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Research paper

Revisiting land use classification and spatial aggregation for modelling integrated urban water systems

Peter M. Bach[a,b,*], Severin Staalesen[a], David T. McCarthy[a,b], Ana Deletic[a,b]

[a] Monash Water for Liveability, Department of Civil Engineering, Monash University, 23 College Walk, Clayton 3800, VIC, Australia
[b] Cooperative Research Centre (CRC) for Water Sensitive Cities, Monash University, Clayton 3800, VIC, Australia

HIGHLIGHTS

- Existing land use classifications are inadequate for integrated urban water models.
- A new water-centric classification system was applied to Greater Melbourne.
- Melbourne's land use mix reveals strong contrasts between inner city and fringes.
- Spatial aggregation in urban water models causes loss of significant information.
- Land use as only model input is insufficient for depicting urban water environments.

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ABSTRACT

Land use and different scales of spatial data aggregation are important for integrated urban water modelling. Inadequacy of land use classification in such models, however, prompted development of a new water-centric classification. A thirteen-category system (considering land cover, utilisation, and urban zoning aspects) was devised and applied to Melbourne, Australia. Sensitivity of the classification to spatial aggregation was tested by analysing randomly sampled subsets of Melbourne's urban fabric for variation in landscape patterns, land use dominance and fragmentation. Significant differences were found when comparing inner city (highly fragmented, dominated by many land use categories) to fringes, (only few dominant categories e.g. residential, reserves), which are challenging to accurately represent in urban water models if oversimplified. The new classification encompasses key integrated urban water management aspects, but does not capture local-scale features of the urban environment. Significant shortcomings for using spatial aggregation methods to simplify data for urban water models were found. Solely focussing on spatial coverage of land use instead of land use mix neglects important water interactions between categories (e.g. open space and residential). Trade-offs between spatial resolution and computational efficiency, for example, can degrade accuracy of representing urban water characteristics as less-dominant land uses are systematically removed. Finally, spatial aggregation methods likely result in the loss of minor (yet important) land uses (e.g. *Civic*). More effective methods for representing the variability of urban environments, which depart from simple aggregated rasters and sole reliance on land use, may be required to better define urban complexity in our water models.

1. Introduction

Understanding the relationship between urban form (e.g. city layout, land-use, building density, etc.) and urban water systems (i.e. water supply, sanitation and drainage) is essential to making well-informed decisions about placement of new and adaptation of existing water infrastructure. Models are proven to aid stakeholders in this challenging process (e.g. Bankes, 1993). However, if they are to support effective integrated urban water management (IUWM), it is important that these models can reliably capture interactions between the urban water cycle and the built environment. This could, for example, include simulating variability in water quantity and quality fluxes for different spatial (from household to neighbourhood and broader region) and temporal (daily and/or annual) scales, which requires an accurate assessment of a number of features such as resident population (distribution and

* Corresponding author. Tel.: +61 4 3217 5283.
E-mail addresses: peterbach@gmail.com (P.M. Bach), severin.staalesen@gmail.com (S. Staalesen), david.mccarthy@monash.edu (D.T. McCarthy), ana.deletic@monash.edu (A. Deletic).

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density), industry and commercial activities, surface cover (e.g. paved or unpaved), topography and urban form.

Integrated modelling of urban water systems has been widely researched since the late 1970s and has evolved rapidly over the last three decades from simple interactions between components of a single system to the integration with urban models (see e.g. Bach, Rauch, Mikkelsen, McCarthy, & Deletic, 2014). With the increasing complexity of interactions being modelled within the urban water system and the adoption of Geographic Information Systems (GIS) in urban water management (Niemczynowicz, 1999; Sample, Heaney, Wright, & Koustas, 2001), spatial representation of both water infrastructure and its surrounding urban environment in models has been brought to researchers' attention (e.g. Bach et al., 2013). Two significant topics that should be considered conjointly and are underdeveloped in current urban water modelling literature include the consideration of land use and representation of geospatial information. Classification of different land uses – defined in this study as both land utilisation and land cover (Burley, 1961) – helps subdivide an urban system into smaller, measurable units, relates to pertinent characteristics of the urban water cycle such as stormwater quality (Goonetilleke, Thomas, Ginn, & Gilbert, 2005) or water demands (demonstrated by Last, 2010; Ward et al., 2012) and also aids in collating spatial data, all of which can potentially improve the efficiency of urban water models and add value to the information gained from them. Coupled with land use, however, is its spatial representation, either through a raster grid (Ludwig et al., 2003; Sitzenfrei, Fach, Kinzel, & Rauch, 2010), polygonal geometry (Stevens, Dragicevic, & Rothley, 2007) or other formats (e.g. Mitchell, Mein, & McMahon, 2001; Ward et al., 2012), the choice of which can significantly affect the integrity of geographic data and consequently affect model outputs due to the propagation of significantly altered information.

The literature on water systems modelling contains ways of examining land use and representing geospatial information in diverse ways. Some models draw upon existing land use classification studies, while others use conceptualised representations of the urban environment. For example, Aquacycle (Mitchell et al., 2001) simulates the urban water cycle in residential subdivisions using a conceptual cluster-based representation guided by occupancy, land cover and water flow characteristics. Similarly, the Urban Water Optioneering Tool (UWOT) (Makropoulos, Natsis, Liu, Mittas, & Butler, 2008) defines an array of household types and considers multiple scales for sustainable water management strategies across residential developments. City Water Balance (Last, 2010) models similar aspects to Aquacycle, but introduces an extensive list of possible land uses in a conceptualised manner (49 different urban typologies, which consider building types, infrastructure and open spaces, grouped into 20 main categories). The Regional Visions tool (ReVisions) (Ward et al., 2012) reconstructs the urban environment using a pre-defined database of 'tiles', each with information about the local land use, surface cover, urban form and possible water infrastructure options. Some approaches have relied on GIS. The Virtual Infrastructure Benchmarking (VIBe) approach (Sitzenfrei, Fach, et al., 2010), for example, generates spatially-explicit virtual alpine cities, represented as a 100 m raster grid of uniform land uses and topography, for the design of water infrastructure. The urban land use category within the model is, however, an aggregated category that does not distinguish between residential and non-residential aspects, which is significant from an urban water management perspective. Similarly, integrated modelling of urban growth, flood hazards and changes to rainfall-intensity–duration relationships uses readily available land cover maps with data on morphology and existing infrastructure to characterise three cities (Veerbeek et al., 2011). The work, however, does not explicitly integrate land use with the urban water system, but instead links it with land cover information from the urban model.

The varied approaches presented above share four commonalities: (1) considering how the land is utilised, (2) defining surface cover characteristics, (3) considering local demographic information and (4) aggregating spatial data to discrete spatial 'units' that can be efficiently modelled (in order to overcome the intractable complexity from integrating multiple subsystems into a common model). The adequacy of land use and raster-based representation in some these models is, however, questionable. Existing land use classifications are either too simplified or not spatially explicit enough to appropriately support urban water infrastructure models. Furthermore, little is understood about the how raster-based representation and spatial resolution alter the geographic information that is input to our urban water modelling algorithms. If we are to develop tools to support future urban planning and IUWM, we will need to advance our understanding of these two aspects. As such, our aim in this paper is twofold:

1. develop a new water-centric land use classification and
2. investigate (using this classification) the integrity of urban geospatial information from aggregation through raster-based representation.

This study is divided into three sections. We first review a variety of approaches to land use classification and propose a set of land use categories suited to integrated urban water system modelling. We then apply the proposed classification to Melbourne, Australia as a case study, and, finally, examine sensitivity of land use patterns (resulting from using the proposed classification) and data aggregation effects to spatial resolution using a raster-based representation.

There are two reasons for using Melbourne as a case study in this paper: (a) the city is significantly "sprawled" (approximately 8000 km^2 in area) making it suitable for the discussion of computational challenges in city-wide integrated modelling and (b) Melbourne's land use mix is diverse, allowing for robust development and application of an urban water-centric land use classification. Therefore, findings will be transferable to other cities in the world. Furthermore, although we develop and test the sensitivity of this new water-centric classification in this study, testing impact of this on actual modelling results is beyond the scope of the paper. Key findings from this study will, however, aid modellers in improving the development of spatial integrated urban water models.

2. Urban water-centric land use classification

2.1. Overview of land use classifications and their shortcomings

Land use classification dates back to the early 19th Century and began to be applied in urban environments a century later (Guttenberg, 2002). Initial results in the 1950s to aid planning (and controlling) the post World War II urbanisation boom (Gurran, 2011; Guttenberg, 2002) were fraught with ambiguity and failed to meet their intended purpose: understanding the organisation of urban environments (Shapiro, 1959) and how it affects environmental fluxes (e.g. water). Dominant forms of land use classification were largely one-dimensional, activity-based systems derived from urban economic attributes (Berry, 1974; Guttenberg, 2002; U.S. Urban Renewal Administration, Housing and Home Finance Agency, and Bureau of Public Roads, 1965; Shapiro, 1959). One of the few systematic (possibly effective) attempts to classify land was by the Australian Bureau of Rural Sciences (BRS). Differences between land use and land cover are detailed in their ACLUMP classification, which has 100 specific uses of which slightly more than 20 apply to urban areas (BRS, 2005). The COoRdination of INformation on the Environment (CORINE) land cover project's