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Mapping long-term temporal change in imperviousness using topographic maps

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ABSTRACT

Change in urban land use and impervious surface cover are valuable sources of information for determining the environmental impacts of urban development. However, our understanding of these impacts is limited due to the general lack of historical data beyond the last few decades. This study presents two methodologies for mapping and revealing long-term change in urban land use and imperviousness from topographic maps. Method 1 involves the generation of maps of fractional impervious surface for direct computation of catchment-level imperviousness. Method 2 generates maps of urban land use for subsequent computation of estimates of catchment imperviousness based on an urban extent index. Both methods are applied to estimate change in catchment imperviousness in a town in the South of England, at decadal intervals for the period 1960–2010. The performance of each method is assessed using contemporary reference data obtained from aerial photographs, with the results indicating that both methods are capable of providing good estimates of catchment imperviousness. Both methods reveal that peri-urban developments within the study area have undergone a significant expansion of impervious cover over the period 1960–2010, which is likely to have resulted in changes to the hydrological response of the previously rural areas. Overall, results of this study suggest that topographic maps provide a useful source for determining long-term change in imperviousness in the absence of suitable data, such as remotely sensed imagery. Potential applications of the two methods presented here include hydrological modelling, environmental investigations and urban planning.

1. Introduction

Accurate estimates of impervious surface coverage (commonly known as imperviousness) within watersheds (catchments) are required for hydrological modelling and urban land use planning because increased imperviousness results in decreases in infiltration and soil storage capacities (Kidd and Lowing, 1979). Furthermore, replacement of natural drainage with artificial conveyance pathways can also reduce catchment response times (Packman, 1980). These impacts can subsequently combine to increase the frequency and magnitude of flood events through increased and more rapid runoff (Huang et al., 2008; Villarini et al., 2009), and lead to disruption of natural groundwater recharge (Shuster et al., 2005; Im et al., 2012). Moreover, the hydrological alterations caused by increasing imperviousness typically give rise to environmental issues, such as degraded water quality, decreased biodiversity in water bodies, and increased stream-bank erosion (Schueler, 1994; Arnold and Gibbons, 1996; Hurd and Civco, 2004; Amirsalari et al., 2013). Such impacts can be especially pronounced in peri-urban developments; areas surrounding existing towns, which convert previously permeable rural land into highly impermeable and artificially drained catchments (Tavares et al., 2012).

Understanding and modelling the long-term hydrological impacts of increased urban development requires concurrent information on the change in impervious surface coverage. Maps of impervious surfaces can be produced from either field surveys, manually digitising from hard-copy topographic maps, or the use of remote sensing (RS) data. Whereas field surveys and manual digitisation can be time-consuming and laborious, the large continuous areal coverage provided by RS datasets can be exploited using image processing algorithms to rapidly map impervious surfaces for only a fraction of the time and cost. Accordingly, RS is becoming increasingly recognised as a valuable tool for mapping imperviousness.

A comprehensive, authoritative review of the different methodologies employed to map impervious cover from RS data is provided by Weng (2012). To summarise, RS-based approaches to mapping imperviousness generally fall into three broad categories: per-pixel, object-based and sub-pixel. Per-pixel approaches commonly involve producing a binary map by determining whether individual image pixels correspond to either pervious or impervious surfaces,

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typically through aggregating the classes of an initial land cover classification (Yuan and Bauer, 2006; Im et al., 2012; Amirsalari et al., 2013). In contrast, object-based approaches involved the classification of groups of contiguous image pixels (i.e., objects or regions) by also considering various shape, contextual and neighbourhood information (Benz et al., 2004; Weng, 2012). Classifying an image based on objects helps to overcome the "speckled" effect often encountered with per-pixel classification in urban areas (Van de Voorde et al., 2003), thus enabling improved mapping results (Yuan and Bauer, 2006; Zhou and Wang, 2008). A major limitation of per-pixel approaches is that they assume each pixel comprises a single land use or land cover type. However, pixels containing a mixture of land use or cover types are common in low-to-moderate resolution imagery acquired over complex heterogeneous landscapes such as urban areas (Weng, 2012). Sub-pixel approaches can be used to overcome this to derive accurate estimates of imperviousness because they decompose the pixel spectra into their constituent parts, therefore providing fractional measures of impervious surface area. Popular approaches in this category include unmixing the pixel spectra to determine the fractional abundance of each constituent end-member surface type (Lu et al., 2006), or modelling fractional imperviousness through statistical regression and scaling of spectral vegetation indices (Bauer et al., 2004; Van de Voorde et al., 2011).

With the earliest source of RS data comprising panchromatic aerial photograph lacking in sufficient spectral information, the mapping of imperviousness using RS is restricted to the last few decades since the emergence of spectral satellite imagery (e.g., Landsat). Consequently, few studies have assessed long-term land cover change using RS data (e.g., Gerard et al., 2010; Tavares et al., 2012), and even fewer have mapped long-term changes in impervious cover (Weng, 2012). Therefore, our understanding of the hydrological impact and non-stationary flooding trends in relation to impervious surface change is somewhat limited (Ogden et al., 2011; Vogel et al., 2011; Dams et al., 2013).

Linking imperviousness to alternative sources of digital geoinformation could provide a means of mapping long-term changes in impervious cover. However, such datasets are not usually available at the national scale or comparable over long periods of time. National land cover mapping products such as the UK Land Cover Map (LCM) 1990, 2000 and 2007 (Centre for Ecology and Hydrology) cover only a short time period and are inconsistent due to the different processing algorithms applied to derive each product from the RS data (Morton et al., 2011). While methods such as land use trajectory analysis (Verbeiren et al., 2013) could be applied to help improve the consistency of the time-series somewhat, there will still likely be a residual error arising from the use of contrasting algorithms for generating each data product. Physical settlement boundaries and land use change statistics may be a useful alternative source of information (e.g., Bibby, 2009) but can only be loosely regarded as proxies for imperviousness. In most cases, the only consistent and long-term sources are topographic maps produced by national agencies. Within the UK topographic maps have been produced by the Ordnance Survey – the national mapping agency for Great Britain – since the mid-19th century. Despite representing a potentially valuable source for deriving long-term change in land use or land cover, studies assessing the use of such information are scarce (e.g. Hooftman and Bullock, 2012).

The aim of this study is to utilise historical topographic maps for semi-automated mapping of urban land use change and change in impervious cover. Two novel methods are presented that utilise topographic maps to: (i) derive maps of fractional impervious surface for direct computation of catchment-level imperviousness; (ii) derive maps of urban land use for subsequent computation of estimates of catchment-level imperviousness based on an urban extent index. Impervious surface cover estimates computed using these two methods are validated using reference data generated through a RS-based image classification of high-resolution aerial photographs. The methods presented herein are employed in an attempt to determine their suitability for indicating change in urban land use and imperviousness – here throughout a 50-year period from 1960 to 2010 in a number of hydrological catchments surrounding a UK town that exemplifies rapid peri-urban development.

2. Study area

The study area (Fig. 1) encompasses two adjacent small urban stream catchments located to the north of Swindon in the south of England; comprising the Haydon Wick brook and Rodbourne stream, both tributaries of the River Thames (Fig. 1 inset). Swindon was designated as an Expanded Town under the Town Development Act in 1952 which encouraged town development in county districts to relieve over-population elsewhere. The Rodbourne stream catchment has been highly urbanised since the 1950s and comprises a large area of commerce and industry on the northern edge of Swindon town, along with highly urbanised housing developments. The Haydon Wick brook catchment is located further to the north of Swindon and has undergone widespread development since the 1990s, prior to which it was a predominantly agricultural landscape. Within the Haydon Wick catchment a number of distinct catchments (1–5) have been selected (Fig. 1) that capture and reflect the diversity and age of different developments within the area. The Rodbourne catchment, in which development has incrementally expanded since the 1950s, remains one single catchment unit (6) for this study. The focus of this study is to test two methodologies for mapping changes in urban land use and associated imperviousness in each of these six catchments during the period 1960 to 2010.

3. Material and methods

The ability to utilise traditional topographic maps for long-term, historical mapping of urban extent and estimation of catchment imperviousness is assessed using a three-pronged approach (Fig. 2). The approach involves first estimating contemporary catchment fractional impervious surface area directly from aerial photographs for use as reference data. These reference data are then used to validate the two methods presented in this paper for mapping historical change in impervious cover topographic maps. Following validation, a comparison of the two methods is undertaken to assess their relative performance revealing long-term change in catchment impervious cover between 1960 and 2010. More detailed information regarding the methodological approach is provided in the following sub-sections.

3.1. Deriving catchment imperviousness from aerial photographs

Reference data for quantifying the catchment fractional impervious cover were obtained from aerial photographs for three decadal time-slices within the 50-year period of interest – namely 1991, 1999 and 2010 (herein referred to as 1990, 2000 and 2010, respectively). The reference data were generated by first classifying 0.5 m true-colour aerial photographs into pervious land cover classes: grass, trees, bare soil and water; and impervious land cover classes: roads/pavements, commercial buildings and residential buildings. It was anticipated that land cover classes such as bare soil and roofing tiles could be particularly difficult to discriminate using the limited spectral information contained in only the red, green, blue bands of the aerial photographs. Therefore, textural information was also incorporated in the form of the Grey-Level