Journal of Environmental Management 92 (2011) 1438–1448

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review

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ARTICLE INFO

Article history:
Received 8 July 2010
Received in revised form
9 December 2010
Accepted 20 January 2011
Available online 18 February 2011

Keywords:
Impervious surfaces
Urbanisation
Runoff
Urban remote sensing
Stormwater models

ABSTRACT

Urbanisation produces numerous changes in the natural environments it replaces. The impacts include habitat fragmentation and changes to both the quality and quantity of the stormwater runoff, and result in changes to hydrological systems. This review integrates research in relatively diverse areas to examine how the impacts of urban imperviousness on hydrological systems can be quantified and modelled. It examines the nature of reported impacts of urbanisation on hydrological systems over four decades, including the effects of changes in imperviousness within catchments, and some inconsistencies in studies of the impacts of urbanisation. The distribution of imperviousness within urban areas is important in understanding the impacts of urbanisation and quantification requires detailed characterisation of urban areas. As a result most mapping of urban areas uses remote sensing techniques and this review examines a range of techniques using medium and high resolution imagery, including spectral unmixing. The third section examines the ways in which scientists and hydrological and environmental engineers model and quantify water flows in urban areas, the nature of hydrological models and methods for their calibration. The final section examines additional factors which influence the impact of impervious surfaces and some uncertainties that exist in current knowledge.

1. Introduction

Urbanisation produces numerous changes in the natural environment it replaces and it is increasing. It is predicted to rise from 75% of people in developed countries in 2000 to 83% in 2030, while over the same period it will rise from 40% to 56% in less developed countries (Cohen, 2003). Many environmental impacts of urbanisation have been documented, for example, Faulkner (2004) identified habitat fragmentation and biochemical and physical changes to hydrological systems. Changes in the chemical and biochemical characteristics of hydrological systems have been associated with the effects of urban sources of pollution, such as stormwater. For example, Owens and Walling (2002) reported that in sediments in rural and urban catchments the total phosphorous content increased with increasing levels of urbanisation, and Bay et al. (2003) reported that differences in the level of urbanisation in differing watersheds were likely to be responsible for the differences in toxicity in stormwater plumes. There is also documentation of the physical disruption of natural hydrological systems, but changes to hydrological properties are more difficult to quantify than changes in pollutant concentrations. These changes are complex and include components such as groundwater flow that are invisible and others that are not immediately observable. For example, the effects of massive stormwater flows become apparent only after storms which are associated with lengthy return periods. In this review, research in relatively diverse areas is integrated to examine how the impacts of urban imperviousness on hydrological systems can be quantified and modelled, and where uncertainties exist.

The hydrological impacts of urbanisation originate from the reduction of the perviousness of urban areas compared to rural and natural land uses. Impervious surfaces such as buildings, roads and other paved areas reduce rainwater infiltration and increase stormwater runoff. Numerous factors influence the amount of runoff but an indicative finding from Rose and Peters (2001) is that peak flows are from 30% to more than 100% greater in urbanised catchments compared to the less urbanised and non-urbanised catchments. In addition, in accordance with Manning's equation which indicates that the velocity of flow of water is indirectly proportional to the roughness of the land surface (Leopold et al., 1995), stormwater flows more rapidly across smooth urban surfaces than across rough natural surfaces. Discharge is important because it provides the energy of a hydrological system. As water flows downhill potential energy is converted into kinetic energy and is available to perform work in the form of erosion (Knighton,

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doi:10.1016/j.jenvman.2011.01.018

1999). The greatly increased stream powers associated with urban settings can potentially alter the shape of a channel and the form of surrounding landscapes. Impacts of urbanisation documented by White and Greer (2006) include increases in flood magnitudes and changes to stream channel morphology and riparian vegetation. A final effect of the reduction of perviousness in urban areas is the resultant reduction in groundwater. Groundwater is located in soil pores and fractures in the bedrock and is replenished by water from precipitation and streams. It is a long-term reservoir of the natural water cycle and is important because it sustains waterways and wetlands. An important potential outcome of reductions in groundwater due to increases in impervious surfaces is a drop in the steady-state streamflow in urban areas (Leopold, 1968).

This review assesses the factors which influence the impact of changes in surfaces and perviousness of urban areas and integrates studies from different fields. It first examines some of the early reports of impacts of urbanisation on hydrological systems and then compares these results with those reported in the last two decades. Some factors which affect the functioning of hydrological systems under increased flow and some effects of changes to the hydrological characteristics of catchments are considered, along with some of the anomalies and uncertainties in current studies of the impacts of urbanisation. The location and character of different land covers within urban areas are important in understanding the impacts of urbanisation, so methods that are used to quantify the areal extent and characteristics of urban surfaces are described. Then, the ways in which scientists and hydrological and environmental engineers model and quantify water flows in urban areas are examined. The final section of the review examines some additional factors which influence the impact of impervious surfaces and some uncertainties that exist in current knowledge. This review does not examine the quality of stormwater runoff or the impacts that contamination may inflict on ecosystems. Urban pollution of stormwater is known to contribute significantly to the contamination of receiving waters and for this topic the reader is referred to the review of impervious surfaces and water quality by Brabec et al. (2002) and observations on the "urban stream syndrome" by Walsh et al. (2005).

2. The impacts of urban imperviousness and runoff

2.1. Initial studies of the effects of urban imperviousness

Research into the impacts of urbanisation intensified in the 1960s, when urban areas in US and European cities began to expand in the post-war period. Leopold (1968) noted that there were four interrelated but separable effects on the hydrology of an area from land use changes associated with urbanisation: changes in peak flow characteristics, changes in total runoff, changes in water quality, and changes in the hydrological amenity. Studies over the next three decades tended to confirm conventional hydrological theory that runoff increases as a result of urbanisation and is governed by the fraction of the area made impervious, and also that imperviousness and the rate at which water is transmitted across the land to stream channels result in decreased groundwater recharge and decreased low flows between rainfall events (Leopold, 1968). Table 1 provides a chronological summary of the findings of some typical studies. The methods used to identify the presence and magnitude of the impacts of urbanisation differed between studies and include: longitudinal studies over time (e.g. Graf, 1977; Arnold et al., 1982), studies of similar catchments with differing urban extents (e.g. Hammer, 1972), computer modelling to predict changes in the urban catchments (e.g. studies cited in Leopold, 1968) and synthesis of the results of other studies (e.g. Leopold, 1968; Hollis, 1975).

Table 1
A summary of some typical early studies of the hydrological impacts of urbanisation.

Authors	Hydrological Characteristic	Impact
Espey et al., 1966	Lag time (time for floods to peak)	Shortened
	Flood discharges	Increased
Leopold, 1968	Bankfull discharge	Increased
Seaburn, 1969	Flood duration	Shortened
Hammer, 1972	Channel cross-sectional area	Increased
Hollis, 1975	Recurrence interval "small" floods	Greatly increased
	Recurrence interval "large" floods	Slightly increased
Graf, 1977	Drainage density	Increased
	Lag time	Reduced
	Peakedness (flashiness) of storm flow	Increased
Arnold et al., 1982	Bank erosion	Increased
	Size of bed material	Increased
	Rate of bed load discharge	Increased
Simmons and Reynolds, 1982	Base flow	Reduced

2.2. More recent studies of urban imperviousness

Over the last two decades, studies of the impacts of urbanisation have examined an increasing number of the hydrological and geomorphic processes within urban catchments and included indirect effects in addition to direct effects such as changes to lag time and flood discharges. In a study of a partially urbanised catchment, Sheeder et al. (2002) found dual hydrograph peaks for urban and rural areas and that they appeared to be based on the degree and spatial location of urbanisation in their study area. The hydrographs also showed that direct runoff did not drain the entire catchment but only a portion of the area (approximately 5–10%), an effect they called "partial drainage". Carlson (2004) noted that the partial drainage area is not known *a priori*.

Many studies identify increased stream "flashiness" as a fundamental change in urban streams. McMahon et al. (2003) compared variables including the number of periods in which the stream stage rose or fell with measures of urbanisation and confirmed that urbanisation is positively correlated with stream flashiness. However the correlation was stronger in some locations than others which was attributed to differences in the fragmentation of the urban land cover. Baker et al. (2004) noted that the term "flashy" (as applied to streamflow) had no set definition, but that flashiness was often equated with the rate of change in flow. These authors devised a flashiness index to quantify oscillations in flow relative to total flow. Analysis using the index showed that streams in urbanised areas had higher rankings than those in less developed areas, but differences between regions were noted and it was suggested that agriculture and conservation measures also influence stream flashiness.

Although a number of studies including Hammer (1972) and Arnold et al. (1982) found changes in channel morphology with urbanisation, other studies have reported ambiguous results. Pizzuto et al. (2000) examined the effects of urbanisation on fluvial morphology by surveying eight paired urban and rural watersheds. They found that the median width of (non-artificial) urban channels was 26% larger than that of rural channels, and channel sinuosity was slightly lower in urban streams, but that bankfull depth and grain size were similar in both streams. Kang and Marston (2006) investigated the impact of conversion to urban land use on channel morphology in three watersheds: one urban, one rural, and one which was changing from rural to urban land cover. A regression analysis of variables including sinuosity, mean bankfull depth and bankfull width failed to explain differences in channel morphology between the three streams. The authors concluded that local geological conditions were mitigating the effects of urbanisation. A study by Nelson et al. (2006) also failed to find effects of urbanisation on channel planform. The study used a hydraulic model to provide information on the locations that experienced high values of shear stress and stream power during large floods, but field surveys showed that the channel planform was stable despite urban development and extreme flooding. This was thought to be linked to geological controls on channel and floodplain morphology. These and other similar studies indicate that local factors (e.g. geology, sediment supply and anthropogenic structures) may influence the impacts of urbanisation on the fluvial morphology of urban streams.

Base flows are normally expected to decrease as a result of urbanisation, but activities associated with urbanisation may change the net result. A study of base flow by Ku et al. (1992) found that the use of recharge basins for collection and disposal of urban storm runoff enabled groundwater recharge to increase, which counterbalanced the use of storm sewers to route runoff directly to streams and coastal waters. The study found a net increase in annual recharge of about 12% in areas served by recharge basins (and a decrease of about 10% in areas without such basins). Brandes et al. (2005) investigated trends in annual base flow volumes using hydrograph data to determine if land development was diminishing the ability of urbanised watersheds to sustain adequate base flow during periods of drought. The expected effects of declining base flow volumes and increasing storm flows were seen in only one watershed which was approximately 20% impervious. However, historical records indicated that groundwater pumping and changes in wastewater discharges had resulted in a net water export over the time period of the study. Hence, changes in urbanisation may not result in measurable reductions in base flow at the watershed scale as transfer of water between basins (which is also associated with urban developments) may be important.

The existence of a threshold level of urbanisation below which changes in the hydrological responses of catchments are not apparent has been noted by some authors, although others disagree. Booth and Jackson (1997) state that changes begin at very low levels of urban development, but there is an accumulation of readily measured effects when the impervious area reaches about 10%. Brun and Band (2000) found only very small changes in the runoff ratio (storm flow divided by precipitation) occurred in their study catchment, and postulated that this was because the impervious area had not exceeded a threshold, which the data for their study area indicated was approximately 20% impervious cover. Recently, Yang et al. (2010) suggested that 3–5% impervious surface area is the threshold, beyond which urbanisation effects start to have a statistically significant influence on streamflow regime.

2.3. The influence of the distribution of imperviousness on its impacts

The difference between total impervious area (TIA) and effective (or directly connected) impervious area (EIA or DCIA) is sometimes used to explain why relationships between impervious surface area and stream parameters do not follow expected patterns. Shuster et al. (2005) defined EIA as impervious areas that are hydraulically connected to a drainage system (e.g. streets with gutters that are sewered to an outfall). Ineffective impervious surface routes runoff to pervious surfaces (e.g. a roof that drains onto a grassed area). In urban settings connectedness is difficult to quantify. For example, it may be dependent on rainfall, as gutters and guttering on roofs may connect rainfall to drainage systems when rainfall is low, but runoff may spill onto pervious areas when rainfall is higher. Quantification of TIA and DCIA is discussed in subsection 3.4.

Studies of the hydrological impacts of urbanisation generally seek an association between a change in an environmental system and a readily measured metric of urbanisation. Some studies employ surrogates such as human population density or road density which may not adequately represent the elements of the urban environment which cause the impact. Urban areas are complex, and both competing and reinforcing effects occur, including covariation of anthropogenic and natural effects and the difficulty of separating present-day from historical influences (Allan, 2004). In particular, where fractional land use is used to quantify urbanisation, differing measures of land use may predict stream condition equally well and so the interpretation that a particular land use variable is the primary driver of stream condition must be made with care. In addition, comparisons which substitute space for time with the use of paired catchments may misinterpret the origin and cause of the recorded differences. Alberti et al. (2007) also state that studies of the relationships between land use and hydrological variables do not generally consider the location of the impervious area within the catchment, its proximity to the stream channel, or its connectedness with other similar areas and the channel. They examined the spatial distribution of imperviousness in urban areas and reported statistically significant relationships between stream condition and both the total impervious area and the mean patch size of impervious areas.

2.4. Other factors which influence the effects of imperviousness

In addition to the local factors in the previous section, the effects of urban development are not easily evaluated because the variability in streamflows is not simply a consequence of anthropogenic activities. Konrad and Booth (2002) provided insights into both temporal issues and the choice of parameter to characterise the effects of urbanisation in a study which assessed the suitability of four streamflow statistics for monitoring hydrological changes associated with urban development. Changes in the statistics were assessed for ten streams and the potential for errors (i.e. detecting trends that were unrelated to land use changes) were evaluated by comparing the trends over the entire period of records (30 years) to trends over subsets of the entire period. Trends were observed in each of the four statistics in some of the streams, but the trends were not consistent in urban streams (and similar trends were observed in some rural streams with no changes in land use). In addition, trends over 10-year periods frequently produced results that were inconsistent with those for the entire period of record. The authors cautioned that streamflow records spanning only a decade are generally unreliable for identifying trends due to urban development because of the background variability in streamflow.

An increased understanding of all the processes that control the hydrological response of catchments to urbanisation will enable a more thorough appreciation of processes in individual catchments. To overcome the difficulties created by the competing effects of urbanisation and other unrelated changes, research examining responses under different management strategies is theoretically desirable but unachievable, as land management decisions must aim to provide the best outcomes based on current knowledge for all the current occupants of a catchment. Due to the complexity of the causal agent (urbanisation) and the numerous processes which occur in catchments, establishing empirical relationships between cause and effect is difficult. Detailed knowledge of the quantity and distribution of impervious areas associated with urbanisation is valuable, and the application of appropriate hydrological models can enhance understanding of causal relationships. Research in these areas is described in the following sections.

3. Quantification of fractional impervious area

Quantification of impervious areas requires detailed characterisation of urban areas, but the use of conventional mapping techniques in intricate urban areas is expensive and time consuming. As a result, most mapping of urban areas uses remote sensing and GIS (geographic information systems) techniques. There are many techniques to extract land cover information from remotely sensed satellite imagery. Traditional classification methods use typical reflectance characteristics of relevant land covers and a Maximum Likelihood Classifier (MLC) to assign each pixel to the land cover class that it best matches. Medium resolution sensors such as Landsat TM (at 30 m pixel resolution) and SPOT HRV (at 20 m) have been shown to provide useful data for urban land covers in many studies (e.g. Weng, 2001). However, some acknowledged weaknesses when mapping urban areas using a MLC are the imperfect differentiation of some anthropogenic surfaces such as concrete from soil features (e.g. Myeong et al., 2001), and that tree canopies may obscure impervious surfaces. In addition, sensors with these resolutions are unable to distinguish features with dimensions smaller than the pixel dimensions, and some pixels within an image are “mixed “(i.e. the pixels represent areas which are partially one land cover type and partially another).

3.1. *The V-I-S model*

Many of the methods in current use for mapping urban areas reflect ideas proposed by Ridd in 1995. He asserted that satellite imagery provided the facility to characterise and compare urban areas and proposed the vegetation-impervious surface-soil (V-I-S) model as a basis for standardisation and comparison. Ridd’s (1995) model uses a ternary diagram to quantify the spatial composition of segments of urban landscapes. He noted that the V-I-S model had the following benefits: (a) an objective-quantitative way to characterise pixels; and (b) an objective-quantitative means for aggregating pixels into eco-units. In his study the modelling stormwater runoff is briefly mentioned among other potential applications of the model, but the focus of the impervious surfaces is their non-natural nature rather than their porosity. The V-I-S model became widely used following the technological advance of spectral mixture analysis (SMA) or spectral unmixing. This technique assumes the reflectance values of each pixel are a linear combination of the fractional area of the pixel occupied by each land cover (Ichoku and Karnieli, 1996). SMA provides a mathematical framework that addresses the problems of mixed pixels and provides pixels fractions of spectrally pure pixels (called endmembers). When combined with Ridd’s model, estimates of vegetation, soil and impervious surfaces within pixels can potentially be derived. Small (2001) noted that the heterogeneity of urban areas at scales comparable to sensor resolution limits the utility of conventional classification methods in urban areas and first proposed the use of SMA. He found that using Landsat TM data for New York City, US, urban reflectance could be described by linear unmixing of low albedo (i.e. low reflectance values across multiple wavelengths, e.g. water and asphalt), high albedo (e.g. concrete and soil) and vegetative endmembers. Phinn et al. (2002) compared results derived using a SMA approach in Brisbane, Australia with the locations in Salt Lake City, US used as a case study by Ridd, and concluded SMA was a robust technique for monitoring urban composition. The method has also been applied to a number of other cities, e.g. Shanghai, China (Wu et al., 2005).

3.2. *Enhancements of the V-I-S model*

Other researchers have noted some limitations in results obtained using this method and searched for enhancements that would overcome them. Wu and Murray (2003) observed that the impervious surfaces in urban landscapes cannot be an endmember because of their spectral variability. In their study (of Columbus, US), a maximum noise fraction (MNF) transformation was used to minimise the influence of band to band correlation and noise in the image data before the selection of the endmembers: low albedo, high albedo, vegetation and soil. They proposed that the impervious surface fraction be calculated by adding low and high albedo fractions, but noted that some low reflectance materials (e.g. water and shade) and high reflectance materials (e.g. clouds and sand) adversely affect the estimation, and that these materials should be identified and masked to ensure that only vegetation, impervious surface and soil are analysed. (Unlike other studies, this study was not affected by the problem of distinguishing between soil and non-natural features such as concrete.) Other studies have also found that the components identified by Ridd (1995) are not the endmembers identified using SMA and have suggested enhancements to the SMA approach. Lu and Weng (2004) analysed a Landsat image of Indianapolis, US and selected five endmembers (shade, green vegetation, impervious surface, dry soil and dark soil) from the MNF components. In another study, Lu and Weng (2006) proposed using temperature data to differentiate between pervious and impervious surfaces in high albedo and low albedo fraction images. (Temperature data are included in Landsat imagery.) Rashed et al. (2003) evaluated the application of multiple endmember spectral mixture analysis to map the urban morphology of Los Angeles County, US using Landsat data. This study included eight endmembers for water and shade, grass, natural vegetation, two for soil, and three for impervious surfaces (dark areas, light areas and red tile roofs). The differences between Ridd’s V-I-S model and methods to map urban surfaces using remotely sensed data were summarised by Small and Lu (2006) who stated “the VIS model represents biophysical land cover classes”, while models that are developed using remotely sensed data represent features that can be distinguished from their reflectance properties. These two sets of features are not necessarily identical.

3.3. *Other methodologies using remotely sensed data*

Many other remote sensing technologies and techniques have also been successfully used to map urban areas. The fraction of urban surfaces that are bare soil is small, and as a result a number of studies have utilised the inverse relationship between vegetation and impervious surfaces in urban areas. The variable most often used to indicate vegetation is NDVI (Normalized Difference Vegetation Index). For example, Yang and Artigas (2008) compared the vegetation fraction from SMA and NDVI to estimate impervious surfaces area for an urban watershed in New Jersey, US. The results showed that nearly 90% of the variation in impervious surfaces in their study area could be predicted using both techniques. In another study, Morawitz et al. (2006) compared change NDVI values over three 5-year time blocks with current conditions in the Puget Sound region, US. They found that various processes could be detected using changes in NDVI, e.g. the metric “percent paved” was highly correlated with negative NDVI change. An alternative to NDVI is the Normalized Difference Built-up Index (the normalized difference between reflectance at mid-infrared and near-infrared wavelengths) which was proposed by Zha et al. (2003), and used to map the city of Nanjing, China. Other studies have used remotely acquired thermal data to map urban landscapes. Some of these studies focus on the overall urbanised area rather than impervious surfaces, but for example Xiao et al. (2007) examined the relationship between impervious surfaces and land surface temperature (LST) in Beijing, China and found the estimated fraction of impervious surfaces was highly correlated with LST.

High-resolution imagery with pixel sizes as small as 0.5 m resolution is capable of providing greater detail in complex urban areas and has been used successfully in a number of studies.

However there are also accuracy issues associated with this imagery. Myeong et al. (2001) noted two challenges: a shadow effect and similarity in spectral response between some classes, but they found that texture analysis and a majority filter were helpful with these problems. Goetz et al. (2003) identified the following issues: the logistics of image acquisition related to phenological conditions, shadowing, and in addition, the cost of the imagery. However, Cablk and Minor (2003) found the nature of shadowed surfaces was detectable using a combination of processing methods including image sharpening and spatial morphological operators. In general, image segmentation techniques to group pixels are often advantageous when high spatial resolution data are used. These algorithms include both spectral and spatial information and create areas which are spectrally homogeneous and recognisable as segments of a landscape, and this method has been proved useful by Thomas et al. (2003).

Other image products have also been found to be useful. Hodgson et al. (2003) mapped imperviousness using high spatial resolution aerial photography and surface-cover height from LIDAR data. Also, high spectral resolution datasets which are gathered at very narrow bandwidths have been used to map urban areas. Ben-Dor et al. (2001) used high spectral resolution CASI imagery to map Tel-Aviv, Israel. However, although the objects in the urban environment (e.g. pavement, shade, vegetation and soil) could be mapped, they had fewer identifying spectral features than expected.

3.4. *Quantification of directly connected impervious area*

The methods for determining impervious surfaces using remotely sensed imagery described in this section are methods which quantify total impervious areas. A number of studies have examined the relationship between TIA and DCIA, and it has been shown to be very variable. Shuster et al. (2005) cite studies by Wibben (1976) which calculated the average ratio of DCIA to TIA to be 0.22, Miller (1979) which reported a ratio of 0.14, and Dinicola (1989) which reported a ratio of approximately 0.60 for high density residential housing. Lee and Heaney (2003) found the ratio of DCIA to TIA was approximately 0.36 in a residential area, and that the ratio of roadways to TIA was approximately 0.33. However, Alley and Veenhuis (1983) found the relationship between EIA and TIA obeyed a power law ($\mathrm{EIA} = 0.15(\mathrm{TIA})^{1.41}$), and that the ratio between curbed-guttered urban area to total area was 0.56 for residential areas. It is possible that these studies may not be comparable as land covers may have been totalled differently in different studies, but the variability in these estimates indicates that a relationship between DCIA and TIA may be elusive. National differences in sizes of residential blocks of land, placement of houses on residential blocks, and design of driveways and footpaths will also affect ratios.

3.5. *Summary*

This summary of methods that have been used to map impervious surfaces is not exhaustive, but the papers cited illustrate general trends. There are many conclusions from these studies. Although Ridd (1995) recommended standardisation, standardisation has not been achieved. It is suggested that there are at least three reasons for this. Firstly, although SMA is a promising technique for the application of the V-I-S model, it is not always possible to distinguish distinct endmembers for impervious surfaces (which have multiple characteristics) and soil (which may be similar to some impervious surfaces). Therefore experimentation to find methods to implement the concept is necessary, and ongoing. Secondly, since Ridd proposed the V-I-S model, newer technologies such as high resolution imagery have become widely available, their application to mapping urban areas is potentially promising, and optimal methodologies for these data must be investigated. Finally, it appears that local factors such as soil colour and the colour of roofing material have a role in determining the limitations of particular techniques. Although standardisation is elusive, high accuracies have been reported when impervious areas are mapped using many remote sensing techniques. The detailed information on the area and location of impervious surfaces that these methods provide is useful to urban planners and environmental scientists. It is also potentially useful when combined with hydrological models to predict the impacts that may occur under increasing urbanisation.

4. Modelling the quantity of urban runoff

Singh and Woolhiser (2002) identified the first documented modelling of runoff to have been by Imbeau (1892), who created an “event” model for relating storm runoff peak to rainfall intensity. The current generation of models which simulate storm water quality and quantity appeared in the early 1970s and were initially developed primarily by US government agencies, such as the US Environment Protection Agency (Zoppou, 2001). Today, there are numerous models that have been developed by academic institutions, government departments and engineering consultants and the number continues to increase. Singh and Woolhiser (2002) listed over 70 models which were designed for general modelling of watershed hydrology, and Elliott and Trowsdale (2007) identified approximately 40 models which were designed specifically or generally to model flows for water sensitive urban design (WSUD). This review examines the characteristics of modelling tools which are available for storm flows in urbanised catchments, the balance between model complexity and data availability, and model calibration. For an analysis of the characteristics and strengths and weaknesses of particular models with the aim of informing model selection, the reader may wish to consult Elliott and Trowsdale (2007).

4.1. *The roles and design of hydrological models*

Mathematical modelling of urban runoff is undertaken by multiple groups of scientists and engineers for a variety of reasons. A major use of urban runoff models is by engineers and planners implementing water sensitive urban design (often referred to as ‘BMP’ in the US) within a planning or local government framework. As a result, many models have been developed by government agencies, such as the US Environment Protection Agency. Table 2 provides the names and example design features of some widely used models from government agencies and other sources. Runoff models are also used for research into various impacts of altered flows in urban catchments (e.g. Choi and Deal, 2008; Nelson et al., 2006) and the likely impacts of climate change on these flows (e.g. Evans and Schreider, 2002; Pfister et al., 2004). The intended uses of a model underpin its general design, complexity and input data. Grayson and Blöschl (2001) use Fig. 1 to illustrate the relationship between model complexity, the availability of data for modelling, and predictive performance of the model. The term ‘data availability’ includes both the amount and quality of the data and the availability of data for model testing. Complex models include more processes and are likely to have more variables. The figure indicates that for a given data availability, there is an optimum model complexity beyond which the predictive performance decreases because there are too many model parameters and not enough data to test if the model is working properly, and that if a simple model is used with high data availability, the information in the data will not

Table 2
Examples of commonly-used hydrological models and their functionality.

Model	Organisation or author	Internet address	Stated purpose	Example model components (and use)
HSPF (Hydrological Simulation Program – Fortran)	USGS (US Geological Survey)	http://water.usgs.gov/software/HSPF/	Simulates hydrologic and water quality processes for pervious and impervious surfaces	Green–Ampt equation (infiltration) Kinematic wave model (overland and channel flow)
HydroCAD	HydroCAD Software Solutions LLC	http://www.hydrocad.net/	Design of urban drainage systems	SCS unit hydrographs and Rational Method (runoff) Muskingum-Cunge method (flow routing)
MIKE Products (e.g. MIKE SHE, MIKE URBAN)	DHI	http://www.mikebydhi.com/	MIKE SHE models groundwater and surface water. MIKE URBAN models sewers, storm water drainage systems, and overland flow	(Components are product dependent) Dynamic flow equations (St. Venant) (channel flow) Muskingum-Cunge method (flow routing) Darcy equation (saturated flow of groundwater)
SWAT (Soil and Water Analysis Tool)	US DA (Department of Agriculture)	http://www.brc.tamus.edu/swat/	A river basin scale model to quantify the impact of land management practices	Green–Ampt method (infiltration) SCS curve number (CN) method (runoff) Muskingum method (flow routing)
SWMM (Storm Water Management Model)	US EPA (Environmental Protection Agency)	http://www.epa.gov/ednnrmrl/models/swmm/	A dynamic rainfall runoff simulation model primarily for urban areas	SCS unit hydrographs and Rational Method (runoff) Horton and Green–Ampt methods (infiltration) Manning's equation (overland flow)
WetSpa (Water and Energy Transfer between Soil, Plants and Atmosphere)	Wang et al. (1997); Liu et al. (2003)	http://code.google.com/p/wetspa/	A GIS-based distributed model for flood and water balance simulation on a catchment scale	Dynamic flow equations (St. Venant) (channel flow) Manning's equation (flow velocity)
WinTR-55	US DA	http://www.wsi.nrcs.usda.gov/products/w2q/h&h/Tools_Models/WinTR55.html	Analysis of the hydrology of small watersheds	SCS unit hydrographs (runoff) Manning's equation (flow velocity)

be fully exploited. For a given model complexity, increasing data availability initially leads to better predictive performance but there is a threshold for each model after which more data does not improve predictive performance. For example, a relatively complex model may require spatially variable data for fractional imperviousness or soil moisture. If these data are not available, it may not be possible to accurately calibrate the model and its predictive performance may be low. Conversely, simpler models are likely to be unable to utilise complex data, and there may be no advantage in obtaining detailed data, for example for fractional imperviousness, because they will not improve the predictive accuracy of the simple model. Grayson et al. (2002) found that the most common situation for practical applications of modelling was the use of a complex model with limited data, and that increased data availability was needed to improve the predictive performance.

Models which are used to predict water flows through catchments are frequently described as having either 'distributed' or 'lumped' input data (e.g. Beven, 1989). A lumped model takes little or no account of the spatial distribution of the input, whereas distributed models include spatial variability. Models which forecast the magnitude of urban runoff during storms and those designed to simulate water sensitive urban design generally use distributed data models. Conversely, models which focus on water quality and those that model large scale processes such as climate change often use lumped data models. However, even in distributed models, spatial detail is potentially limited by the size and complexity of the study area to be modelled. Generally, the areal unit which is used to represent complex urban areas is the subcatchment, but although subcatchments are chosen to be homogeneous units, spatially detailed data (such as the impervious ratio) are aggregated to the subcatchment scale and a degree of complexity is lost. There is seldom a lower limit on the size of a subcatchment, but models often limit the number of catchment elements, e.g. HydroCAD currently has 20 catchment elements in the most popular system (HydroCAD, 2010). In addition, although there is spatial variability in many factors that influence the production of runoff (e.g. infiltration of rainfall into soil layers) the variability is often difficult to quantify spatially (Maheepala et al., 2001) and as a result many factors are estimated for land use types rather than spatially. Therefore in urban areas a distributed model may often incorporate some data which are lumped or aggregated rather than distributed. In general, the models which provide the greatest degree of spatial variability are those which use GIS-derived grid cells (e.g. the WetSpa model, Liu et al., 2003).

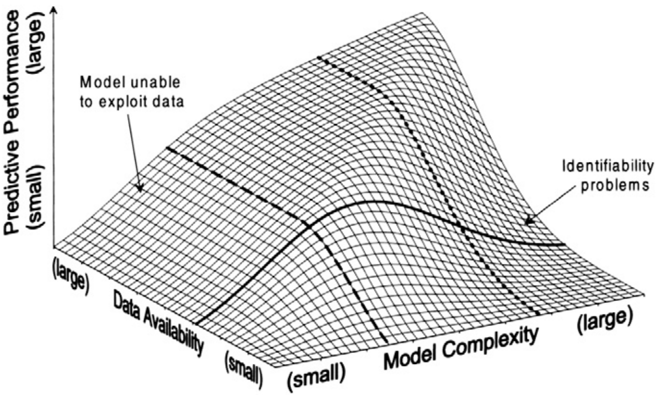

Fig. 1. Schematic diagram of the relationship between model complexity, data availability and predictive performance. (From Grayson and Blöschl, 2001, p. 73.)

4.2. *Common components of hydrological models used for urban areas*

The components of the hydrological cycle which may be included in urban stormwater models are precipitation (amount and intensity), infiltration and runoff, evaporation, soil moisture, streamflow and groundwater flow. All these variables vary spatially.

Rainfall hyetographs are linked to some models e.g. XPSWMM and design storms for differing durations and return periods may be created. Estimation of infiltration of rainfall into pervious areas of a subcatchment and rainfall runoff are key components and are modelled in different ways in different packages: some packages include one method and others multiple methods. The rate of infiltration is affected by surface characteristics including ease of entry, storage capacity, and transmission rate through the soil, so the ratio of natural surfaces to impervious manmade surfaces (and their location) along with vegetation cover, water content of the soil, and rainfall intensity all have important impacts. In hydrological models, infiltration of rainfall into the soil zone is commonly described using the following methods: Green–Ampt infiltration (e.g. HSPF and SWMM) and Horton infiltration (e.g. SWMM). Runoff may also be modelled in different ways. The most common method of predicting runoff is the curve number method developed by the USDA (United States Department of Agriculture) Natural Resources Conservation Service (NRCS) formerly the Soil Conservation Service (SCS). The runoff curve number is used to predict runoff based on the amount of impervious area, soil group, land cover type, hydrological condition, and antecedent runoff (USDA NRCS, 1986). Examples of hydrological models using this method include TR-55, HydroCAD, SWAT and SWMM. Runoff may also be modelled using the Rational method, which utilises the relationship between discharge, rainfall intensity and catchment area (Beven, 2001). Other functionality which is included in some models includes overland flow which is commonly modelled using the Manning formula, and storm flows in channels which are often modelled using the Muskingum-Cunge method (Cunge, 1969). Finally, models designed to model urban drainage systems often quantify the effect of WSUD technology and may include ponds and retention systems, infiltration systems, buffer strips, permeable paving, green roofs and domestic rainwater tanks.

4.3. Calibration of model parameters

Due to the large number of parameters included in hydrological models, they require calibration so that the model simulates the hydrological behaviour of the target catchment as closely as possible. In this process, the model response is fitted to observed catchment data by adjusting the model parameters. Muleta and Nicklow (2005) noted that the high number of parameters and variables in a distributed model makes the parameterisation of these models particularly complex. Calibration can be very time-consuming and manual methods may depend on the subjective judgements of the modeller (Eckhardt and Arnold, 2001). Methods of automatic calibration can overcome these shortcomings, however robust and reliable methods are required. Table 3 summarises some examples of models and calibration methods from recent studies and indicates the wide range of calibration methods that have been found to provide accurate results from the calibration process. A popular method is the shuffled complex evolution (SCE) optimisation method. (Detailed explanations of the SCE method appear in Duan et al., 1992.) However, although many calibration techniques provide useful outputs, there are very few studies that compare results using different calibration methods. Madsen et al. (2002) undertook a study which compared calibration results using three methods including calibration using SCE and a knowledge based expert system which simulated a trial-and-error calibration by an experienced hydrologist. This study found that overall the SCE calibration had the best performance.

Some other comparative studies have sought to divorce calibration outcomes from site-specific effects which may exist in a test catchment and model inadequacies. Reed et al. (2004) summarise some results from the Distributed Model Intercomparison Project (DMIP). The project calculated the gains in performance from distributed models relative to the lumped models, and calibrated models relative to un-calibrated models by comparing simulated and observed flows for multiple time-steps and selected storm events. It was found that the lumped models outperformed distributed models in more cases than distributed models outperformed the lumped models, but some calibrated distributed models performed better than calibrated lumped models. The range of accuracies suggested that factors such as model formulation and the skill of the modeller can have a larger impact on accuracy than whether or not the model is lumped or distributed. (The catchments used in this study were larger in size than most urban catchments.)

4.4. Model calibration in urban catchments

The majority of calibration studies are of catchments which are predominantly agricultural or forested, and although most of these catchments include some urban areas, few studies focus on urban catchments. Ackerman et al. (2005) noted that modelling challenges are greater in urban areas, as the impervious surfaces intensify the episodic flow. Among the few studies which focus on urban catchments, Rodriguez et al. (2000) examined the use of multiple parameters to calibrate the SURF (semi-urbanised runoff flow) model and found that the parameters for maximum groundwater storage and a saturated permeability parameter were most important. Mitchell et al. (2001) developed a model

Table 3
A summary of examples of models and calibration methods from recent studies.

Authors	Model	Methods used for calibration	Test catchment	Main land cover
Eckhardt and Arnold (2001)	SWAT	Automatic calibration with the SCE algorithm	Dietzholz catchment, Germany	Woodland
Zaghloul and Kiefa (2001)	SWMM	General Regression Neural Network (GRNN)	Hypothetical	100% Impervious
Choi and Ball (2002)	SWMM	Optimisation using Sequential Quadratic Programming (SQP)	In east Sydney, Australia	Residential
Madsen (2003)	MIKE SHE	Multi-objective optimisation based on the SCE algorithm	Karup catchment, Denmark	Agricultural
Brath et al. (2004)	A distributed model created by the authors	Automatic calibration using the SCE method	Reno river basin, North-Central Italy	Farmlands
Khu et al. (2006)	BEMUS rainfall runoff model (Belgrade model)	Multi-objective preference order genetic algorithm (POGA)	Miljakovac catchment in Belgrade, Serbia	Urban
He and Croley (2007)	DLBRM (Distributed Large Basin Runoff Model)	A systematic method to minimise the root mean square error for daily outflow volumes	Kalamazoo River Watershed, Michigan	Agricultural
Khu et al. (2008)	MIKE SHE	Grouping using an artificial neural network (ANN) and multi-objective POGA	Karup catchment, Denmark	Agricultural

(Aquacycle) which included both water supply and wastewater disposal and examined 16 calibration parameters including: pervious groundwater storage, effective roof area, effective paved area and base flow index. They found that sub-areas of their study catchment required different parameter values to represent the varying urban characteristics. Choi and Ball (2002) calibrated the SWMM model by adjusting the following parameters: the impervious fractions of specific land uses including low and medium density residential and commercial areas, the depression storage for the land uses, and the subcatchment overland flow length, and surface roughness (Manning's n). There are currently few clear guidelines about how best to calibrate urban catchments, but these three studies all incorporated spatially detailed data on land covers, indicating that this information, which is readily obtained from remote sensing, is important in calibrating models of urban catchments. Further research in this area is required as every catchment has unique properties, and calibration parameters which are derived for a particular catchment cannot usually be transferred to another catchment.

4.5. *Summary*

Runoff models provide potentially powerful tools to inform management decisions about how changes in urban catchments (e.g. in-filling of medium density urban areas) will impact on urban streamflows, and to assess the likely impacts of climate change and changing rainfall patterns on urban runoff. Many different hydrological models have been developed by different organisations, and the choice of a model is not simple. Models require calibration so that the model simulates the hydrological behaviour of the target catchment as closely as possible, and currently this requirement potentially limits the application of models in some study areas. Sensitivity analyses which examine how calibration parameters affect the behaviour of models could perhaps provide a better understanding of the role of the parameters when there are insufficient data for a particular catchment. However, Pappenberger et al. (2008) found that different methods of sensitivity analysis resulted in different rankings of importance of the parameters and that it was impossible to draw firm conclusions about the relative sensitivity of different factors.

5. Other factors in the quantification of the impacts of impervious surfaces

5.1. *Topographic influences on runoff*

Slope shares an intuitive relationship with runoff volume, as steep slopes lead to larger amounts of surface flow and gentle slopes result in more infiltration (Liu et al., 2006). Both the volume of runoff and the lag time to peak flood flows are known to be governed by land slope as well as the amount of impervious area and vegetative cover (e.g. Leopold, 1968), but few studies of the impacts of imperviousness in urban catchments have analysed the effects of slope. A reason for this may be the difficulty in obtaining field measurements which would unequivocally characterise the effect of slope. Detailed measurements would require paired urban catchments similar in every respect except for slope, and the arbitrary nature of urban development makes candidate catchments difficult to find. Information from studies based in agricultural areas is helpful as pervious areas in urban catchments are often grassed areas. These studies indicate that the effect of slope may be inherently difficult to characterise. For example, Joel et al. (2002) cite several field studies of mainly agricultural land and note that the effects of slope on runoff are contradictory: in some cases the runoff increases as slope increases, in others it decreases or is not significantly different. However, discrepancies across multiple studies may be the result of variability in experimental methods. Many hydrological models do not explicitly include slope, although the modelling of infiltration of rainfall into the soil zone may account for some slope effects. Slope data are readily available from DEM (digital elevation model) data via GIS and are included in some hydrological models, e.g. WetSpa (Liu and De Smedt, 2004). Further research, which may include model simulations is desirable.

5.2. *Sources of uncertainty in hydrological models*

Coon and Reddy (2008) identified the following sources of uncertainty in the outputs from hydrological models: (1) errors in precipitation data due to measurement error or an insufficient number of precipitation monitoring sites, (2) limitations in model structure, (3) errors or bias in data used to calibrate the model, (4) non-uniqueness of values for parameters, (5) misclassification of land cover data, (6) changes in land use during the simulation period, and (7) differences between the large calibrated catchments and the small subcatchments to which calibrated parameter values may be transferred. The uncertainty associated with simulation of the components of the model will unavoidably contribute to the uncertainty in the output. When these outputs are used in management decisions, modellers should communicate the limitations of their predictions to the wider community. Uncertainty analysis has been acknowledged as important in some studies, but Pappenberger and Beven (2006) state that uncertainty analysis is still not standard practice and it is common to show results without acknowledging uncertainty to decision makers, at scientific conferences, in refereed publications and in consultancy reports.

5.3. *Prediction of future conditions using hydrological models*

Although the hydrological and geomorphic processes associated with urbanisation are not completely understood, current knowledge can be applied to simulate future changes in urbanised catchments. Computer modelling can simulate future conditions for at least two types of change: changes due to increased urbanisation, and changes in weather patterns due to climate change. For example, Carlson (2004) used estimates of urban surfaces derived from remotely sensed imagery as input to the urban growth model called SLEUTH to predict land use changes to the year 2025. These data were combined with other methods (e.g. the SCS method) to predict future runoff and impacts of land use change. In this study area, surface runoff was predicted to change only slightly because increases in urban areas were balanced by increases in woodland. Choi and Deal (2008) coupled an urban growth model and a semi-distributed hydrology model to predict streamflow in response to future urban growth. This study, also predicted little change in total runoff as a result of land use change, but the claim that low flows tend to decrease with urbanisation was confirmed. These studies show that the combination of land use change models with hydrological models can provide long-term scenario-based assessments.

Predictions of the impacts of climate change on urban catchments can be generated by coupling a hydrological model to predict runoff with a climate change model. At present, most studies which combine the effects of climate change with runoff predictions use catchments which are in a natural state. For example, Evans and Schreider (2002) used results from a General Circulation Model (GCM) and a stochastic weather generator, to model the response of six catchments upstream of a major city. They found that changes in streamflow varied between catchments and were dependent on the physical attributes of the catchment, but predicted an increase in the magnitude of rare flood events. Semadeni-Davies et al. (2008) examined the potential impacts of climate change and continued urbanisation on stormwater flows to a suburban stream in Helsingborg, Sweden. Climate change was simulated using a regional climate model and urbanisation was simulated by altering model parameters chosen to reflect trends in demographics and water management. They found that city growth and increases in heavy rainfalls were likely to increase peak flow volumes and flood risk, and as a result recommended the installation of a urban drainage system that could allay many of the adverse impacts. This type of simulation modelling increases the potential uses and value of distributed hydrological models.

Finally, urban land surfaces may also have an indirect effect on the hydrological regime. For example, Gero et al. (2006) used the RAMS (Regional Atmospheric Modelling System) climate model over Sydney, Australia to assess the impact of land cover change on storms and found that dense urban surfaces appeared to trigger intense (simulated) convective storms. Similarly, Lei et al. (2008) used the RAMS model to simulate a rainfall event in Mumbai, India and found that precipitation was influenced by interactions between sea surface temperatures and heterogeneity in surface temperatures due to urbanisation. These studies indicate how future weather patterns and storm events are likely to be influenced by changes in urban land surfaces and that this influence can also be included in predictions of future conditions.

6. Concluding comments

An increased awareness of all the processes that control the hydrological response of catchments to urbanisation will enable a more thorough appreciation of processes in individual catchments; better models of the hydrological processes to better manage urbanisation within catchments; and better predictions for future scenarios. The three areas of research examined in this review provide insights into the impacts of impervious surfaces and can be conceived to act synergistically to increase understanding. Studies and measurements of the impacts in the field provide new information about hydrological process in urban environments. These studies enable the construction of enhanced hydrological models that represent the multiple processes which occur in the real world. Remotely sensed imagery and other spatial data provide detailed information about locations of impervious surfaces and allow both field studies and hydrological models to use data with a high degree of relevancy (rather than surrogate data) when examining urbanised catchments. Hydrological models enable the inclusion of multiple hydrological processes in studies which examine relationships between changes in urban conditions and changes in hydrological conditions. It can be argued that hydrological models are built using current understanding of hydrological processes and will reinforce the importance of these known processes, yet field-based studies are inherently limited in the data they can collect and models can provide information about scenarios that cannot be measured in a field study.

Although the complexities in the processes that occur in urban catchments make them difficult to be modelled and uncertainties exist about some details of the impacts of impervious surfaces, understanding the processes associated with urbanisation is essential. Data from the United Nations Population Division (2006) shows that in 2005, urbanisation was already high in developed countries in the regions of Northern America, Latin America and Europe and that less developed countries in Africa and Asia will experience a very large rate of urbanisation between 2005 and 2030. Both further research and integration of current fields of research are needed to enhance our understanding of the changes which urbanisation bring to urban catchments, and to facilitate the development of planning strategies to minimise the negative impacts of future urban growth.

Acknowledgements

The author is grateful to Dr Subra Velmupad who commented on an early draft of this manuscript. Two anonymous reviewers also provided valuable comments on an earlier version of the manuscript.

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