urbanization, Morphology, Scaling, Urban hydrology.

1 INTRODUCTION

Urbanization represents a modification of the natural conditions of a watershed. The main features of natural areas modified by urbanization and directly related to the quantity and rate of stormwater runoff are (Akan and Houghtalen, 2003): the natural surface detention, the infiltration characteristics and the drainage pattern formed by natural flow paths.

Until now, the aspects related both to the surface detention and infiltration are used to describe urban catchments. Concepts such us the total impervious area (TIA), the effective impervious area (EIA) or the land-use are utilized to depict how much natural basins are modified, to determine impacts caused by the development of these natural areas, and to characterize urbanization from an hydrologic and environmental point of view. Additionally, approaches used in stormwater drainage and control practices look for the replication of storage and infiltration characteristics once urbanization takes place. However, a characterization of urban areas that does not take into account morphological and topological features is incomplete. Up to this point, the quantification of changes to the structure of the drainage patterns caused by urbanization has not been developed in detail, and no formal methodologies are used to characterize urban catchments from a morphological and topological point of view. Finally, no special measures in stormawater management are being taken in order to imitate natural conditions of the drainage pattern.

This paper discusses and illustrates the importance of a comprehensive description of urban catchments from a morphological point of view. This approach can give us innovative tools to evaluate the impacts of urbanization, and moreover, to better understand the hydrologic response of urban basins, given the strong relationship between the morphology of a catchment and its hydrologic response.

2 THE STUDY OF MORPHOLOGIC AND TOPOLOGIC FEATURES IN NATURAL AND URBAN CATCHMENTS

2.1 Natural catchments

Hydrologists have always tried to relate morphologic or topographic features of the basin to its response (Bras, 1990). The hydrologic response of a catchment is primarily influenced by the morphological characteristics such as the shape, size, land use distribution of the catchment and the geometry of the drainage network. Eagleson (1970) summarized the beginning of the study of basin morphology and characterization of channel networks: “The combined effects of climate and geology on catchment topography yield an erosional pattern which is characterized by a network of channels and streams. Beginning with the early work of Horton, many supposedly independent and fundamental laws governing the relative structure of these patterns have been proposed, and a wealth of geometric parameters has been devised to describe them in absolute terms”. From these initial years, the most important contributions are the classification scheme of channel networks proposed by Horton and Strahler, the empirical laws characterizing the geometry of drainage networks proposed by Horton and Schumm, their confirmation and application by many later studies, and the introduction of models to describe drainage networks.

Since Rodríguez-Iturbe and Valdés (1979) and Gupta *et al.* (1980) developed the geomorphologic instantaneous unit hydrograph (GIUH), which corresponds to an explicit connection between the hydrologic response and the geomorphology of a catchment, research in the field of fluvial geomorphology has increased enormously. Several topics have been studied, including (Bras, 1990): network growth, landscape morphology and patterns, channel network organization, channel geometry studies, landscape evolution, and the relationship between hydrologic response and fluvial geomorphology. Currently, several methods to characterize morphologic and topologic features and properties of natural basins are available. These methods allow the quantification of these features through morphologic or topologic indexes and metrics, power functions and scaling laws. Extensive research has proven that comparable characteristics and scaling properties can be observed at different locations with diverse geological conditions, climate, vegetation and soil, with scaling parameters and the morphologic descriptors being very similar for all these locations (Rigon *et al*., 1996; Dodds and Rothmann, 1999). These similarities respond to general operating criteria that control the manner in which river basins perform.

Because of this extensive research, we have a much better understanding of how processes that form drainage networks work, how morphological features in natural basins can be quantified, and how fundamental laws describe these features. This knowledge gives us new research opportunities oriented to better understand the modifications caused by urbanization. A study of these changes from a morphological point of view may give us a useful set of tools to evaluate how natural areas are changing as they are urbanized, how these modifications affect the hydrologic response, and how urban drainage criteria can be improved.

2.2 Semi-urban and urban catchments

Few studies have been conducted to describe the morphology and topology of drainage networks in urban areas, and the idea of relating the shape of the hydrologic response (*i.e.,* unit hydrograph) to the morphological characteristics of urban areas has been examined even less, with the work of Rodriguez *et al*. (2003, 2005) being one of the first attempts. Moreover, changes in the global morphology and topology of natural basins once they are urbanized have not been explored in detail. Finally, the task of transferring new knowledge from these studies into improvements in planning and design criteria for urbanization and drainage systems remains to be solved.

Significant changes to the morphology of basins occur once they are urbanized. Simply stated, new impervious surfaces require additional water to be conducted out of the catchment, so new transport elements become part of the drainage system and old ones are modified. The first works that studied these changes started in the 70's. Graf (1977) pointed out that the typical suburban channel network may have spatial characteristics that are substantially different from totally natural networks and that have profound effects on streamflow attributes. The author evaluated how stream networks change in suburbanizing areas and how the characteristics of stream discharge are affected. Finally, he concluded that changes in the characteristics of channel networks should be considered in addition to changes in areas of impervious surfaces when the hydrologic impact of suburbanization is assessed. Many authors (Graf, 1977; Bannister, 1979; Hayden, 1981; Phillips, 1985, Smith *et al*., 2002) have observed that urbanization leads to an increase of the overall drainage densities, with a greater number of internal links (gutters, streets, etc.) that contribute to increased flood velocity and the hydraulic efficiency of the drainage system. Bannister (1979) determined that road networks truncate natural drainage channels, forcing the coalescence of smaller order basins, thereby increasing downcutting and runoff in channels whose natural erosional development would have been much less. Hayden (1981) evaluated the effects of road drainage on the geomorphic equilibrium of small stream basins using Horton's law of stream length. He then analyzed the effects of different types of road networks using a hypothetical stream basin and eight hypothetical road networks, suggesting a method to predict the location and extent of disequilibrium in a stream basin system as a result of road drainage.

All this work has used concepts from the classical geomorphology developed for natural watersheds, but a few recent works have considered the new knowledge originated after Rodríguez-Iturbe and Valdés (1979), and have studied morphological and topological features in urban areas as well as the modifications of natural basins. Smith *et al*. (2002) derived and compared the width function of an urban watershed based on their stormwater drainage system and the equivalent natural drainage system. Lhomme *et al*. (2004) simulated urban stormwater runoff using a GIS-based geomorphological routing in which they had to modify the Digital Elevation Model (DEM) to represent the components of the drainage network of the study area. Rodriguez *et al*. (2003, 2005), using the GIUH approach, derived a unit hydrograph for urban areas based on the analysis of urban databanks allowing an explicit description of the runoff production areas and their downstream flow channels once simplifications in the routing process were assumed. Additionally, Rodriguez *et al*. (2005) computed a unit hydrograph of two urban watersheds based on the catchment order Ω according to the Strahler ordering scheme. In this study it is considered that house-street connections constitute streams of order one. Finally, Smith *et al*. (2005) used the GIUH to evaluate the hydrologic response of an urbanizing watershed.

3 RESULTS

To illustrate how morphological properties and features can change with urbanization, some preliminary results from a study of a totally urbanized catchment located in the city of Raleigh, North Carolina, USA, are presented. This catchment has an area of 40.1 Ha, and a 10 m resolution DEM was used in computing the results. An analysis of the width function, *W(x)*, for pre- and post-development conditions, can illustrate the magnitude and characteristics of these modifications. The width function corresponds to the number of links in the network at a flow distance *x* from the outlet (Rodríguez-Iturbe and Rinaldo, 1997). It is an important morphological characteristic since it gives a good idea of the hydrologic response, and under certain conditions, there is a strong relationship between this function and the instantaneous unit hydrograph in natural catchments. Figure 1a presents a comparison of *W(x)* for the urban area and the natural area previously existent there. The width function is computed by directly counting the available links. In the urban basin, all the transport elements that conform drainage paths are considered as links, including gutters, pipes and a natural channel that drains the urban area. Based on observation, the beginning of a link is given by a critical area of two normal residential parcels. Two assumptions were considered in calculating *W(x)* for the natural catchment, (1) the topography given by the DEM corresponds to the natural topography, and (2) a critical area of 3000 m^2 to determine the headwater of a stream. Smith *et al.* (2002) used this methodology and named the drainage network obtained for the natural catchment as the "equivalent natural network". Figure 1b presents the same functions normalized by the total number of links contributing to the outlet in each case, 313 and 142 for the developed and undeveloped case respectively. Figures 1a and 1b show a clear increase in the number of channels and also changes in the distribution of these channels over the total area. These modifications in the drainage network are important because of the already mentioned strong relationship between the morphology of the drainage network and the hydrologic response of the basin. By studying how this function changes depending on the urbanization criteria or the design of the drainage system, a better planning can eventually be achieved in which the natural conditions and hydrologic response are preserved.

A second way to compare the pre- and post-developed cases is computing the scaling function of contributing areas. This function is computed by finding the probability distribution for the area *A* contributing to a randomly chosen point in the drainage network (Rodríguez-Iturbe and Rinaldo, 1997). It has been observed in nature that this distribution follows the power law $P[A > a] \alpha a^{-\beta}$, where β has been found to be approximately in the range between 0.41 and 0.45 in a wide variety of basins. This scaling function was computed for the same urban catchment previously described. For the pre-development case, the function was calculated by computing the area drained by every single pixel using the existent DEM, which is assumed to represent the natural topography. The result is presented in Figure 2a. A similar process can be done to compute a comparable result for the post-development case. However, to do this, the existent DEM has to be modified since drainage flow paths do not only depend on the topography but also on the presence of artificial elements within the basin. Because of this, there are preferential drainage ways in urban drainage systems that cannot be obtained directly from the DEM's using the traditional tools. An initial approximation to find this curve is to compute the area draining at several different points within the basin and compute the distribution function. Figure 2b shows the scaling function of contributing areas for the developed area.

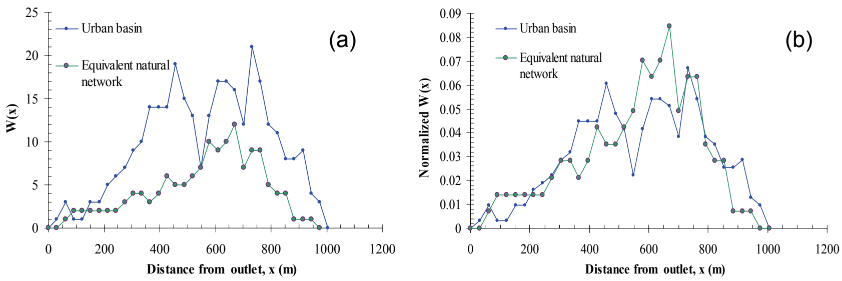

Figure 1. Width functions for pre- and post-development conditions: (a) Comparison of the width functions, (b) Comparison of the normalized width functions.

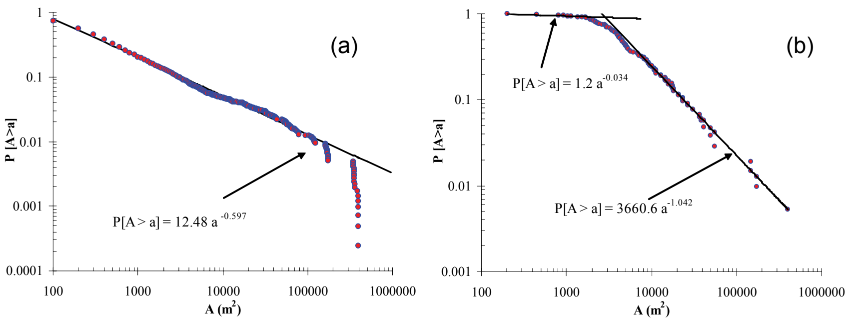

Figure 2. P [A > a] versus area: (a) pre-development conditions, (b) post-development conditions.

The results show power relationships in both cases, however, two clear differences between the distribution are observed: (1) there is a break point for an area of 2000 – 3000 m^2 that defines two power relationships in the developed case; (2) the exponent values of the power relationships are different to the one describing the natural conditions.

Before the break, the probability function is represented as a power law with a very small exponent β, equal to 0.0342. This value implies an almost constant probability of exceedance at small scales, which is explained by the high drainage density at these scales. This is mainly due to the presence of street and residential parcels all over the basin and the observation, based on the impervious level, that a relative small area is necessary to define the beginning of a channel (or flow in a gutter). These results confirm what was founded by Graf (1977) who reported an increase of the surface drainage systems caused by streets and other artificial channels. The break and the higher slope (β=1.042) for the second section of the function show how at larger scales, the branch structure of the drainage network in the developed case becomes poor. These observations show how at small spatial scales we replace hillslopes with several transport elements when we urbanize, but at larger scales, we replace the organized natural drainage with a simpler one, which is based on few main transport elements or pipes. These changes in the drainage structure are also illustrated by the modifications observed in the stream length exceedance probability once the area is developed (See Figure 3). It has been observed in nature that this distribution follows the power law $P[L > l]\ \alpha\ l^{-D}$, where D has been found to be approximately 2. This function corresponds to the probability distribution for the Strahler streams lengths L, with a stream being considered in the urban case as the union of links with the same Horton-Strahler order, regardless if they are streets, pipes or natural channels. Figure 3b shows that in the developed case, there are more short streams with similar lengths all over the basin (mostly streets) than in the undeveloped case. This supports the observation that at small scales there is an increase of drainage density caused by urbanization. However, the well-branched structure is lost at bigger scales, where streams in the downstream direction do not change their order as frequently as in natural drainage networks. This observation can be confirmed by noticing the length of the highest order stream in cases (a) and (b), 200 m and 318 m respectively. This stream in case (b) is around 50% longer than the one in case (a), which suggests that in urban areas, and because of the high drainage density at small scales, the highest stream order is reached very close to the beginning of the streams of order one. Then, because of the poor branched structure, changes in the stream order are not noticed since no other important branches connect to the main stream.

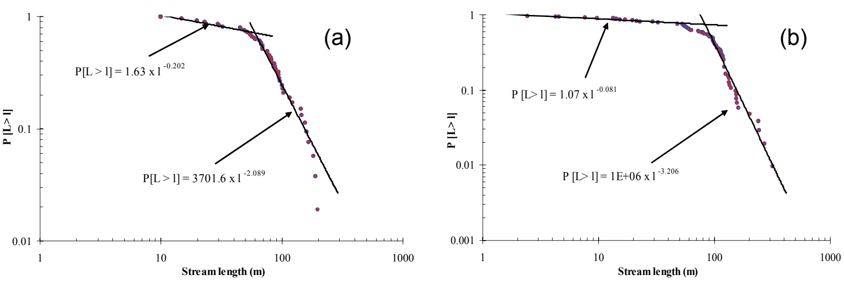

Figure 3. P [L > l] versus area for post-development conditions: (a) pre-development conditions, (b) post-development conditions.

Studies like this can be done at larger scales where the natural structure of the drainage network becomes relevant again, and where changes in the discharges, but not in the configuration of the hydrographic network, are observed. All of this tells us how dramatic modifications to the drainage network are and how these changes should be studied differently depending on the spatial scale involved.

4 REMARKS AND CONCLUSIONS

The application of a morphological approach by using tools of the types shown here, has the following advantages and possibilities to be explored yet:

- Accurate hydrological data are not critically necessary. These data are very difficult to collect, especially in sub-urban and urban areas. Additionally, morphological properties are observed for a wide range of conditions, locations and climates. This consistency gives a useful reference against which modifications due to urbanization can be evaluated and computed.
- The approach gives a better understanding of urban morphology and its effects in the hydrologic response of the basin. Many of the models currently used to simulate the rainfall-runoff process in urban areas characterize urban developments based almost solely on the imperviousness. However, it does not seem reasonable to use this parameter as the only one in comparing two urban or sub-urbanized areas, or to evaluate how much a natural area has changed. Recent studies linking watershed planning, stormwater and water quality degradation are showing that other indicators can and should be used to determine watershed impacts (Brabec *et al*., 2002). The complex set of actions and changes that takes place as natural areas are urbanized have to be depicted by other indicators -and thresholds values for them- that describe the catchments features not well characterized by the impervious surface. Therefore, better perspectives to enhance the conceptualization of urban catchments and to improve the planning and design of sub-urban and urban areas from a hydrologic and environmental point of view are possible.
- Using a morphological approach, it may be possible to develop innovative tools to qualify and quantify the influence of sub-urbanization, or partially urbanized basins, on its hydrologic regime. These types of catchments straddle the line between classical hydrology and urban hydrology. The influence of urbanization on watersheds as is classically described is valid when a small natural catchment becomes fully urbanized. However, the effects of a sub-urbanization in the hydrological regime of a basin are less evident. In effect, catchments are partially affected by changes that often last decades and are not easily detected in flows, which display a strong natural variability. These limitations could eventually be overcome with a morphological approach, which can also be used to develop methods to describe the location and extent of the main disequilibrium points in the drainage network.
- The approach allows the simultaneous evaluation of urbanization and its effects over a wide range of spatial scales. Therefore, methodologies that consider the effects of small developments at larger scales (big cities or partially urbanized areas) can be developed and introduced in design criteria for drainage systems.
- The morphological description can give new perspectives to study the so called Low-impact development approach (LID) (Prince George’s County, 1999) or other environmentally friendly urban design philosophies (Pickett *et al*., 2004; Ahern, 2006), and compare them with traditional approaches. They propose that a “functional landscape” should conserve the ecological processes and, from a hydrologic point of view, emulate the predevelopment temporary storage (detention) and infiltration (retention) functions of the site. This functional landscape is designed to mimic the predevelopment hydrologic conditions through runoff volume control, peak runoff rate control, flow frequency/duration control, and water quality control (Prince George’s County, 1999). The analysis of morphological properties may show that future urbanization have to emulate the morphologic and topologic structure of the natural basin and the drainage network as much as possible.

Morphology and topology of river basins, and the strong relationship between these characteristics and the hydrologic response, have been studied in detail in natural watersheds. Nevertheless, only a portion of this research has occurred in urban watersheds even though the documentation existing in land use, area delineations, and topography is very complete in many urban locations. It is our belief that future research in the characterization of morphologic and topologic features in sub-urbanized and urbanized watersheds will lead to important advances in better understanding the modifications due to urbanization and improve runoff management criteria, reducing the negative impacts of urban areas.

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