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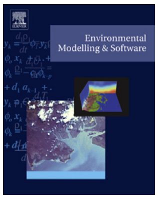

Modelling characteristics of the urban form to support water systems planning

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ABSTRACT

A spatial model is presented, based on urban planning concepts for abstracting urban form characteristics in new and existing areas. Requiring input maps of land use, elevation, population and parameters from planning regulations, the model conceptualises (on a spatial grid) attributes including impervious fraction, allotment geometry and roof areas among other relevant characteristics for integrated urban water management. The model is calibrated to three different Melbourne districts, varying in size (10–60 km^2) and land use. Performance was evaluated by comparing modelled outputs with observations of total dwelling count, employment and spatial distribution of impervious fraction and residential roof areas. Results not only highlight reasonably good prediction, particularly with spatially variable indicators such as imperviousness across all case studies, but also logical contrasts and consistency in the chosen planning parameters across the different case study districts. Discrepancies highlight aspects needing improvement and potential for exploring auto-calibration and model sensitivity.

Software availability

Name of Software: UrbanBEATSv1.0 – Urban Planning Module (*md_delinblocks.py* and *md_urbplanbb.py*)
Contact Address: Peter M. Bach, Monash Infrastructure Research Institute, Department of Civil Engineering, 23 College Walk, Monash University, Clayton 3800 VIC, Australia. Email: peterbach@gmail.com
Year first available: 2016
Supported Platform(s): PC (Windows 7, 8, 10), Mac, Linux
Program Language: Python 2.7
Program Size: ~78 MB (source files for modules are ~1 MB)
Availability: Contact corresponding author to obtain full software, also visit www.urbanbeatsmodel.com for updates
Cost: Free (GNU General Public License)

1. Introduction

With the emergence of urban ecology in recent decades (Niemelä, 1999; Grimm et al., 2008) and over half of the world's population now living in urban areas (United Nations, 2012), cities have become an important focal point in future sustainable development. Understanding the impact that urban planning can have on environmental outcomes has been of interest in the last two decades (e.g. Pauleit and Duhme, 2000; Alberti et al., 2007). Research has uncovered intricate interactions between urban form and water infrastructure, which include, for example, the effects of land use planning (Lee et al., 2009), impervious cover (Arnold and Gibbons, 1996), density, street layout and residential neighbourhood design (Stone, 2004) on stormwater runoff, water quality, water supply security and other aspects that affect ecosystem services and the overall liveability of cities (Vlachos and Braga, 2001). Despite evolution of urban and water systems planning disciplines over the last few decades (Klosterman, 1997; Brown et al., 2009; Gurran, 2011) towards becoming more complex and 'wicked problems' (Rittel and Webber, 1973; Campbell, 1996; Gauthiez, 2004), considerable advancements have also been concurrently made in the numerical and computational tools to support this

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process (Geertman and Stillwell, 2004; McIntosh et al., 2007; Bach et al., 2014).

Following the advancements in Geographic Information Systems (GIS), researchers have acquired new and efficient ways of generating, manipulating and communicating spatial information (Harris and Batty, 1993; Chang, 2010; Eggimann et al., 2017). The underlying concepts of spatial data processing have since found their foothold in many existing urban water models and quantitative studies (comprehensive reviews are offered by both Elliott and Trowsdale, 2007 and, Bach et al., 2014). Obtaining and preparing maps of desired urban information as model input (e.g. impervious cover, roof areas, housing demographics, land surface cover) is often a laborious and time-consuming process and fraught with errors and uncertainty that may have originated from the initial digitization or drawing process. Sometimes the information is also non-existent (e.g. a scenario of a future urban development). As such, more systematic and pragmatic methods are often encouraged in the integrated modelling literature (see e.g. Bach et al., 2014; Lerer et al., 2015; Eggimann et al., 2017) that are sufficiently detailed to serve its desired purpose. Of the variety and diversity of studies in the literature, three prominent groups of methods have been identified: (1) empirical relationships, (2) conceptual techniques and (3) procedural methods.

Empirical relationships are used, for example, to estimate impervious surface cover from basic geographic information such as population or land use (Butler and Davis, 2004; Majid, 2006; Chabaeva et al., 2009). Such techniques are also common in assessments of centralised water infrastructure (see e.g. Fu et al., 2009; Sitzenfrei et al., 2013) and urban ecology (e.g. Uuemaa et al., 2005; Alberti et al., 2007) where impact of urbanisation on the natural environment is of interest. In contrast, there are also more complex integrated models that require users to conceptualise the urban landscape in greater detail, either as a subset of demographic input parameters or by selecting suitable templates from a pre-defined database and matching them to available geographic data. Examples of such models include Aquacycle (Mitchell et al., 2001), City Water Balance (Last, 2010) and the ReVisions framework (Ward et al., 2012). Quantitative studies by Bach et al. (2013a) and Stone (2004) also demonstrate how urban form can be conceptualised to assess their interaction with specific urban water system characteristics. A third, but less common methodology (in current urban water modelling research), involves procedural algorithms, i.e. geometric rules (e.g. space syntax, see Hillier and Hanson, 1984) that are used to generate highly detailed geometry of the urban environment, but are also more computationally intensive (e.g. Parish and Müller, 2001; Vanegas et al., 2012). Procedural methods have the potential of generating a much greater level of spatial detail that can support the increasing complexity of integrated urban water models. For example, applications of procedural algorithms by Urich and Rauch (2014) and Mikovits et al. (2014) demonstrate how this richness of spatial information can be used to explore climate and flood adaptation strategies.

Modelling the planning of urban water systems has been increasingly embracing exploratory modelling techniques (Bankes, 1993), evidenced by recent work in both models of the biophysical environment (Sitzenfrei et al., 2010; Urich and Rauch, 2014) and social water system (De Haan et al., 2016). Recent reviews also highlight a progression towards greater participation of affected stakeholders (Voinov and Bousquet, 2010; Bach et al., 2014; Voinov et al., 2016). The success and robustness of these modelling exercises depends not only on an accurate representation of the spatial environment that is being simulated (suited to the planning objective and that stakeholders can relate to), but also on the computational efficiency of these models. Although conceptual methods are more computationally efficient than procedural algorithms, their level of spatial detail is constrained by gross simplification (using highly aggregated parameters and/or limited number of pre-defined templates). As such, their flexibility, transferability and level of realism become questionable. Conversely, procedural algorithms, which are also grounded in architecture and urban planning theory, offer highly detailed representation of urban space, but can require a large amount of input data and powerful hardware or cloud-based solutions when simulating large urban districts.

To cope with the rapidly growing needs for integrated urban water management and the collaborative nature that planning has evolved into (Klosterman, 1997; Voinov and Bousquet, 2010), models should remain pragmatic (Bach et al., 2014), but bridge language, knowledge and communication across disciplines. Designing sustainable urban water technologies or water management policies has embraced the need for better integration with the urban form and demographics and accounting for local context and spatial variability to more effectively harness the multiple benefits that these solutions provide (Kuller et al., 2017). This must not only consider greater and more flexible spatial detail in models, but concurrently make them pragmatic and computationally efficient to support an exploratory process (Bankes, 1993; Urich and Rauch, 2014), facilitate improved dialogue and understanding of interactions and nuances between urban planner, water managers and other stakeholders throughout the process (Tewdwr-Jones and Allmendinger, 1998). Conceptual methods oversimplify the spatial detail with many assumptions and procedural methods are complex and deeply rooted in the architectural and urban planning disciplines. However, we see a necessity in their combination and exploring a new hybrid approach to spatially representing the urban environment. Such a combination leverages the advantages of both conceptual (in terms of simplicity and computational efficiency) and procedural methods (in terms of closer relation to architectural and urban planning language). Although not as prevalent in the urban water literature, the concept of using planning regulations to create abstractions of urban form has been investigated in the energy sector to improve allotment-scale energy calculations for city-scale decision-support models (Yamaguchi et al., 2007; Hargreaves et al., 2017; Salter et al., 2017). Many of these techniques, however, limit the representation of urban form to a pre-defined subset of commonly occurring neighbourhood blocks. Our technique differs in that it does not use pre-defined archetypes, but rather generates the urban form based on geographic input data and planning parameters, which are specified in the form of distributions to account for inherent spatial variability.

Although we previously demonstrate a simpler conceptual approach, which uses planning regulations to conceptualise the urban environment (see Bach et al., 2013a), there are a number of shortcomings: (1) it cannot be adapted directly to real-world data due to its non-spatially explicit nature, (2) it does not cover enough diversity in land use planning both in terms of variety of land uses (e.g. residential, non-residential) and variability within a single land use type (e.g. residential houses or apartments). Furthermore, many of the concepts, whilst they are representative of typical residential urban forms, have neither been validated against real-world data nor been rigorously supported by urban planning theory. In this paper, we build upon this initial concept by developing and testing a more advanced *Urban Planning Module* for characterising the spatial urban environment that, whilst largely a conceptual representation, incorporates more extensive procedural modelling elements. More specifically, this study focuses on: