# Space metrics modeling to analyse correlations between urban form and surface water drainage performance

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## ABSTRACT

Cities exhibit unique spatial patterns, and thus a distinctive heterogeneity. At different scales of influence, they introduce changes in the physical properties of the natural environment, as the diffusion of impervious surfaces. While climate change is expected to increase the frequency of hazards, patterns of urbanization might be critical in balancing the exposure of cities to extreme weather events, such as heavy rainfalls. Therefore, the adaptability of urban structures to stormwater management measures is vital to safeguard cities against increasing flooding. Yet, planning and design practices are challenged to address the resiliency of future urban landscapes. There is necessity for a new set of planning tools able to analyse the performance of specific urban patterns to extreme stormwater events. This study describes a new hydrologic model designed to operate on the meso-scale level, which uses a limited dataset but yet is able to identify flood prone areas in dense urban environments. Initial experiments on case-study areas has been develop to determine the behavior and robustness of the model. Although further research needs to be performed, the use of urban form metrics, in assessing future developments, has a strategic role in bringing together urban planning and flood impact reduction.

## KEYWORDS

Network analysis; scenario testing; surface drainage; sustainable urban drainage systems; urban form; urban planning

## INTRODUCTION

Recent studies have examined urban morphology as a network of interconnected open spaces shaped by building blocks (Hillier and Hanson, 1984; Hillier et al., 2007). Analysis of this network reveals many urban characteristics that as a whole describe relations, spatial distributions, sequences and hierarchies, thus allowing characterization and analysis of urban patterns in a quantitative fashion (e.g. Carvalho and Penn, 2004). Furthermore, critical in the description and modeling of urban form are spatial (landscape) metrics, a set of quantitative indices able to analyse the explicit profile of an urban area, providing the link between the landscape structure and the urban form (Herold et al., 2003; Alberti, 2009).

At different scales of influence, urban patterns introduce changes in the physical properties of the natural environment, as the diffusion of impervious surfaces. The later has a direct impact on the hydrological cycle, decreasing the concentration time and time to peak discharge and increasing surface runoff (Campana and Tucci, 2001). Spatial patterns of flooding, therefore, encode variations in land surface properties and the underlying morphology of the terrain. While urban growth scenarios results in higher exposure and sensitivity of cities to stormwater (e.g. Carlson et al., 2000), climate change is expected to amplify the impact of urbanization on surface runoff due to the frequency of extreme rainstorm events and peak flows (Milly et al., 2002; Semadeni-Davies et al. 2008). In densely urbanized environments, natural and manmade urban drainage systems are unlikely to successfully absorb such events. In this case, surface runoff will flood streets and public spaces to ultimately reach adjacent buildings and facilities. In extremely densified areas in which the natural drainage capacity is non existent, roads act as a conveyer network for floodwater.

In current practice, urban drainage is still often regarded as a technical matter, designed and applied after the urban planning stage. This practice eventually leads to costly subsurface stormwater drainage systems while earlier adoption of sustainable urban drainage measures into the planning and design phase could potentially be more cost efficient, increase quality of life and most importantly increase the resiliency of urban areas to a larger range of stormwater events.

Computation of urban flooding is generally performed using detailed coupled models that are data intensive and often have difficulties in processing flat areas. Moreover, the availability and usability of these models are restricted to hydraulic engineers who often do not participate in the early design stages of urban areas. For the urban planner, only fairly limited sets of indicators are available (e.g. runoff coefficients) to assess hydrologic performance of their designs. These provide no clues about the hydrologic performance on neighbourhood level, nor connect the drainage performance of individual plots or patches to adjacent areas, neighbourhoods or cities. Yet, on an urban planning level, understanding the neighbourhood or ‘meso-scale’ is vital for the development of flood resilient areas able to cope with stormwater beyond the design storms. To overcome this disparity, a new hydrologic model has been developed that operates on meso-scale, using only a limited dataset but yet is able to identify flood prone areas in dense urban environments. Although the model is still under development, a set of initial experiments on case-study areas has been performed to determine the behaviour, outcomes and robustness of the model.

In this paper the conceptualization, setup and initial outcomes are described as well as a discussion on the relevance and future development goals. Furthermore, knowledge gaps are identified.

## BACKGROUND

While flood modeling on catchment scale has a long history, the modeling of urban flooding is still very much under development. This is mainly due to the complexity of the urban drainage system, in which man-made features are the leading elements. Models coupling stormwater drainage networks and overland surfaces have been developed successfully, but require detailed datasets on the stormwater drainage networks as well as high resolution digital terrain models. Furthermore, the contributions of the individual elements to the overall performance differ per case-study and need to be calibrated using substantial datasets covering the performance during different rain events. This means that they can only be applied during final design stages in which exact building contours, street designs and stormwater drainage network designs have been completed. Yet, even in existing cities, the required data is often not available. On the other hand, few models and indicators have been developed that can give a 'rough' indication of flood prone areas, vital stream networks or the strategic placement of retention areas (e.g. green zones). Either these are based on the distribution of impervious areas or require a DTM (Chen et al, 2009) which is not always available on urban scale level.

To cross modeling scales, requirements and expressiveness, a 'hydro-syntax' model has been developed that acknowledges natural drainage areas, their relation with the street network and individual drainage compartments. The model is especially developed for flat, densely urbanized areas and is therefore usable for many of the world's delta cities.

## MODEL OVERVIEW

The first requirement of the model is to represent the 'meso-scale' level in a minimal but expressive manner, able to identify flow paths, spatial hierarchies, sources and sinks. This has been achieved by abstracting the road network (edges), building blocks and drainage areas (nodes) into a graph network. Determination of hierarchies in the network has been performed by applying a distributed shortest path algorithm from sources to sinks. Actual physical properties (e.g. distances, drainage areas) were introduced by applying weights. Furthermore, the conceptualization of the model introduced the following set of requirements and constrains:

(1) *Focus on cities located on flat areas*. Therefore the terrain morphology is expected to have limited influence since the dominating factors in urban areas are building blocks, streets and (green) public space.
(2) *Dense urban areas*. Land surfaces of urbanized areas, i.e. building blocks and road network, are impervious with an exception of public green spaces;
(3) *Spatially bounded*. A closed boundary is applied to the selected area of analysis, excluding in this way the contribution and influence of adjacent districts;
(4) *Generally applicable*. The model does not take into account actual precipitation rates, surface runoff volumes (including infiltration rates), surface flow calculation nor temporal aspects (flow rates, peaks)
(5) *Computationally efficient*. The model should be capable of calculating large urban areas within reasonable time.
(6) *Expressive*. Although a range of indicators might be used, the model should present results in a straightforward and easily interpreted manner.

This leads to the following design:

(1) *Graphs*. The model is setup as a directed graph consisting of nodes and edges;
(2) *Nodes and edges*. Nodes represent sources or sinks, while edges are used for representing the street network used for convening flow;
(3) *Paths*. Paths are defined as the shortest paths between sources and sinks;
(4) Nodes are located on street intersections, draining adjacent impervious areas (sources) while sinks represent natural drainage areas. Sinks are fed by paths.

# METHODOLOGY

In this study, the potential impacts of the urban form on surface drainage performance are evaluated. A set of space metrics indicators compute the spatial extension of the impervious area contributing to a single node (road intersection/source), the length, frequency and drainage density of the edges and the travelled distance from an upstream source to a downstream pervious sink along the minimal path. Gradients express the cumulative load of individual edges along the path in one direction. By the minimal paths, every source is connected with every sink, thus forming a set of paths. The edges of the minimal path are significantly more heavily used.

## Data

To verify the output and performance, urban districts were selected in nine cities in Asia and Europe. The districts encompass the meso-scale level of analysis where virtual boundaries and pervious areas and the road network were outlined for the purpose of this study. More detailed analysis were performed on two districts of Barcelona, Spain, where the data was gathered from the Cartographic Institute of Catalunya. Urban road network and land cover maps were used to elaborate the network graph; assign drainage areas to road intersections and determine target public green spaces for surface drainage retention and infiltration.

# MODEL ANALYSIS

The final graph acquired from the road network map defines gradients of connectivity among parts of the urban structure weighted by the position and size of retention and infiltration areas (sinks) in the given environment. Every single edge encode the relative drainage area and the contribution from upstream edges along the same path. The closest is the edge to a sink, the higher is the load of stormwater to be drained.

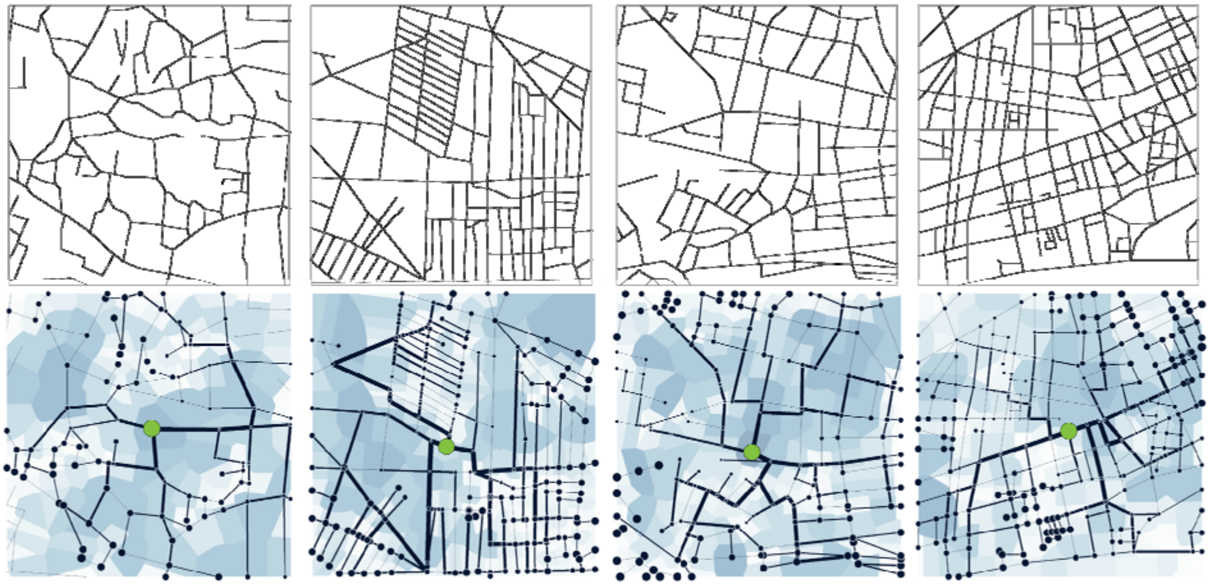
The network distance, i.e. the distance traversing the edges from source to sink, provides a first indicator for flooding. Far away sources have less opportunities to discharge surface runoff in sinks. The drainage accumulation in individual edges shows how important an edge (which represents a street) is in the conveyance of stormwater to the sinks. Edges with large accumulations are identified as important pathways in the drainage on meso-scale.

## Diversity and performance

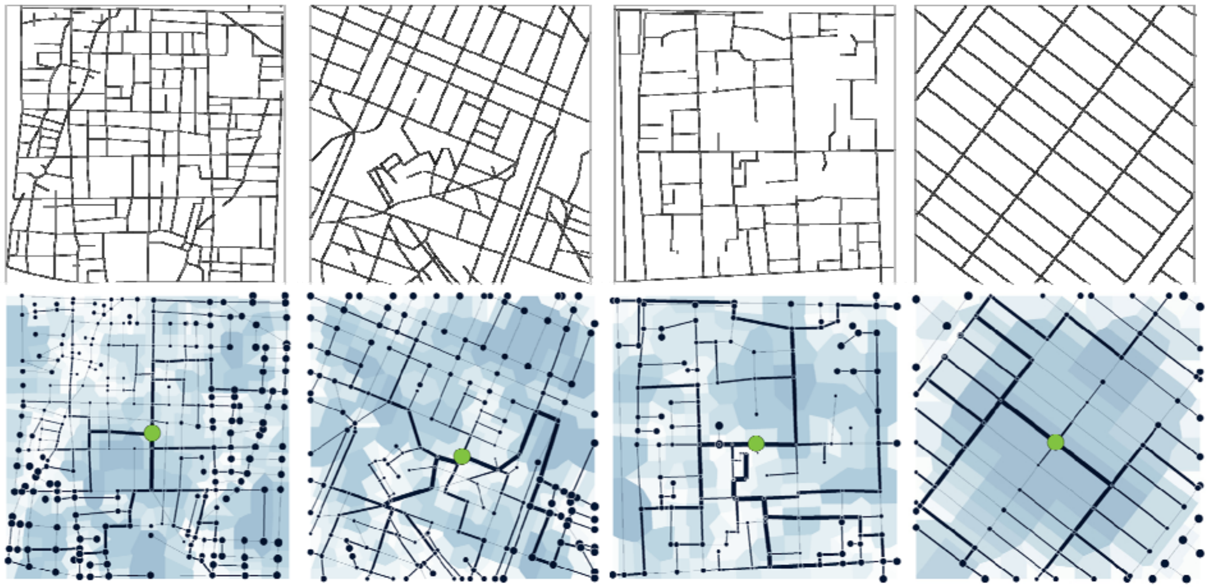
### *Patterns of urban structures and surface drainage performance*

Case study cities in Asia and Europe were used to verify the model and unfold possible relations between differences in the urban layout and the behavior of stormwater flows in the selected environments. This first trial was based on a comparison between a one square kilometer area of eight significantly different cities, which allows for a representative area to investigate the meso-scale level. Shared features for the eight scenarios are the virtual boundary of a 1sqkm and the location of the sink. In order to make the cases comparable, only one sink was placed in the centroid of each area, thus constraining the overall network of source nodes to react towards an unit draining node.

The eight scenarios present a range in regularity and scale of the urban structure. Furthest apart are the organic grid of Dhaka, Bangladesh, and the rigid grid of Songdo, South Korea (see Figure 1).



Dhaka, Bangladesh Mumbai, India Hamburg, Germany Nice, France

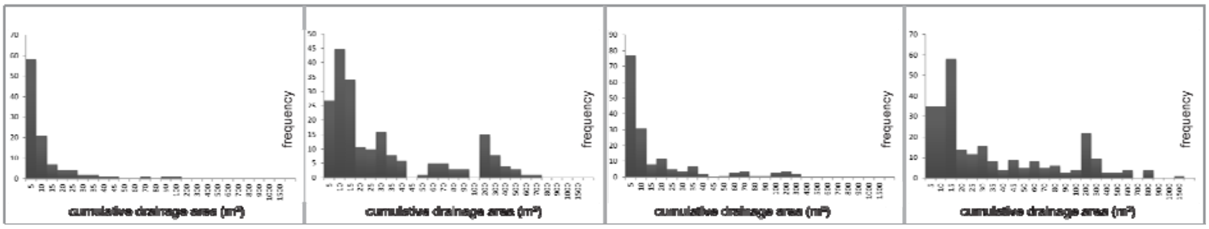


Taipei, Taiwan Seoul, South Korea Beijing, China Songdo, South Korea

**Figure 1**. Urban grids in Asia and Europe and related output scenarios from the model. Green nodes represent the sinks placed on the centroids of each urban grid; thicker lines represent dominant edges.

The model outcomes clearly demonstrate different hierarchy of edges. In some areas single edges are dominating the drainage paths (e.g. Dhaka), while in other areas these are more dispersed (e.g. Mumbai). Another aspect is the ‘nesting’ within the networks; successive reductions in the intensities along the branches seem repeated on lower scales. These emergent fractal-like properties need further study to identify if scaling effects indeed occur. In all, this proves the concept that the distribution of flows is sensitive to the configuration of the urban grid.

The histograms (see Figure 2) show the distribution of cumulative loads of drainage areas along the minimal paths. The values rank minimal and maximum drainage areas per bin. Obviously, the distribution shows the highest values for lower drain nodes, indicating edges further away from the sinks. What is significant is the distribution of less frequent values, which classifies the areas according to their drainage load distributions While Dhaka, Songdo, Taipei, Hamburg and Beijing show expected distributions, with few dominating edges in the graph, Mumbai and Nice show different outcomes. Here, drainage paths are more evenly distributed indicating a larger contributing drainage network close to the sink. This means that during extreme events, in Mumbai and Nice, the expected flow is more evenly conveyed over the street network, while in the other cities a much smaller set of streets are absorbing the excess water, making them possibly less resilient to extreme rainfall events.



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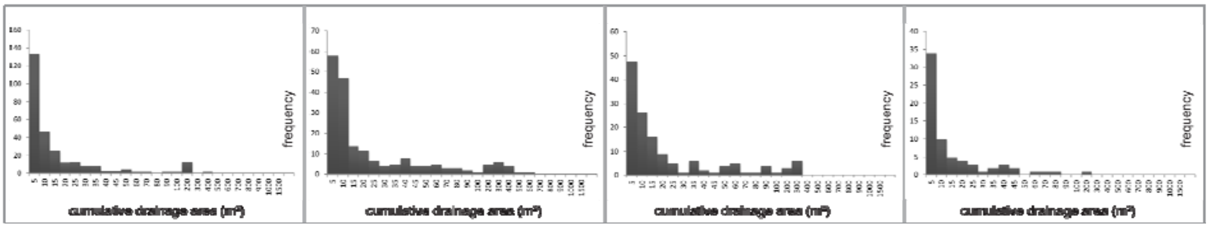

Taipei, Taiwan Seoul, South Korea Beijing, China Songdo, South Korea

**Figure 2**. Distribution of drainage area values. The intervals in the horizontal axis of the histograms represent the cumulative drainage area assigned to the road network edges. The vertical axis shows the frequency of drainage area values.

## Validation

Barcelona, in the northeast coast of Spain, was chosen for further validating the model. The city incorporates both regular urban grid patterns as well as organically grown neighborhoods. The selected areas consist of Poblenou, based on the particular regular grid structure designed by the Cerdà Plan in 1860, and Raval, a historical area in the center of the city. Both districts are sited next to the coastline.

Important aspects in this validation trial (see Figure 3 and 4) were the presence of multiple sinks in the network and the fact that it relates to the actual physical properties of the city. Sinks were acquired from the land cover map of Barcelona, representing public green areas conceptualized as suitable spaces for the implementation of sustainable drainage systems. As a result, the complexity increases due to the number and uneven distribution of these draining areas. The selected districts are different in the overall area extent and in size of the street profiles. The majority of the streets in Poblenou have similar sections, up to 25m wide. In contrast, the historical structure of Raval is mostly formed by a network of smaller streets (often less than 10 meters).

One of the most important observations from applying the methodology for the two areas is that despite the introduction of multiple sinks at different locations, dominating edges further away from the sinks can still be observed in both networks. This shows that even in the regular structure of Poblenou flow path organize around a limited set of edges, encoding the constrained conveyance of the flows towards key locations (sinks). When these main paths are checked for available capacity at the actual locations, the street profiles do not necessarily comply with their dominant position in the drainage network. For edges with relatively high drainage accumulation values, we found that the corresponding street profiles in the Raval area often are only 4.5m wide. This might cause drainage blockage in comparison to similar edge values in Poblenou. This observation addresses particular questions about different impacts that are likely to be found according to different street widths. Given the distribution and size of open spaces, Poblenou presents a type of urban structure suitable to adaption for stormwater source control, e.g. by application of bioretention areas. Additionally, due to their width, the streets might have enough capacity for flood conveyance. The outcomes of the model indicate that strategical areas for the implementation of source control measures are the ones along the dominant edges of the graph, where most of the excess of water is being hold.

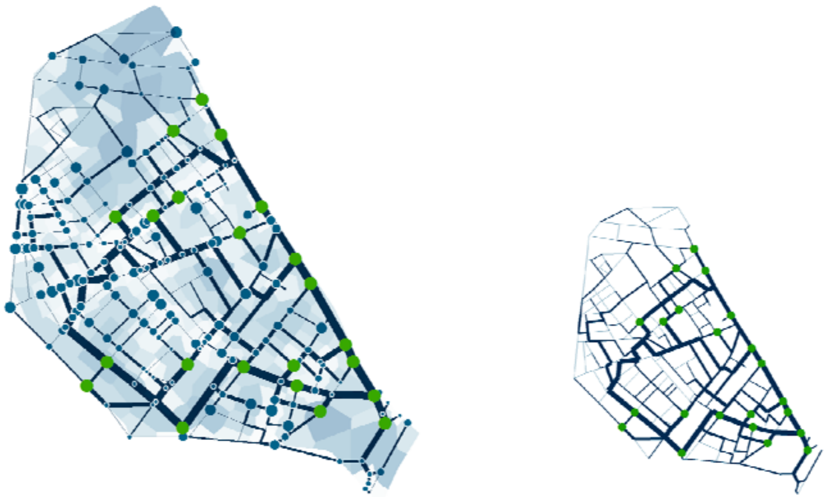

**Figure 3**. Raval district. Irregular road network structure. Larger nodes express longer distances between sources and the closest sink and thicker lines represent dominant edges. The smaller figure on the right clearly show the hierarchy of paths.

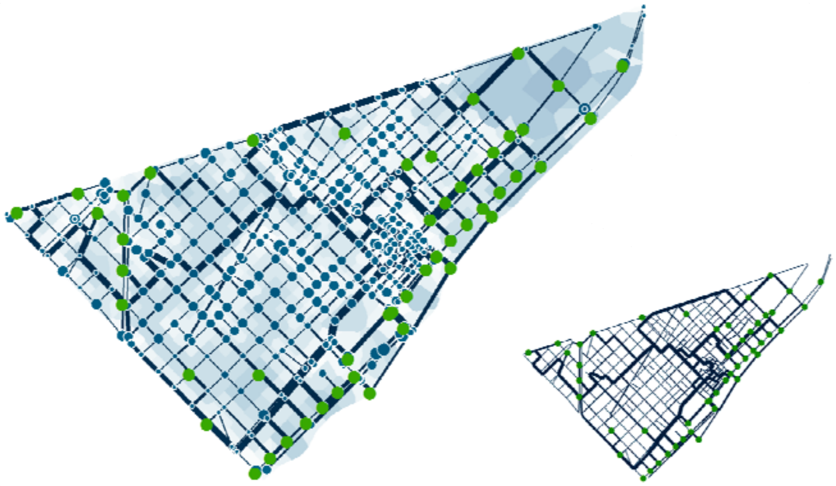

**Figure 4**. Poblenou district. Regular road network structure. The higher number of sinks in this scenario is supported by the overall district area, which is four times the size of Raval.

## DISCUSSION

Preliminary findings show the importance of further research on the performance of the network following changes in the optimal number, size and distribution of natural drainage areas. In order to achieve this aim, the implementation in the model of more efficient search algorithms (e.g. genetic algorithms) is required, enabling the test of different scenarios for a selected area. Another aspect is the appropriate choice of the spatial boundary, an essential criterion that can determine accuracy of the outputs. Furthermore, the inference of scaling geometries in the road network system is required to explore fractal properties (Batty and Longley, 1994) and conclusions that can be made from this on higher or lower scale levels, thus improving the applicability for larger urban areas. Finally, since several conceptualizations were made for this approach to drainage modeling, future studies must verify the outcomes of the model by comparing results to either empirical data or outcomes from more sophisticated flood models.

## CONCLUSIONS

The acceptance of climate change and urbanization as main drivers of future flooding causes cities to act upon the occurrence of extreme rainfall events. Megacities like Mumbai or Dhaka, which are essentially vast, flat urban agglomerations, are coping with tremendous precipitation rates. Connecting retention areas, green infiltration areas and other sustainable urban drainage measures are vital in keeping those cities safeguarded against an increasing flood risk. This study addressed the development of a new approach to flood modeling on a meso-scale level, which identifies dominant flow paths in the street network with limited required data. Although the model shows promising initial results, the outcomes must be validated and verified to judge the model on its practical merits.

## AKNOWLEDGEMENT

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