Green-Blue Multifunctional Infrastructure: An Urban Landscape System Design New Approach

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ABSTRACT

Cities exhibit unique and ever-changing spatial layouts formed by nested natural and socio-economic systems, sub-systems and components resulting from exchange, interaction, and interdependency processes. In this context, managing surface water in urban areas requires new approaches that integrate the knowledge about territorial patterns and processes into the development of management practices and control structures designed for hydraulic and ecological performance. As integrated systems, green, blue and grey water infrastructure can reduce runoff, increase biodiversity and offer cultural/health benefits through public access to valued natural resources. This article introduces a tool using ArcGIS and EPA SWMM platforms to analyse the spatial configuration and composition of the urbanised landscape, designing nested networks of green, blue and grey spaces relevant to the scale of analysis. An example was provided for the City of Porto Alegre, Brazil. The article demonstrates the use of combined spatial/network analysis, hierarchical design and hydrodynamic modelling in playing a strategic role in advancing the integration of urban planning, ecosystems services objectives and sustainable stormwater management practices.

KEYWORDS

Urban landscape planning, urban ecology, ecosystem services, multifunctional infrastructure, flood risk, sustainable stormwater management, liveability

INTRODUCTION

Traditional approaches to the management of stormwater in urban areas are increasingly being challenged by the need to deliver greater sustainability and also to secure as many benefits and as much value as possible from urban systems, services and utilities (Ashley et al, 2014). It is no longer sufficient to consider stormwater management in isolation from these systems and services, rather to take an integrated and synergistic perspective in order to get ‘more from less’ in any investment. For this to be effective, the place of stormwater management within land use, urban design and city planning needs to be properly acknowledged by all involved and the opportunities exploited from managing water in a way that brings it more into the open within green and blue spaces (e.g. Ashley et al, 2011). Until recently, there were many barriers inhibiting effective cooperation between urban planners, architects and the ‘engineers’ who made stormwater ‘disappear’ from urban areas into underground pipes and infrastructure. A new rapprochement between the various professionals and also with policy makers is creating a new vision for the role and place of surface water in urban environments that seeks to make the most use of water in all it’s forms, rather than seeing it as a nuisance, health risk and hazard as in the past (Ashley et al, 2014). For this vision to be realised there is a need for new ideas, guidance and tools to assist planners and designers in delivery and also in engaging policy makers, communities and others in the vision and associated value to society.

This paper describes a prototype approach and set of tools established within a planning framework for retrofitting stormwater management using green infrastructure. The new approach starts from a city planning perspective and, through a set of nested physical scales, encompassing: city; district; neighbourhood; block and plot, uses a hierarchical design approach to harness the ongoing vectors of change in urban development to identify synergistic and opportunistic foci for preferential retrofitting of surface based stormwater management measures. The suite of tools utilises an ArcGIS platform, new algorithms for suitability/network analysis, corridor design and EPA SWMM modeling to demonstrate effectiveness in delivery of drainage system performance. The new approach is illustrated using a 2.85 ha sub-catchment in the City of Porto Alegre, Brazil.

CONTEMPORARY URBAN PLANNING

In contemporary urban planning, design theory and practices, urban landscape ecology is increasingly being used as part of a paradigm shift; redefining infrastructure in the context of the future growth of cities (e.g. Hung et al, 2012) – i.e. ‘nature as infrastructure’ and steering away from tech-fix-solutions. Notions about ecological processes and the multiple-values brought *inter alia* by and for ecosystem services are being used as a responsive set of strategies, addressing the predominant challenges faced by today’s urban economies – including climate dynamics with increased flooding and drought frequency, intensity, and demographic growth, with attendant higher natural resource demands. Landscape infrastructure is being explored in urban studies as a concept and a reality that expands the traditional set of spatial planning and design strategies towards the definition and realisation of a multifunctional system. The notion of landscape infrastructure, e.g. green and blue open spaces as a structurally performing system, is developing new ways to conceive and shape the organization of the human/natural environment for the future transformation of urban regions. This concept is being discussed widely in terms of its implications for design and planning practices; particularly the role of retrofitting nature into highly urbanized areas. Examples of projects that design natural areas to reach performance objectives, such as flood alleviation, show multi-purpose use of urban spaces with many additional social, economic and environmental benefits (e.g. Kimpton et al, 2012).

CONTEMPORARY STORMWATER MANAGEMENT

Stormwater infrastructure is historically centralized, built below ground in hidden piped drainage networks or concrete basins and conceived sectorial and independently from urban planning and design visions (Marsalek, 2013). Its’ logic, form and functional qualities are not immediately perceived, being that it is for the most part embedded in underground layers. Uncoordinated management of stormwater infrastructure, urban planning and design often leads to conflicts and incompatibility between this infrastructure and its context, resulting in compromise measures such as costly and disruptive conduit replacement to mitigate increasing runoff (Tucci and Bertoni, 2004). In contrast, working synergistically with ongoing urbanization trends and existing layouts provides an opportunity to manage water locally, closer to source, reducing hydraulic loads in existing drainage infrastructure. By retrofitting the layout of built-up areas in a water sensitive fashion, private and public parcels of land and the right-of-way are made greener, carrying additional benefits to the living space; e.g. reducing urban heat islands. Decentralized measures, such as Water Sensitive Urban Design - WSUD (Water Sensitive Cities, 2014), help to alleviate and adapt to floods and droughts and at the same time support the recovery of biodiversity levels and ecosystems. Key to this concept is to manage water above ground rather than below, and to utilise green and blue rather than/ or complementary to traditional piped (grey) infrastructure. Particularly in developing cities, where the pace of urbanization vastly reduces the availability of natural green areas, the retrofitting of WSUD could potentially deliver stormwater management performance objectives along with urban amenity regeneration (e.g. Ashley et al, 2013). Yet, there is a knowledge gap in planning and designing green and blue infrastructure in a systemic way, addressing city (macro-scale), district (meso-scale), and local (micro-scale) planning levels and their interrelationships (Bacchin et al, 2013). The work presented here aims to address this gap; introducing a landscape planning framework to model the design of spatial strategies, i.e. green and blue infrastructure measures, that are appropriate to the chosen level of analysis and reflect the relationship between the various spatial scales.

A NEW SYSTEM DESIGN APPROACH – DELIVERING VALUE

The integration of surface stormwater infrastructure design within the landscape planning framework requires reconsideration of the traditional ways of managing stormwater to one using landscape elements in a new set of spatial arrangements considered through nested scales. Ecological support processes, such as hydrological flows, retention and percolation of water and geographical features, such as geomorphology, soil type, and groundwater table, are critical aspects of the design of landscape infrastructure for hydraulic performance. Once coupled with urban planning and design, landscape architecture, and mobility flows; green and blue infrastructure can more meaningfully promote new forms of interaction (e.g. Hung et al, 2012). Existing centralized drainage infrastructure was conceived as a single-purpose system and may even become obsolete, subjected to climate and urbanization uncertainties that increase loadings. The contingency of today's stormwater management infrastructure requires the system to be designed for flexibility and adaptability (Gersonius et al. 2010). As an alternative pathway, the infrastructure system is decentralized, following a system performance objective (e.g. Sitzenfrei et al. 2013); being adapted to ongoing needs and prepared better for future uncertainties. Within this new paradigm, the system of open spaces between buildings in cities offers a catalyst for urban regeneration, being used to provide form for decentralized WSUD measures, capable of delivering hydraulic functions and improving the overall quality of ecosystem services (e.g. Philadelphia Water Department, 2009). Part of this system of open spaces, roads and pedestrian pathways can carry multiple functions, reflecting the importance of diversity as a general principle in city-making (Jacobs, 1961).

In the work presented here, the system of open spaces (i.e. road network, pedestrian pathways, public squares, gardens, sports fields, and parks) has been used to structure the ecological and hydrological connectivity within the city landscape at different spatial scale levels. The designed green infrastructure enhances the value of public open spaces, identifying their potential contribution to ecosystem services. In parallel, WSUD (blue infrastructure) manages rainwater that falls on the ground through a sequence of management practices and control structures designed to drain surface water as sustainably as possible (Ashley et al., 2014). In addition to the decentralized and multifunctional characteristics that define the sequence of infrastructural elements, this system is further defined by spatial attributes such as composition, configuration, and hierarchy. Here, the effort is to maximize the multiple benefits of these sets of nested attributes through their spatial arrangements, and predict the cascading effects of interconnecting parts within each system at various physical scale levels. The framework introduced in this paper is structured according to the scale of analysis, scope of the project, and influence of target spatial components.

A TOOL FOR MULTI-FUNCTIONAL DELIVERY OF GREEN-BLUE INFRASTRUCTURE

In this section, a tool for retrofitting green-blue infrastructure design is described, first identifying relevant data according to city (catchment), district (sub-catchment), and neighborhood (micro-catchment) levels that later inform the analytical procedures to describe the many landscape elements and their relations. This is applied to generate an understanding of the urbanized landscape in a series of models, focusing on the selection of multifunctional green-blue spaces that are appropriate to the planning level. The framework illustrates the implications of retrofitting natural or semi-natural structures for stormwater management and additional purposes, e.g. green space provision, at nested spatial scales.

Macro-scale (city/ catchment level)

The first module maps flood susceptibility at the city/catchment level. Maximum Likelihood classification of remotely sensed data (Landsat 5 TM) has been used to assign flooded areas for the year 2007 – the highest annual precipitation over the past ten years (INMET - 8º Distrito de Meteorologia - Porto Alegre). This classification has been further calibrated using slope gradients from the Digital Terrain Model (DTM) and the Topographic Position Index (Brost and Beier, 2012). In addition, major woodland areas and wetlands were identified and classified according to their size and elevation. Lastly, the surface hydrology map (Hasenack, Heinrich et al., 2008) was overlain to the initial classification, with the aim of identifying the major flood susceptibility areas and the overall pattern and location of ecological (green) structure in relation to the hydrological (blue) structure linking the upstream to the downstream landscape areas.

At the macro-scale level, the objective has been the territorial infrastructure modelling based on hydrogeological and ecological suitability for retrofitting green and blue corridors. A network of ecological corridors (links) was first designed based on the highest suitability for natural paths between major green nodes – natural areas (woodland blocks) and semi-natural areas (urban district parks > 100 ha). Suitability analysis was used – defined by a function of weighted values of classified layers: soil type, geomorphology, aquifer vulnerability, and biome. The suitability map (Figure 1) was used to model land facets for hydrogeological and ecological corridors. Wessels et al. (1999) described land facets as areas of relatively homogeneous landform and soils, such as flat terraces with hydromorphic soils (clay content from 30 to 40%), found in the pilot sub-catchment area. The land facet design concept (Brost and Beier, 2012) has been adapted in this research to stormwater management (blue) and green infrastructure design. Subsequently, the resulting network of links (geometry/topology) has been overlain and adapted to the existing road/mobility network using shortest-path routing algorithms - Network Analysis toolset, ArcMap 10.1 (Figure 2).

A corridor link is the continuous swath that optimizes connectivity for a single land facet between two major green nodes (natural or semi-natural areas: woodlands, wetlands, regional/district parks). The corridor in the urbanized context is the minimal territorial area containing the link, deemed as critical for stormwater management and habitat for wildlife. The designed network of links establishes the final territorial network of preferred paths adapted to the urban layout structure (Figure 3). Connectivity is enhanced for the full diversity of natural and semi-natural landscape to sustain key hydrogeological and ecological processes. In this final phase at the macro-scale level, urban roads, collectors and arterials were selected according to their fitness – (1) dimensional/spatial criteria: (1.1) road profile, (1.2) spatial contiguity and linearity; and (2) functional criteria: (2.1) proximity to surface hydrology flow paths, (2.2) road link mobility value – for the retrofitting of green and blue infrastructure. Mobility is a function of the topological structure of the road network, i.e. values of local integration or accessibility (Hillier and Hanson, 1984) in relation to the intensity of public transport routes. Higher mobility values correspond to higher road link (or segment) accessibility and intensity of public transport routes.

This design module aimed at further enhancing the connectivity by as much as practicable, exploiting the existing overall connectivity of natural/semi-natural areas using the existing urban layout. Expected results were enhanced accessibility to major green areas, flood risk regulation and increased provision of ecosystems services, e.g., water quality, climate regulation, habitat for wildlife, and community liveability along the designed corridors.

Figure 1:
GREEN-BLUE NETWORK SUITABILITY MAP

Figure 2:
GREEN-BLUE CORRIDOR DESIGN - INITIAL GRAPH ANALYSIS IN RELATION TO THE ROAD NETWORK

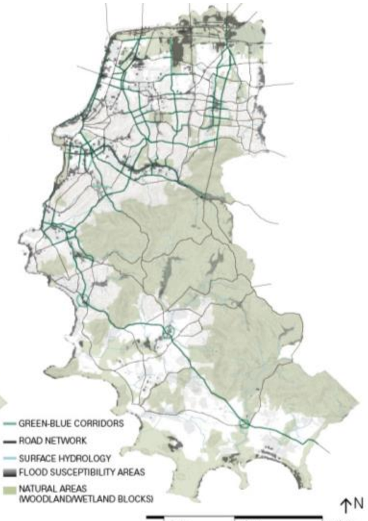

Figure 3:
FINAL GREEN-BLUE NETWORK OF PREFERRED PATHS ADAPTED TO THE URBAN LAYOUT STRUCTURE

Figure 1. Green-blue network suitability map.
Figure 2. Green-blue corridor design – initial graph analysis in relation to the road network.
Figure 3. Final Green-blue network of preferred paths adapted to the urban layout structure.

Meso-scale (district/sub-catchment level)

At the meso-scale, the carrying capacity of the existing drainage infrastructure was modelled using EPA SWMM 5.0 to identify flooded nodes for the design storms of 5, 10, 25 and 50 years return period. Identified flooded nodes and links were analysed in relation to road profiles and positioned in the designed network of green and blue major corridors resulting from the previous module at the macro-scale level. A set of multi-purpose network analyses was introduced, seeking to detect pressures and failures in the existing infrastructural system: green areas at the district level, natural hydrology routes/water bodies and piped drainage network. Furthermore, the availability of potential spaces within built-up areas was modelled for the implementation of the corridor links identified at the macro-scale level using topographic/cadastral maps and built-up/population density values as input data.

In this module, the complementarity between existing surface hydrology routes and proposed new green-blue corridors was designed. The model sequence (Figure 4) first identified the following elements in the hierarchical design within the target sub-catchment ‘Areia Creek Basin’: (a) natural surface hydrology routes; (b) initial connectivity routes/major blue corridors links or arteries “B1” – from the macro-scale analysis; (c) secondary connectivity routes and nodes/links (collectors) and blue nodes (detention/retention areas) between natural surface hydrology routes and the new blue corridors “B1”. Subsequently, flood susceptibility areas (critical nodes/links) provided the information to scale stormwater drainage performance objectives for retrofitting green and blue infrastructure at the sub-catchment level. The spatial integration between ecological corridors (green lines) and surface hydrology corridors (blue lines) enhance the capillarity of the system: minor links were designed to be functioning as collectors ‘B2’ and access ‘B3’ between each major corridor line and nearby neighborhood green squares or green blocks (<100 ha) for multifunctional landscape structures. ‘B3’ elements were modeled as complementary nodes and links between ‘B2’ collectors and the existing piped network. Lastly, retention/detention and infiltration areas, and conveyance pathways were identified following topographic position index analysis, soil type and depth to groundwater table parameters. These were used as input values for the identification of ‘B4’ minor stormwater management spaces (links and nodes) completing the network hierarchy of green-blue infrastructure elements. Service area modelling algorithms have been developed to analyse the provision of green spaces for public use (Figure 5). The need for additional public green areas was identified based on the evaluation of weighted values of area size, location, distribution and accessibility of green spaces. Existing green area provision has been weighted according to the assessment of: (a) biodiversity of area composition; (b) amenities/opportunities for health and cultural activities within the area under analysis. At this level of analysis, the tool set aimed to design the final multifunctional green-blue network having as a structural element the road network space; focusing on stormwater management and the provision of natural/semi-natural spaces for public use. The model approach sought a synthesis between road, green and blue networks in a complementary way, so as to ensure a greater multi-purpose performance.

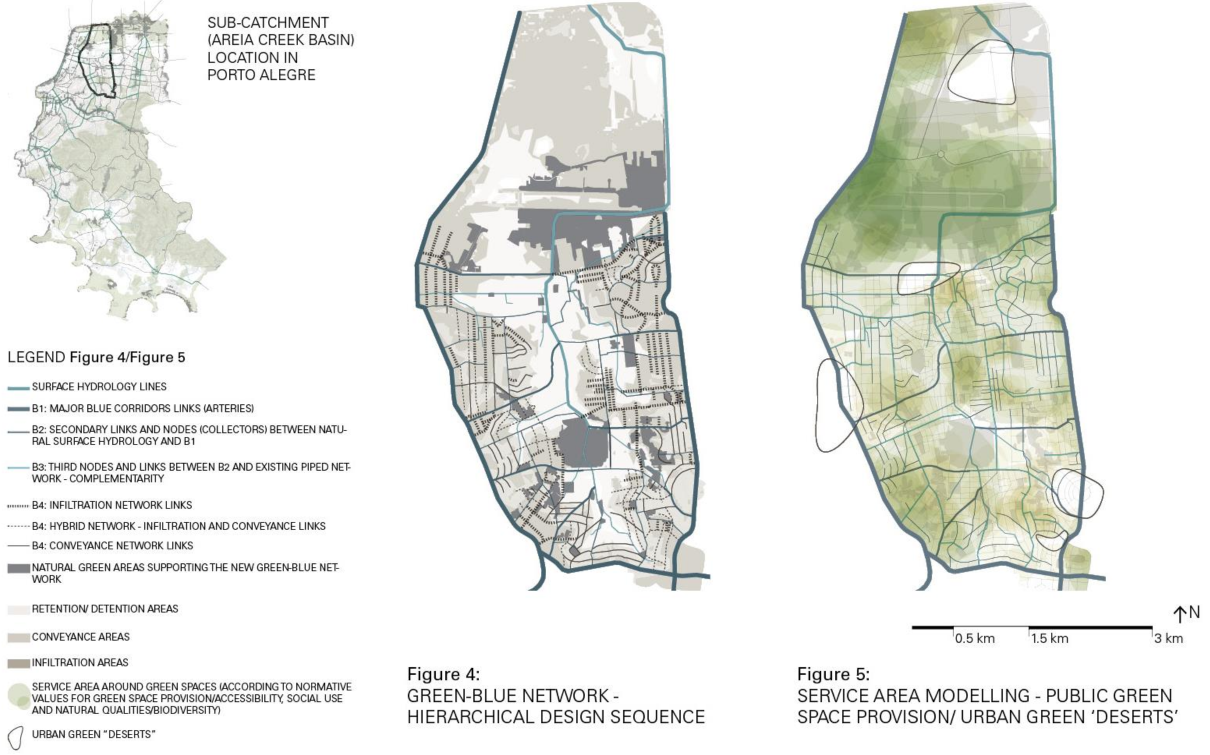

Figure 4:
GREEN-BLUE NETWORK -
HIERARCHICAL DESIGN SEQUENCE

Figure 5:
SERVICE AREA MODELLING - PUBLIC GREEN
SPACE PROVISION/ URBAN GREEN ‘DESERTS’

Figure 4. Green-blue network hierarchical design sequence.
Figure 5. Service area modelling : Public green space provision.

Micro-scale (neighborhood/ micro-catchment level)

In this final module, potential spaces for green-blue measures identified at the meso-scale level have been further evaluated at the micro-catchment (neighborhood level) via urban form parameters such as: (a) built-up density values; (b) setback depths; (c) spatial permeability between public and private spaces (i.e. public sidewalks and private gardens); and (d) road section typologies. Urban form (morphology) values were correlated to a new set of performance criteria which followed sustainable stormwater management and liveability goals; e.g. ecological health, green/open space access and provision to engage in desired open-air activities, interaction and social cohesion via green/blue public areas, etc. Topographic and cadastral maps (built form, vegetation cover and minor green spaces) were used as additional input data to the previous set of geographic layers. Spatial and functional properties at the block/plot level were evaluated for the re-profiling of roads and sidewalks following the design objectives modeled at the meso-scale level. At this stage, the hydraulic connectivity of private gardens (front/ lateral/ back yards) to the surface drainage network was explored. Stormwater drainage performance objectives established for the sub-catchment have been modelled in detail at this level using EPA SWMM 5.0. At each urban block that composes the micro-catchment, effective impervious areas were assessed both for public and private plots. According to its topographic position (valley, gentle or steep slopes, terraces, ridge), modelled using the DTM and the geomorphological structure (Brost and Beier, 2012), the urban block has then been deemed to be suitable for the following WSUD objectives: stormwater conveyance; infiltration; retention/detention goals. In SWMM, LID controls (vegetative swale, infiltration trench, porous pavement, bioretention cell) can be applied following the effective impervious area, urban form parameters and identified design goals.

Surface stormwater drainage performance criteria have been used to model the following scenarios (Figure 6): (a) no water on surfaces other than in ponds or wetlands; (b) controlled exceedance of surface water; (c) manage exceedance pathways along with overall improved spatial quality of the streetscape; (d) controlled flooding (extremes).

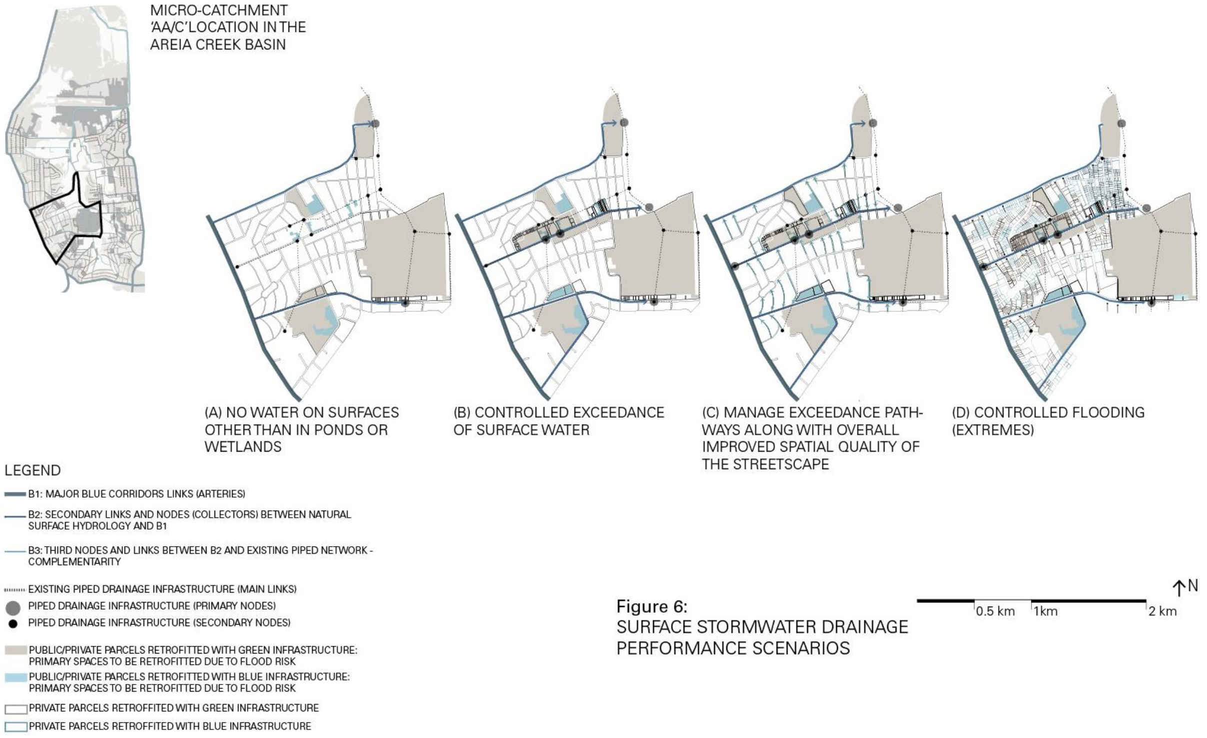

Figure 6. Surface stormwater drainage performance scenarios.

CONCLUSIONS

Stormwater drainage infrastructure is often conceived in isolation from natural (urban) landscape structure and urban layouts, being part of traditional ways of planning layers of infrastructure independently from natural processes and urban form/dynamics. New integrative and synergistic approaches are needed in urban landscape planning design theory and practices that advance stormwater management through the agency of landscape ecology knowledge and liveability goals. Robustness is achieved when infrastructure is consolidated, working in synergy with spatial structures, natural geographic features, and socio-economic aspects. Particularly in developing cities, where the pace of urbanization rapidly reduces the availability of natural areas, designing nature for hydraulic performance plays a vital and multifunctional role that actively contributes to the quality of urban life. By adopting an integrative landscape infrastructure model, the performance and functioning of urban ecosystems can be evaluated and adjusted to maximize (multi)functionality over time. This study has introduced a new tool for urban landscape infrastructure design, where the analyses have identified critical structural elements for stormwater management and ecological performance and modelled a synthesis of the network of green and blue spaces using hierarchical design.. This approach is systemic, describing spatial components and processes through scales. Although the model shows promising initial results, the outcomes must be further validated and verified to judge the model on its practical merits.

AKNOWLEDGEMENT

The first author gratefully acknowledges the financial support of CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), Ministry of Education, Brazil. Part of this work was developed under the Joint Programming Initiative Urban Europe – Green Blue Infrastructure for Sustainable, Attractive Cities.

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