A multi-scale approach in the planning and design of water sensitive environments

Une approche multi-échelle dans la planification et la conception d'environnements soucieux de l'eau

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RÉSUMÉ

Un cadre d'analyse spatiale pour appuyer les pratiques du paysagisme et de l'aménagement urbain a été introduit dans le cadre de cette étude visant à intégrer différentes échelles d'analyse et leur effet lorsqu'on travaille avec des techniques de Water Sensitive Urban Design (WSUD – urbanisme sensible à l'eau) pour la réhabilitation de l'environnement urbain existant. Les analyses multi-échelles sont réalisées en utilisant une plate-forme SIG pour capturer les caractéristiques du paysage (structure spatiale et composition) et les processus (cycle de l'eau, par exemple). L'analyse macro-échelle au niveau du bassin versant urbain permet le développement de stratégies de planification et d'objectifs de performance pour le paysage urbanisé, tandis que la méso-échelle, comprenant les couloirs écologiques (verts), connecte les zones principales et véhicule les écoulements de surface à travers les sous-bassins versants. À l'échelle du quartier, les paramètres de la forme urbaine mesurent la profondeur territoriale (perméabilité) entre terres publiques et privées et l'adaptabilité de chaque site à une réhabilitation par les techniques de Water Sensitive Urban Design. La faisabilité d'une amélioration ou d'une extension de la matrice du paysage bleu-vert existant est évaluée, et ses implications discutées, en utilisant une séquence de mesures du paysage et de techniques d'analyse de réseau. L'étude se concentre sur les possibilités de modélisation pour l'introduction d'éléments du paysage visant à améliorer la gestion des eaux pluviales de surface et, en même temps, à fournir des services écosystémiques multiples.

ABSTRACT

A spatial analytical framework to support landscape planning and urban design practices was introduced in this study aiming to integrate different scales of analysis and their effect when retrofitting Water Sensitive Urban Design (WSUD) in the existing urban environment. The multi-scale analyses are performed using a geographic information system (GIS) platform to capture landscape patterns (spatial structure and composition) and processes (e.g. water cycle). The macro-scale analysis at the urban catchment level allows the development of planning strategies and performance objectives for the urbanized landscape, whilst the meso-scale, comprising the ecological (green) corridors, connects core areas conveying surface flows across the sub-catchments. At the neighbourhood scale, urban form parameters measured the territorial depth (permeability) between public and private land and the suitability of each site to retrofit Water Sensitive Urban Design. The feasibility to improve or extend the existing green-blue landscape matrix is assessed, and its implications discussed, by using a sequence of landscape metrics, land suitability and network analysis techniques. The study focused on modelling opportunities for the introduction of landscape features designed to improve surface stormwater management and, at the same time, provide multiple ecosystem services.

KEYWORDS

Landscape ecology, Landscape planning; Multi-scale model, Network analysis, Urban morphology, Water sensitive urban design

1 INTRODUCTION

Traditional segregated approaches to water management, whereby water supply, stormwater, wastewater, conveyance, treatment and solid residuals are each managed separately often by disparate groups, are no longer tenable. Seeing water as part of a cycle, to be managed efficiently and to maximise the value of each stage of the cycle, is becoming understood to be the most sustainable way of controlling and benefiting from water in urban areas (e.g. Howe & Mitchell, 2012). Emerging practice in USA for example, deals with stormwater synergistically with green areas and the concept of 'green infrastructure' is now prevalent in which cities are simultaneously made greener as well as being drained effectively, with water being used directly at source and recycled where possible (e.g. Thurston, 2012). In parallel with this conceptual shift in water management practice, the notion of ecosystem services has emerged in which the benefits from and to the natural ecosystem have been formally recognised and explicitly monetised (e.g. Moore & Hunt, 2012).

Within this perspective, the performance of urban water systems and the simultaneous provision of ecosystems services are highly reliant on urban landscape patterns resulting from land-use planning and design practices. The role of landscape planning and urban design in the context of sustainable stormwater management science has been widely addressed by the guiding principles and practices of Water Sensitive Urban Design (WSUD), either for the retrofitting or the design of new urban infrastructure systems (e.g. COAG, 2004). The approach combines technical solutions (water sensitivity) with qualitative values (e.g. aesthetics, functionality, usability) provided by the design of landscape elements in the urban context. However, a WSUD approach does not in itself reflect the patterns and processes, at different landscape scales, produced by the introduction of technical and design solutions into the urban area. Therefore a framework that defines a systemic approach for a range of WSUD options according to each location and scale of the landscape is needed to identify opportunities for planning and design of water sensitive land use patterns at regional, district and neighbourhood scales.

The object of the work presented here is to propose a methodology to assess the spatial attributes of the urban landscape to support retrofitting Water Sensitive Urban Design at different scales. The method introduces a multi-scale approach to planning and design of green-blue infrastructure which is informed by landscape structural composition and configuration, urban morphology, stormwater drainage performance, and aspects of ecosystem services. In this paper, the analytical framework to capture the structural characteristics of the landscape at various scales is presented. The scales are those that connect hydrological units and planning levels (Figure 1). The hydrological units are the catchment (macro-scale); the sub-catchment (meso-scale); and the micro-catchment (micro-scale). The planning levels are the city-region (macro-scale); the district and the urban/ecological corridors (meso-scale); and the neighborhood (micro-scale).

Landscape planning frameworks reviewed in the development of this methodology (Alberti, 2009; Botequilha Leitão and Ahern, 2002; Ahern, 1999; Gustafson, 1998; Forman, 1995; Zonneveld, 1995) share common approaches. The planning steps adopted by each can be synthesised into six phases: setting objectives; analysis; diagnosis; prognosis; implementation; and validation. The proposed methodology for planning and design of water sensitive environments includes the first three phases at each scale level sequence.

2 CASE STUDY

The city of Porto Alegre, the capital of the southernmost state in Brazil, was chosen for a pilot study due to the rapid rate of urbanization which has paralleled the increase in the frequency and intensity of urban floods (Campana and Tucci, 2001). In recent years the city experienced a number of fatalities, with direct and indirect damages caused by urban flooding. Porto Alegre is located on the eastern bank of the Guaiba Lake, where five rivers converge to form the large freshwater lagoon Lagoa dos Patos. With approximately 1.4 million inhabitants set in an area of 497 km^2 with 72 km of river shores, the city has 27 drainage basins contributing to the Guaiba Lake, and its topography consists of valleys, urbanized hills and slopes, and a significant portion of rural area. Thirty five percent of the city is located on the lower areas lying close to the level of the Gravatai River (north) and Guaiba Lake (central and southern regions).

Porto Alegre has also, for more than 20 years, a unique decentralized government that allows communities to engage effectively in decision making about urban priorities for investment. The "participatory budget" is a system of popular participation in the definition of public investment, part of a number of innovative reform programs to overcome severe inequality in living standards amongst city residents (Abers, 2000; Goldenfum et al., 2008).

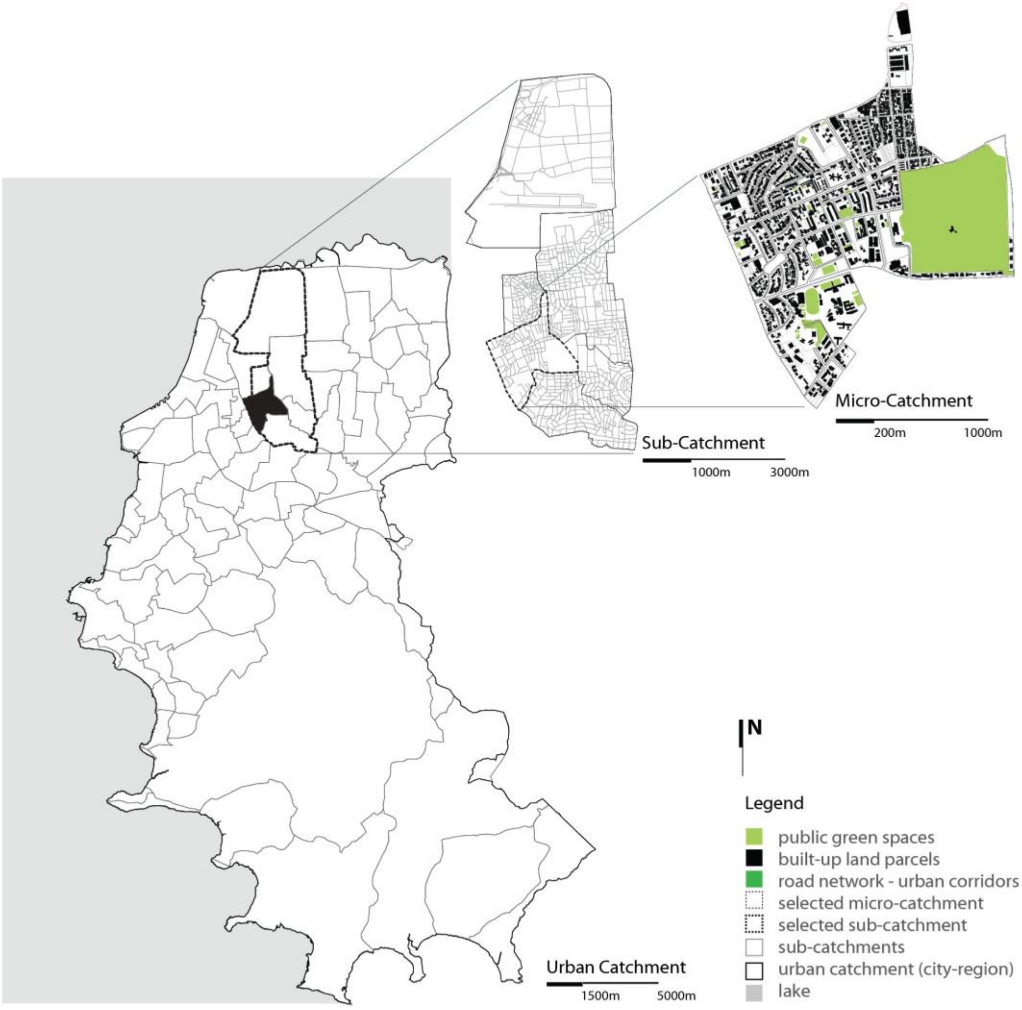

Figure 1. Landscape Analysis Scales

3 MULTI-SCALE METHOD

Scale is critical in landscape analysis, environmental design and planning (Batty, 2008; Pumain, 2003; Botequilha Leitão and Ahern 2002). Because landscapes are spatially heterogeneous areas; their structure, function and change are scale-dependent (Turner, 1989). Several sustainable stormwater management frameworks, e.g. WSUD (Novotny & Novotny, 2012), act at one scale at a time, not considering the scale-dependency and effects of applied technical and design solutions, although there is a strong interest in decentralisation of water systems (Nelson, 2012). Hence, the integration of different landscape scales of analysis provides an important opportunity to further develop the scope and benefits of the existing frameworks. The multi-scale approach proposed here uses the macro-scale analysis (city region / urban catchment) to support the development of planning strategies and performance objectives for the urbanized landscape, whilst the meso-scale, comprising the ecological (green) corridors, connects core areas conveying surface flows across the sub-catchments. The urban form is measured at the neighbourhood scale (micro-catchment) where a set of parameters describes urban density and the interface between public and private spaces characterizing the suitability of each site to retrofit Water Sensitive Urban Design.

Principles of sustainable stormwater management, network analysis, landscape ecology and urban morphology are included in the overall analytical framework shown in Figure 2, and the techniques are described in more detail in Sections 3.2 - 3.4. Developing green-blue infrastructure networks begins with identifying spatial patterns of urban spaces at different scales and the timeliness and land suitability for the implementation of sustainable stormwater management measures. The proposed retrofitting WSUD method includes the protection of existing green areas, wetlands and open water spaces, the design of new landscape elements, and the restoration and maintenance of landscape connectivity at different spatial scales. The work focused on the conservation of critical infrastructure, identifying core areas, potential corridors, and modelling opportunities for the addition of landscape features designed to improve surface stormwater management and, at the same time, provide multiple ecosystem services (e.g. Moore & Hunt, 2012).

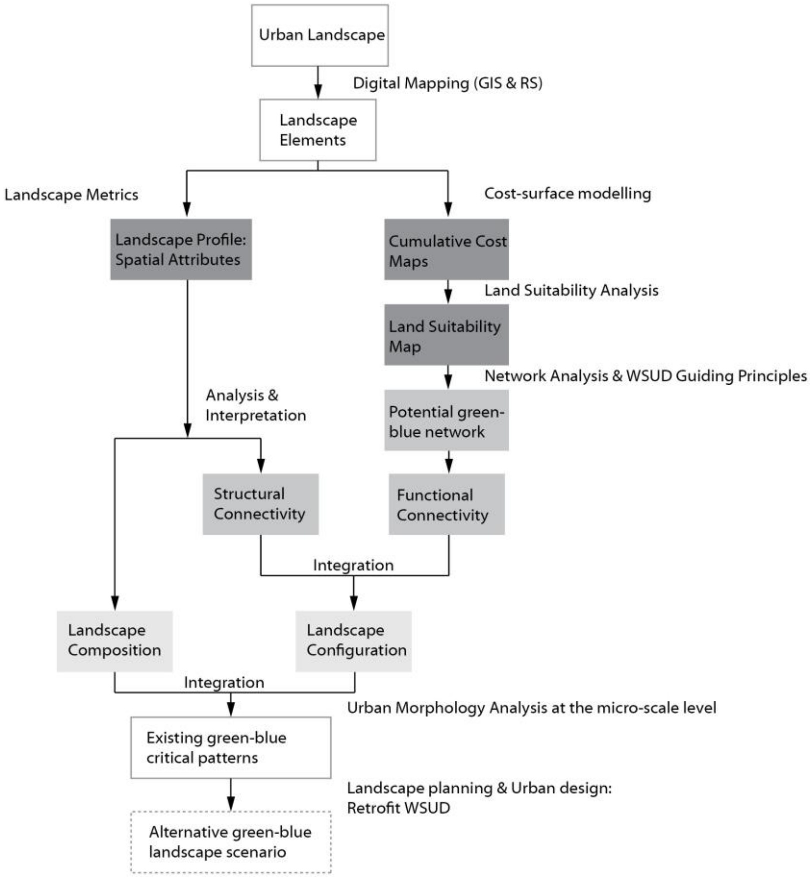

Figure 2. Analytical framework flowchart (adapted from Lafortezza et al. 2005): the landscape patterns analysis supports the development of alternative green-blue landscape scenarios. The framework includes backloops for backcasting and verification of the analytical sequence.

3.1 Tools used

The study used 2008 Quick Bird high-resolution imagery (0.60m panchromatic and 2.4m multispectral resolution) to produce the digital land-use map via remote sensing techniques. The imagery was rectified and georeferenced using a topographic map (1:25,000) produced by the Planning Department of the Municipality of Porto Alegre. Supervised Classification using Maximum Likelihood classifier was performed to define six land-use surface types (LUST) (Figure 3) subdivided into two categories: open areas (comprising green areas, open water, wetlands, barren and agricultural land) and urban or built-up areas.

Measurements of the configuration (arrangement, position) and composition (variety, abundance) (Forman 1995) of these two categories are essential parameters for modelling the correlation with performance indicators, e.g. surface runoff. The characterization of spatial elements (natural and built-up patches, major corridors and special sites) and landscape functions (water flows, urban mobility, and aspects of ecosystem services) was conducted using the classified land-use map and the digital terrain model with a pixel resolution of 5m, the hydrologic and soil maps at 1:25,000 scale, and the cadastral data (urban parcels, buildings and street network) at 1:1,000.

Figure 3. Land-use Surface Type (LUST) Classification

3.2 Macro-scale: the urban hydrologic catchment analysis at the city-regional level

Nine spatial indices have been used (Table 1) to identify potential green-blue networks formed by major areas, functioning as source and sinks (nodes), and conveyance corridors (edges/links). In landscape ecology studies, these indices are used to interpret connectivity, ecological integrity and diversity of landscape patterns at patch, class and landscape levels (McGarigal et al. 2002). The applied landscape metrics characterize aspects of the composition and configuration of the landscape expressed by the ratio, dominance, connectivity, and aggregation of landscape features and the proportion of sealed urbanized areas. Core areas have been selected based on their size, topographic position (upstream or downstream) and relative location (intra or extra-urban) in the network. The cost-benefit is higher when selecting larger areas for retrofitting surface stormwater management infrastructures.

Table 1. Landscape Metrics (adapted from Schwarz, 2010; Kong et al., 2010; McGarigal and Marks, 2002)

Metric Indicator	Description
Size of Continuous Area [km^2] (SCA)	The absolute extent of continuous area indicates the size of the dense sealed urban area.
Area Weighted Mean Shape Index (AWMSI)	AWMSI computes average patch shape in the landscape by weighting patches according to their size. Specifically, larger patches are weighted more heavily than smaller patches. AWMSI equals the sum, across all patches types, of each patch type perimeter (m) divided by the square root of patch area (m^2), adjusted by a constant for square standard, multiplied by the patch area (m^2) divided by total landscape area. AWMSI is represented without units and have values greater or equal to 1. AWMSI equals 1 when all patches in the landscape are square. It increases without limit as the patch shapes become more irregular.
Mean Perimeter-Area Ratio (MPAR)	The MPAR indicates the average complexity of sealed urban patches. (Sum of each sealed urban patch perimeter/area ratio)/number of patches

Class Area (CA)	Sum of areas of all patches belonging to a given class. It measures the landscape composition.
Mean Patch Size (MPS)	MPS equals the sum of the areas (m2) of all patches of the corresponding patch type, divided by the number of patches of the same type, divided by 10000 (to convert to hectares). It indicates the fragmentation of the patch type.
Largest Patch Index (LPI)	LPI equals the area (m2) of the largest patch of the corresponding patch type divided by the total landscape area (m^2). It indicates fragmentation.
Patch Cohesion Index (COHESION)	Measures the physical connectedness of the corresponding patch type. COHESION equals 1 minus the sum of patch perimeter divided by the sum of patch perimeter times the square root of patch area for each patch type, divided by 1 minus 1 over the square root of the total number of cells in the landscape.
Euclidian mean nearest-neighbor distance (MNN)	MNN equals the distance (m) mean value over all urban green space patches to the nearest neighboring patch, based on shortest edge-to-edge distance from cell center to cell center. It indicates patch context and quantifies patch isolation.
Shared of Sealed Urban Area (SSUA)	The share urban/area range from 0 to 100%. The higher the share urban/area, the more surfaces in the city are urbanised.

To maintain or restore connectivity between green-blue landscape features, additional areas for conveyance, infiltration, retention, detention and purification must be identified. Land suitability analysis for improving and/or expanding green-blue areas was carried using a GIS platform through a sequence of steps. First, the spatial information contained in the selected maps (existing land-use provided by the Urban Master Plan, land-use surface type, DTM, surface water, water table, and soil type maps) were normalized into five different classes comprising ranges of performance objectives, e.g. hydraulic permeability. Based on the Analytical Hierarchy Process (AHP) and pairwise comparison, weighting-scores were acquired for each of the new classification maps. Subsequently, using spatial analysis functions of GIS, a final composite map was produced providing the land suitability surface for the development of new green-blue areas.

3.3 Meso-scale: the urban hydrologic sub-catchment and urban corridors analysis at the district level

Landscape ecology studies apply graph theory to explain the spatial configuration of landscape systems and describe flow patterns (Cantwell and Forman, 1993; Forman, 1995). Graph theory is used to reduce the structural complexity, redefining spaces as a finite set of nodes and linkages, and rules to define which links join which pairs of nodes (Linehan et al. 1995). Kong et al. (2010) used least-cost path analysis and gravity modelling to map urban green space networks for biodiversity conservation. In this framework, the green-blue network can be defined using open spaces as nodes and corridors as links. The least-cost path function in GIS is determined using a cumulative-cost surface between nodes. Potential corridors between the core areas identified on the macro-scale can then be evaluated considering the impedance posed by the landscape and land-use expressed by the land suitability surface map. A gravity model algorithm has been developed to compute interactions between sources and sinks according to their corresponding weights and the cumulative impedance of the corridor between the nodes at the district level. Weights have been assigned based on the degree of urbanization expressed by the imperviousness of adjacent areas, and the typology of the open space that characterizes the node, i.e. green space or open water (Table 3). Area size was used to normalize the relative importance of the node (Kong et al. 2010).

Table 2. Land-use type classification according to the spatial scale used on the analysis of the landscape.

Scales	Hydrologic unit	Territorial unit	Category	Space typologies
Macro-scale	Urban Catchment	City-region	Urban green space (ecological green corridors)	Regional parks; metropolitan parks (green wedges); linear parks (green belts)
Meso-scale	Urban Sub-Catchment	District	Urban green space (ecological green corridors)	District parks
Micro-scale	Urban Micro-Catchment / Street Edge	Neighbourhood	Urban green space (ecological green corridors)	Local parks and open spaces (green squares); private open space (attached green spaces, residential gardens); road greenways; riparian green spaces

Macro-scale	Urban Catchment	City-region	Open Water (ecological blue corridors)	River; lagoon; bay; dam
Meso-scale	Urban Sub-Catchment	District	Open Water (ecological blue corridors)	Small pool; natural streams; wet pond (retention basin); wetland
Micro-scale	Urban Micro-Catchment / Street Edge	Neighbourhood	Open Water (ecological blue corridors)	Narrow natural channels; street edge streams; rain gutter
Macro-scale	Urban Catchment	City-region	Urbanized land	Mobility Infrastructure (railway lines; roads; highways)
Meso-scale	Urban Sub-Catchment	District	Urbanized land	Zoning uses built-up land (residential; commercial; institutional; industrial) (cultural-historical sites)
Micro-scale	Urban Micro-Catchment / Street Edge	Neighbourhood	Urbanized land	Urban structure; density (Coverage)

Analysis of open spaces (patch) and corridor characteristics, and the circuitry and connectivity of the networks has been made (Zhang and Wang, 2006) to evaluate the designed green-blue networks. The first step measured area, density and length of patches and corridors. The linkage of network elements were then analysed in terms of circuitry and connectivity.

A number of indices developed for this purpose were used to assess the proportion of the network formed by loops expressed by the alpha index (α), and the level of connectivity expressed by beta (β) and gamma (γ) indexes (explained Haggett and Chorley, 1972). Finally, for the selected green-blue corridors that correspond to the existing road network system, mobility analyses had to be carried out. Traffic density, public transport density and the accessibility described by the topological integration (Hillier and Hanson, 1984) were then used to assign the importance of the selected corridor regarding urban mobility. Important mobility corridors were considered less suitable for retrofitting green-blue infrastructure if extra space is needed to be extracted from the road edge for the addition of new landscape features.

3.4 Micro-scale: the urban hydrologic micro-catchment analysis at the neighbourhood level

The urban form characteristics have been measured both along the corridors (roads or linear parks and streams) identified on the meso-scale as within the neighbourhoods as a whole (public and private parcels). The first set of parameters described the density of occupation. Ground Space Index (GSI) or coverage has been used to demonstrate the relationship between built and open spaces, and the Spaciousness (OSR), to measure the amount of open spaces at the ground level per square meter of gross floor area, providing an indication of the urbanization pressure on unbuilt areas (Berghauser Pont and Haupt, 2010). A second set of attributes have been used to analyse the interface between public and private spaces. Gradients of permeability between the corridors and the urbanized parcels have been measured according to presence of paved or non-paved setbacks, residential or public gardens, and the depth-distance (Hillier and Hanson, 1984) of these minor open spaces to the nearest green-blue edge. Hence, the overall suitability of public and privately owned parcels of land could then be modelled for retrofitting water sensitive urban design solutions at each location, so increasing the capacity of the green-blue corridors to manage surface stormwater and at the same time enhance the multifunctionality of the urbanized landscape.

4 RESULTS OF THE CASE STUDY

Retrofit WSUD in urbanized environments involves the capacity of planning and design to reclaim the urban water system as a shared ecological resource. The analytical framework presented in this study applied Geographic Information Systems and Remote Sensing technologies to derive landscape properties and trends at different scales, supporting decision processes and the integration between urban development, water cycle performance and ecosystem services goals. Frequent urban flooding in the city of Porto Alegre and the diffuse pollution of the Guaiba Lake catchment provides an example of a region in which the pace of territorial transformation has led to an unstable water system.

Permeable areas in the wooded hills descending into low plains of clay soils mark the hydrological conditions of the area, and naturally form floodable zones at the base of the urban macro catchment. Land-use practices cascade problems in downstream areas located in each of the twenty seven hydrologic sub-catchments in the city. Particularly, urbanization in the hills upstream has led to erosion, increasing sediment load and runoff in peak conditions, contributing greatly to flood risk. Together with industrial, commercial and residential areas, agricultural land and farming this contributes significantly to pollutants loads in the water environment.

The multi-scale approach was applied to frame this problem, defining the territory with different degrees of urbanization expressed by the distribution of land-use surface types and the resulting imperviousness in the hydrologic sub-catchments. Through the analysis of the spatial configuration (structural and functional connectivity) and composition, critical landscape patterns were identified. Provision and access to natural sites in the urbanized environment is essential for the maintenance of human and ecosystem health (Tzoulas et al. 2007). According to Harrison et al. (1995), as described in Comber et al. (2008), the provision of open space should be of at least 2 ha of accessible natural green space at a distance radius of 300 m from each resident location. The process used to select open space patches and corridors considered both urban water performance and ecosystem services criteria.

The macro and meso-scale analysis modelled existing core open space patches connected via potential corridors providing the structure for the development of an alternative green-blue landscape. Figure 4 shows core green spaces and open water patches in Porto Alegre extracted from the land-use surface type (LUST) map and related to WSUD technical features. Logic-based Structured Query Language (SQL) rules were performed within the 'Model Builder' module of the GIS platform ESRI ArcGIS 10 to identify retrofit WSUD locations in the macro, meso and micro-scale levels. For the macro-scale analysis, only green spaces larger than 2 ha were selected and further characterized according to their topographic location (upstream or downstream) and relative intra or extra-urban position in the city landscape. Based on the attributes of infiltration, retention, detention and purification, WSUD features were assigned to each open space location. Potential green-blue corridors between core areas were modelled based on least-cost path analysis applied to the existing street edge network. In highly urbanized areas, roads act as a conveyer network for surface runoff. Potential corridors passing by other areas, i.e. built-up land parcels, were not considered in this study. The green-blue space network covers about 34.5% of the total urbanized catchment.

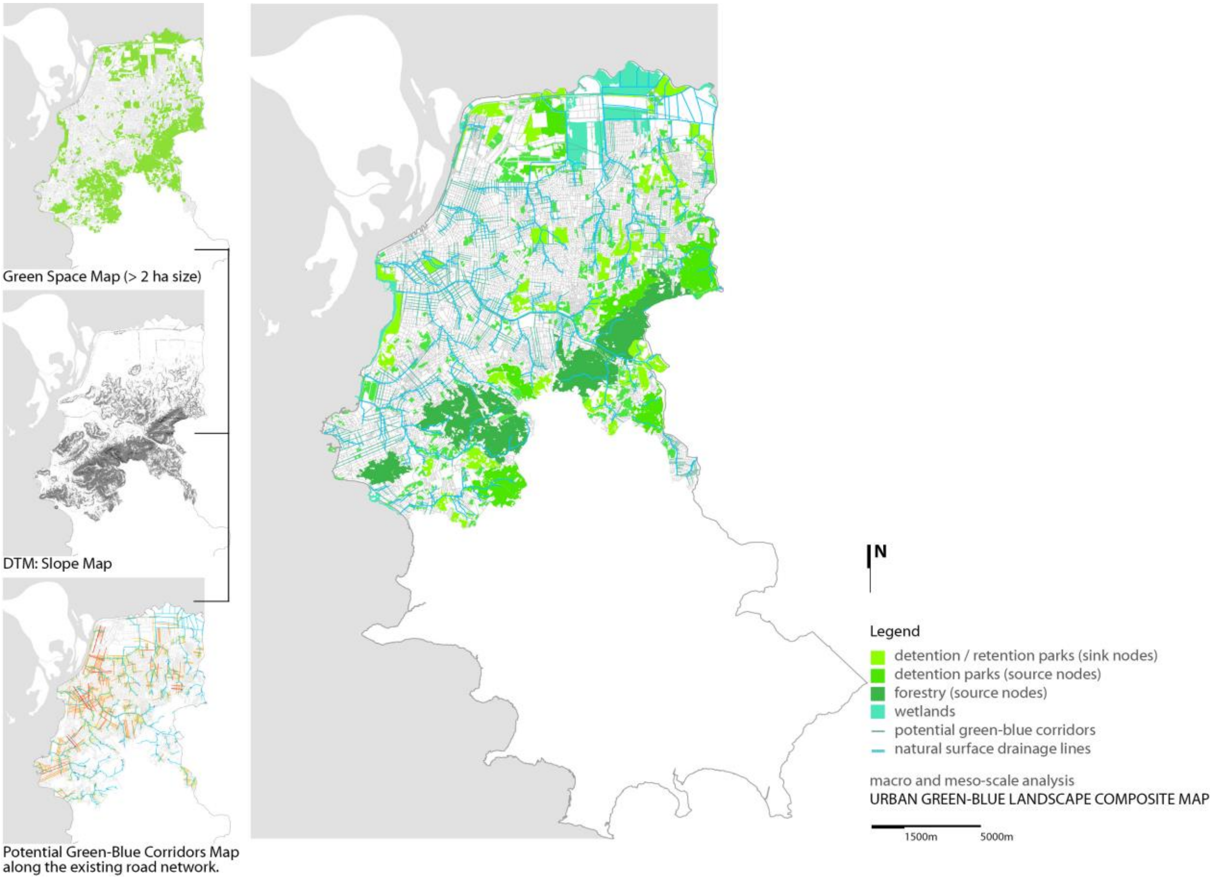

Figure 4. Macro and Meso-scale Analysis: Green-Blue Potential Corridors and Existing Patches.

The micro-scale analysis was conducted on a portion of the sub-catchment that presented the highest risk of flooding in the city (PMPA-DEP, 2005). The density of occupation is shown in Figure 5a based on the distribution of the Ground Space Index values in the neighbourhood. Gradients of permeability between public and privately owned land are shown in Figure 5b according to the depth-distance from residential and public open areas to the nearest green-blue edge. The GIS-based methodology for stormwater disconnection developed by Moore et al. (2012) was used for the selection of parcels of land suitable for a specific retrofit WSUD option. At this scale, minor unbuilt areas were selected for permeable paving, pocket street infiltration, off-site local detention and swale conveyance (Figure 5c).

Figure 5. Micro-scale Analysis: Coverage; Public-Private Spatial Permeability; Retrofit WSUD scenario.

The different models that have been introduced in this study will be used to backcast and hence verify development patterns. In the next stage, hydrological/hydraulic models, e.g. EPA-SWMM, will be applied in selected sub-catchments of the case study city to simulate surface water system performance (quantity and quality).

5 DISCUSSION AND CONCLUSIONS

The scale at which analyses are undertaken may strongly influence the conclusions, since properties that describe processes at one level may not be relevant at another. The methodology presented here is built on the notion of a multi-scale concept to landscape planning and urban design of green-blue infrastructure. The urban environment was modelled using a series of spatial and network analysis routines developed in a GIS platform as outlined in Section 3.

The requirements for planning and designing green-blue infrastructure across different spatial scales were described by physical, ecological and social factors. These factors are connected to the micro-catchment (neighborhood level), sub-catchment (district level), or urban catchment (city-regional level). At each scale of analysis, a sequence of quantitative methods and design principles identified opportunities for retrofit and to improve existing patterns of urban green spaces and for urban surface water. This study presented the first module of a planning based GIS platform that has been developed to semi-automatically generate land-use in terms of green-blue areas, with algorithms that can be used to backcast and forecast development planning and urban space typologies. Further studies are been conducted linking the results of the multi-scale model to hydrological/hydraulic modelling to predict the effects of green-blue landscape retrofits on the water cycle within the city.

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