Advances in Water Resources 51 (2013) 261–279

Contents lists available at SciVerse ScienceDirect

Advances in Water Resources

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

Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art

T.D. Fletcher [a,*], H. Andrieu [b], P. Hamel [c]

[a] Dept. of Geography & Resource Mgt, The University of Melbourne, Burnley Campus, 500 Yarra Boulevard, Burnley, Vic 3121, Australia
[b] PRES LUNAM, IFSTTAR, Département GER and IRSTV-FR CNRS 2488, Bouguenais, France
[c] Dept. of Civil Engineering and Centre for Water Sensitive Cities, Monash University, Vic 3800, Australia

ARTICLE INFO

Article history:
Available online 8 September 2012

Keywords:
Urban hydrology
Rainfall–runoff
Stormwater quality
Integrated stormwater management
Flow regimes
Stormwater models

ABSTRACT

Urban hydrology has evolved to improve the way urban runoff is managed for flood protection, public health and environmental protection. There have been significant recent advances in the measurement and prediction of urban rainfall, with technologies such as radar and microwave networks showing promise. The ability to predict urban hydrology has also evolved, to deliver models suited to the small temporal and spatial scales typical of urban and peri-urban applications. Urban stormwater management increasingly consider the needs of receiving environments as well as those of humans. There is a clear trend towards approaches that attempt to restore pre-development flow-regimes and water quality, with an increasing recognition that restoring a more natural water balance benefits not only the environment, but enhances the liveability of the urban landscape. Once regarded only as a nuisance, stormwater is now increasingly regarded as a resource. Despite the advances, many important challenges in urban hydrology remain. Further research into the spatio-temporal dynamics of urban rainfall is required to improve short-term rainfall prediction. The performance of stormwater technologies in restoring the water balance and in removing emerging priority pollutants remain poorly quantified. All of these challenges are overlaid by the uncertainty of climate change, which imposes a requirement to ensure that stormwater management systems are adaptable and resilient to changes. Urban hydrology will play a critical role in addressing these challenges.

1. Introduction

Urbanisation is a worldwide trend, with more than 50% of the world's population currently living in cities, and over 500 cities now having more than 1 million inhabitants [1]. This growth leads to urban sprawl, with the surface of urban areas growing rapidly. The process of urbanisation has dramatic impacts on catchment hydrology, resulting in increased runoff rates and volumes, losses of infiltration and baseflow (in the absence of other baseflow sources such as leaking water and wastewater systems). The creation of impervious areas and the simplification of the drainage network also result in much faster runoff response to rainfall, leading to shorter times of concentration and reduced recession times. Urban hydrology is also impacted by interactions – both physical and in terms of management – with the sanitary sewer system (which may be either separate or combined with the stormwater sewer system).

The science of urban hydrology has thus developed to improve the management of urban water systems for public health and sanitation, flood protection and more recently, the protection of the environment and of the liveability of cities. Management of urban runoff thus requires several disciplines; engineering, environmental science, public health and sociology. Urban hydrology is far from simple and requires the development of novel technologies that both address the technical challenges in the urban context and work with and respond to the needs of urban communities.

The ability to measure and model hydrology (and its consequences in terms of water quality and impacts on receiving waters) depends on being able to measure and predict rainfall with high levels of temporal and spatial precision, a requirement is even stronger in cities. This has led to many innovations in the measurement of rainfall, such as the use of radar, and the development of models of rainfall for application in urban rainfall–runoff models. The heterogeneity of urban land cover, particularly for peri-urban areas, also necessitates models that can represent the contributions of distributed subcatchments to the catchment outlet.

Changes in rainfall–runoff behaviour, along with the generation of pollutants by urban land surfaces and activities, result in the degradation of water quality in receiving waters. The generation,

* Corresponding author.
E-mail addresses: tim.fletcher@unimelb.edu.au (T.D. Fletcher), herve.andrieu@ifsttar.fr (H. Andrieu), perrine.hamel@monash.edu (P. Hamel).

0309-1708/$ - see front matter
http://dx.doi.org/10.1016/j.advwatres.2012.09.001

transport and consequences of pollutants in urban stormwater systems have been the topic of intensive study over the last two or three decades, but in recent times, a large number of pollutants – such as pesticides, hormones and other synthetic chemicals – have been identified as posing an emerging problem.

A wide range of approaches to mitigating both the hydrologic and water quality impacts of urbanisation have thus been developed over the last few decades (e.g. distributed vs. end-of-pipe), but there still remains significant debate over the best approaches, demonstrating that management of urban stormwater remains a complex and challenging field. There is a clear trend towards more integrated approaches which tackle changes to flow regime and to water quality simultaneously, and which attempt to consider stormwater as a resource, rather than just as a nuisance to be discarded. Development of integrated models to predict and assess the effectiveness of alternative approaches to managing urban stormwater, as part of the broader urban water cycle, has thus received substantial recent attention.

Ultimately, despite its particularity, urban hydrology is not *that* different from 'natural' hydrology; instead, it is the plurality of objectives and interactions with other parts of the urban water system that result in the importance of urban hydrology as an applied science. This is further complicated by the patchwork nature of developed, undeveloped and agricultural lands, crossing catchment boundaries, which accompany urbanisation.

In this paper, we review the state of the art in the understanding, management and modelling of urban hydrology and of its impacts on water quality and receiving waters. We identify the progress made over recent years, the current trends and the gaps that remain as an impediment to a fully integrated approach to urban runoff management, such that the needs of the city and of the receiving environments are met. We thus conclude with an identification of the key research questions which we believe will underpin the advancement of urban hydrology and stormwater management in the near- and medium-term future.

2. Rainfall in the field of urban hydrology

The assessment of rainfall at scales of urbanised catchments is a prerequisite to accurate prediction or assessment of urban rainfall–runoff response. Most urbanised catchments are relatively small (less than a few or even a few tenths of km^2) and display features (e.g. coefficient of imperviousness, artificial drainage network) that reduce the catchment response time (typically to less than 1 h). Orders of magnitude for assessing urban runoff behaviour include temporal scales from 1 to 10 min, a spatial resolution ranging between 100 and 500 m, and the total surface area covered not exceeding 20×20 km. Research on rainfall in the field of urban hydrology addresses the following topics: rainfall measurements, rainfall forecasting, and rainfall modelling at the specific scales associated with urban hydrology. The study of the interactions between urban land use and rainfall includes the influence of the urban environment on rainfall climatology, which is a subject of primary importance in the context of global increases in urbanisation.

2.1. Rainfall measurement

Niemczynowicz [2] considered rainfall input as one of the weak points in the discipline of urban hydrology, due to the lack of rainfall data sufficiently representative of the temporal and spatial variations of natural rainfall processes. In this section we evaluate the capabilities of rainfall sensors, gauges and radar to accurately measure rainfall, and describe the spatio-temporal structures of rainfall fields found at these scales. We deduce from these studies the specifications of rainfall measurement in urban areas, acknowledging that this remains an open and actively debated issue.

Rainfall measurement was first addressed through the use of dense rain gauge networks. Lanza and Stagi [3] tested various rain gauges under laboratory conditions with a 1-min time step for rainfall rates of up to several hundred mm/h and concluded that many rainfall intensity gauges complied with the WMO accuracy specifications (5%), even at the 1-min resolution. Ciach [4] analysed the errors in tipping-bucket rain gauges based on a data sample derived from 15 co-located rain gauges and proposed an analytical expression for the standard relative error as a function of local rainfall intensity and time step. As an example, he obtained a value of approximately 7% for a rainfall intensity of 25 mm/h with a 5-min time step. The representativeness of rain gauge data on rainfall in the vicinity becomes a key point in determining the spatial variability of rainfall fields at very small scales. Ciach and Krajewski [5] analysed data from the EVA-PICONET rainfall monitoring network, which comprised 25 rain gauges arranged in a regular grid covering an area roughly 3×3 km, giving rise to spatial correlograms with short time steps: 5 and 15 min. Moreau et al. [6] studied the small-scale variability of a 6-min rainfall time step. The results of this study did not corroborate previous findings: for instance, they found a correlation coefficient of between 0.5 and 0.6 for a 6-min rainfall vs. a coefficient correlation of 0.8 for a 5-min rainfall, as reported by Ciach and Krajewski [5]. This difference can be explained by the types of rainfall or by differences in the rain gauge networks. These dissimilar results confirm that further research is still needed to describe the small-scale variability of rainfall. Based on the characterisation of this spatial variability and on the relationship between response time and surface area, Berne et al. [7] proposed a method that might lead to the assessment of required rain gauge network density depending on catchment features, i.e. surface area and concentration time.

Very early on, urban hydrologists showed interest in weather radars as a means of mapping rainfall with excellent temporal and spatial resolution. However, conventional radar data are subject to several sources of errors. The identification and correction of these sources of error have been the focus of intense research efforts by the scientific community over the past several decades. Urban hydrologists have contributed to this effort, as reflected by Einfalt et al. [8]. They have considered the type of radar as well as the application requirements, emphasising the fact that urban hydrologists have developed a more mature understanding of radar processes and demonstrated a better understanding of limitations and achievable accuracy. They also addressed the uncertainties and methods for obtaining accurate rainfall measurements at high resolution, using areal extents consistent with urban catchments. The evaluation and improvement of quantitative precipitation measurements are described in this overview with the backing of specific research and operational examples of radar use in urban hydrology. Emmanuel et al. [9] have shown that despite recent progress, the radar data generated through the new operational French radar processing chain are not yet sufficiently reliable for direct use in quantitative applications in urban hydrology. As suggested early on by Delrieu and Creutin [10], X-band light configuration radar (LCR) could offer certain advantages, including lower cost, greater installation and operational flexibility, and reduced sensitivity to ground clutter; on the other hand, LCR application is heavily limited due to attenuation by rainfall. Recent studies have examined this alternative. Pedersen et al. [11] tested an X-band with a 10-degree beam width and found that very careful data processing is required, to correct the sources of errors inherent in the device and obtain accurate rainfall measurements. Thorndahl and Rasmussen [12] demonstrated the value of calibration of radar by the use of rain gauges, while Emmanuel et al. [13] used radar to gain new insights into small-scale (less than 1 km) rainfall variability.

In summary, it would appear that the X-band light configuration of conventional radar does not overcome the classical drawbacks encountered when measuring rainfall by radar. Users are not yet confident enough in weather radar to consider them as reliable sensors of rainfall. One significant improvement might result from the development of X-band polarimetric radars, which are potentially capable of compensating for several sources of errors introduced with conventional radar, by featuring: ground clutter detection, a more accurate transformation of radar reflectivity into rainfall rates because of the use of polarimetric parameters, and attenuation correction. Diss et al. [14] obtained very encouraging rainfall measurement results, for example, without any rain gauge calibration, through use of the HYDRIX radar prototype under severe measurement conditions. High-resolution rainfall data has also been used to characterise spatial variability in rainfall and to examine the influences of landscape on this variability [15].

More recently, there have been several exploratory studies conducted on the potential of microwave links for measuring rainfall. The attenuation of a signal along the link offers a near-linear function of the mean rainfall intensity between the transmitter and receiver. Upton et al. [16] discussed the set of conditions specific to rainfall measurement, in addition to illustrating results and listing possible applications. Leijnse et al. [17] investigated the suitability of a 27-GHz microwave link for measuring path-averaged precipitation; they concluded the technique was feasible if a correction for the wet antenna was applied. Cummings et al. [18] showed that the path-integrated rainfall estimates provided by microwave could be used to calibrate radar. One highly exploratory application of microwave in urban areas concerns rainfall field retrieval by means of tomography. Urban areas are equipped with densely configured mobile networks. Giuli et al. [19] attempted to reconstruct rainfall fields by means of tomography, based on microwave attenuation. Since then, mobile networks have developed tremendously, and urban areas are equipped with a dense pattern of commercial microwaves serving mobile networks. Despite not being specifically designed for the purpose, Zinevitch et al. [20] proposed a nonlinear tomographic algorithm for rainfall measurement and demonstrated its effectiveness. Along the same lines, Cuccoli et al. [21] tested a tomographic algorithm specifically developed for the typical topology of urban radiobase station networks. Both of these numerical feasibility studies appear to be promising for application to urban areas and confirm the scientific benefit of using microwave links to estimate rainfall.

The rapid development of new technologies bodes well for increasing our ability to capture the spatial and temporal variability of rainfall. However, validation of these new techniques will be necessary to ensure they provide useful data.

2.2. Rainfall forecasting

The small surface areas and short response times associated with urban catchments make quantitative precipitation forecasts (hereafter referred to as QPF) a very valuable input for stormwater management, such as pollution mitigation or flood warning. A QPF with a lead-time of 1–2 h over surface areas of a few km^2, accompanied by a reliability indicator, is needed to develop an accurate model of runoff with small time steps. Dense raingauge networks are not suited for very short-term QPFs. This was confirmed by Luk et al. [22] who concluded, for a network of 16 devices over 112 km^2, that adjacent devices contributed little information for a forecast lead-time longer than 15 min. The development of very short term QPF methods (i.e. 1–2 h), is essentially based on a real-time observation of rainfall fields by weather radar. Different types of methods have been developed to analyse radar images for QPF.

Firstly, Lagrangian methods aim to determine the mean movement of rain echoes between successive images, in most instances by cross-correlation, and then extrapolate this movement [23]. The well-known COTREC method developed by Li et al. [24] makes it possible to determine a smoothed field of local advection vectors and identify regions of radar echo growth or decay. Secondly, Eulerian methods identify individual rain cells, track their displacements and extrapolate their velocity along with other characteristics such as shape, intensity and size [25–27]. Faure et al. [28] showed that in the case of homogeneous rainfields, a decently accurate QPF could be obtained for lead times of down to 1.5 h over the total depth of rainfall throughout this period, on catchments measuring a few km^2. Moreover, in the case of rapidly changing rain cells, the QPF accuracy decreased abruptly after 10–15 min. In order to overcome the limitations inherent in advection methods, which assume the advected rainfield is in a steady-state during the forecast lead-time, Thielen et al. [29] and Boudevillain et al. [30] proposed voluminal radar scanning. This approach consists of a simple conceptual model depicting the evolution of vertically integrated liquid (VIL) water content derived from voluminal scans. The VIL evolution anticipates the rainfall evolution at ground. A numerical feasibility study plus a case study indicate that the modelling of VIL evolution could complement advection methods. Despite the research effort on this topic during the last two decades, there remains a lack of comprehensive studies of the various QPF methods for urban hydrology: (i) assessing their performance and limitations [8], (ii) providing the forecast uncertainties according to the forecast lead-time and rainfall variability, and (iii) evaluating their utility in urban water management [8,25]. Recently, the concept of ensemble of precipitation fields has been built into short-term QPFs [31] allowing forecast uncertainties to be taken into account.

Recent research on QPF has been based on combining various types of information provided by radar data and numerical models. Liguori et al. [32] assessed an application of the STEPS method to urban catchments [33]; this work produced a probabilistic ensemble QPF by merging an extrapolation of radar rain echoes with the downscaling of a Numerical Weather Prediction (NWP) model. These authors then applied the method to three rain events and found that further investigation was needed to draw a substantive conclusion. Vasiloff et al. [34] considered that the very short-term QPF should consist of blending an extrapolation of rainfall radar images with predictive NWP components in order to combine information on rainfield displacement (radar images) and rainfall dynamics (NWP). Closer collaboration between urban hydrologists and atmospheric scientists would help account for the specificities of urban hydrology while progressing towards the development of original methods adapted to this given need. Importantly, such work should also begin to address the likely impacts of climate change on rainfall patterns [35].

2.3. Rainfall modelling

The time series modelling of rainfall rates has many applications in urban hydrology, including the design of structures such as stormwater storage, treatment and infiltration devices [36], or the simulation of rainfall intensities over time drawn from rainfall series measured with a longer time step. This is a topic of active research, partly due to the fact that extended rainfall measurement time series recorded using shorter time steps are typically available with a relatively low spatial resolution or without other climatic data to assist in their interpretation. The modelling of rainfall time series may be performed by two types of models: point process stochastic models (PPSM), and random multiplicative cascades (RMC).

Onof et al. [37] reviewed the development and applications of PPSMs, considering the representation of rain cell occurrence (following a Poisson process), grouping, timing, duration and mean intensity (all random variables derived from observed rainfall intensities). The Neyman–Scott (NS) model considers the arrival time of cells from the storm beginning as independent and identically distributed, whereas the Bartlett–Lewis (BL) model considers the time interval between cells as independent and identically distributed [38]. The applications and improvements of these models have led to a rich scientific literature which includes studies in urban hydrology. For example, Cowpertwait et al. [39] have adapted the BL model to account for small-scale temporal rainfall variability. Onof and Arnbjerg-Nielsen [40] used a BL model to anticipate future changes in urban design rainfall from outputs of Global Circulation Models.

The application of RMCs to rainfall was initiated by Schertzer and Lovejoy [41], who demonstrated their advantages of parameter parsimony and easy application. From a practical standpoint, RMC models consist of distributing a rainfall intensity R over a time step into b values over b sub-time steps (typically $b = 2$). This operation is referred to as disaggregation; its repetition constitutes a cascade. Two types of cascades can be distinguished. In microcanonical cascades, the weights sum to exactly 1 in each cascade split. On the other hand, for canonical cascades, the weights of each branch of a cascade only sum to 1 on average. Molnar and Burlando [42] applied both canonical and microcanonical cascades to disaggregate 1280-min rain data into 10-min data for a 20-year recording period in Zurich, Switzerland and concluded that canonical models better captured rainfall variability. Licznar et al. [43] tested six random microcanonical and canonical cascade models for generating rainfall time series with a 5-min time step, from quasi-daily rainfall series recorded at Wroclaw (Poland). Onof et al. [44] tested a random cascade with a log-Poisson generator in order to disaggregate hourly to 5-min rainfall rates, successfully reproducing the main rainfall statistics (including extreme values). Gaume et al. [45] addressed the calibration and validation of RMC models based on an 8-year time series of 1-min rainfall rates recorded in Nantes (France) and demonstrated that model calibration is very sensitive to sampling fluctuations. RMC models are not the only candidates for disaggregating rainfall. Burian and Durran [46] used a neural network to disaggregate hourly rainfall values into sub-hourly values. Jennings et al. [47] disaggregated daily rainfall data into 6-min resolution rainfall values by means of a new method, called the "master-target scaling technique". Segond et al. [48] presented a method to simulate the time series of rainfall fields by combining a single-site disaggregation model with a generalised linear model capable of representing the multi-site spatial and temporal non-stationarities of rainfall.

2.4. Influence of urban areas on rainfall

The influence of large cities on rainfall was detected in the early 1970s [49] and studied in the METROMEX project, which showed decreased summer rainfall downwind of urban areas. This topic has remained an active research subject since these pioneering investigations. In his review paper, Shepherd [50] proposes a synthesis of observational and modelling studies on urban induced rainfall changes, and details the processes liable to induce this urban influence. Both aerosol-microphysics and the forcing mechanisms related to urban land use play a role in urban-rainfall modification [51,52]. Burian and Shepherd [53] analysed data from 19 raingauges in the Houston metropolitan area during the period 1940–1999 and detected the influence of urbanisation (covering the period 1984–1999), while Smith et al. and Krajewski et al. [54] used the Hydro-NEXRAD system to generate radar rainfall fields and assess the influence of urbanisation on rainfall patterns and spatial heterogeneity. The effect is strongest from noon to midnight during the warm season and results in an 80% increase in rainfall occurrence in the urban area, with rainfall downwind increasing relative to that experienced upwind. The climatological influence of the urban area on regional thunderstorms was confirmed by Niyogi et al. [55], who performed a radar-based assessment of 91 unique summertime thunderstorms and by Rose et al. [56], who mapped 8 years (1995–2003) of mean accumulated precipitation from the North American Regional Reanalysis model. Modelling studies by Miao et al. [57] and Shem and Shepherd [58] confirm observational evidence of the significant effect of urban land cover on rainfall variability.

3. Urban hydrological processes

The presence of impervious surfaces and constructed drainage systems are fundamental drivers of the change in hydrology, with increases to peak flows, annual runoff volumes and flow variability, along with decreased infiltration and shorter lag times all well documented, dating back to the 1960s [59]. Here we review the mechanisms of urbanisation (surface and subsurface hydrology, as well as evapotranspiration) which influence the water balance components and their interactions, and conclude with a summary of observed consequences for streamflow.

3.1. Surface runoff processes

Impervious surfaces have profound impacts on hydrology, eliminating infiltration and thus increasing dramatically the volume of surface runoff. Streets and pavements are usually considered as impervious, but in reality their hydrologic behaviour varies with the intensity and duration of rainfall. Ragab et al. [60], who studied water fluxes in a residential area from various types of roofs in Great Britain, found significant differences in runoff and evaporation depending on roof slope, material type and height, as confirmed by observed variations in the monthly runoff–rainfall ratio, i.e. from 0.61 to 0.91, depending on the season and roof characteristics. Ragab et al. [61] then investigated infiltration and runoff processes in three car parks, a road and a grassy site in Wallingford. They concluded that between 6% and 9% of rainfall infiltrates through the road surfaces; 21–24% of annual rainfall evaporates, not surprisingly with a higher percentage during summer than in winter. These results have been confirmed by Ramier et al. [62], who studied two street segments over a 38-month period in the oceanic climate of Nantes (France), concluding that losses represent 30–40% of total rainfall and can be split into evaporation (20% of total rainfall) and infiltration (10–20% of total rainfall). Their study is of course site-specific, but the figures are generally applicable.

However, it is not just the surface type that determines its hydrologic behaviour, but the nature of its connection to the receiving water [59,63]. Where impervious surfaces discharge informally to adjacent pervious areas, or where there are significant overland flow paths between the impervious area and the receiving water, the hydrologic signal of the impervious surface is likely to be significantly attenuated [64]. This issue is discussed further in Sections 4 and 5.

The influence of impervious areas on runoff temperature is a recent and original topic of research. Herb et al. [65] simulated both surface runoff and runoff temperature for an asphalt parking lot using 6 years of climate data from Minnesota (USA), with 282 individual rainfall events. They found that runoff temperatures from asphalt were correlated with three parameters, namely: average dew point temperature during the storm, air temperature prior to the storm, and solar radiation prior to the storm. This conclusion has been confirmed by others [66,67].

There is also considerable literature on the runoff behaviour of pervious surfaces in urban areas. The combined effect of removal of topsoil and compaction (due to construction, traffic, as well as loss of organic matter and vegetation, which increase permeability) means that pervious areas have uncertain rainfall–runoff behaviour [68–70]. Urban soil also contains trenches for pipes and other urban infrastructure, which may act as drains, thus influencing flow paths. The influence of changes to pervious areas is particularly unclear for low flows [71], added to by the potential for water and wastewater infrastructure leakage. The effect of urbanisation-induced changes to soil will depend on the geology (soil depth, presence of a confining layer) and presence of deep-rooted plants creating macropores through the soil profile [71]. Several authors have observed that the contribution of pervious areas to urban runoff is relatively insignificant (e.g. [72,73]), while others argue that it may be significant [70,74]. Importantly, the variable nature of pervious area contributions, resulting from a combination of surface runoff, throughflow and baseflow processes, means that the timing of pervious flow contributions to catchment flows are quite variable and difficult to predict and will require statistical [75] or distributed hydrology-soil-vegetation models [76].

3.2. Subsurface flow processes

The relationships between urbanisation and subsurface flow processes are detailed in several thorough reviews [71,77], and are shown to be complex, resulting from variation in natural catchment characteristics (geology, topography, vegetation, etc.) and characteristics of the urbanisation itself (spatial arrangement of impervious areas, nature of drainage, etc.) [77]. Consequently, baseflows in catchments subject to urbanisation may be observed to increase or decrease. For example, while impervious surfaces will result in less infiltration in some parts of the catchment, the reduction in vegetation in other pervious areas may decrease evapotranspiration, potentially increasing infiltration. Conversely, the loss of vegetation, along with the above-mentioned changes to soil properties, may decrease infiltration, thus reducing subsurface flows [71,77].

Urban drainage, sewer and water supply infrastructure may also have important interactions with subsurface flow processes. Lowering of the groundwater level [78] is a common but not necessarily ubiquitous consequence of building urban infrastructure such as sewer systems. Conversely, leakage from supply water systems feeding groundwater leakage from wastewater systems is one possible source of groundwater contamination [79]. Belhadj et al. [80] studied the reaction to rainfall of a wastewater sewer without any direct rainwater input and showed, not surprisingly, that when the water table level reaches the depth of the network, groundwater seeps into non-watertight pipes. In the unique context of the Rezé experimental catchment [81], the soil contribution represents on average 14% of the total event runoff volume and explains the majority of variations in the event runoff–rainfall ratio. These results have been confirmed by Ruban et al. [82], who observed that the "base flow" into the sewer network within an urban catchment was well correlated with the water table level. Moreover, they concluded that at an annual scale, the volume of groundwater drained by both the wastewater and stormwater systems exceeded the volume of runoff during rain events. Berthier et al. [83] proposed a detailed model of the interactions between urban soil and a sewer trench in order to simulate event variations in the runoff coefficient. Karpf and Krebs [84] developed a model to represent groundwater infiltration into sewers, based on a sewer pipe classification according to both year of manufacturing and groundwater impact; they went on to establish a relationship between these classifications and infiltration behaviour. The NEIMO model (for "Network Exfiltration and Infiltration Model"), developed by DeSilva et al. [85], calculates the water level in the sewer pipe and then applies it to a Darcy-based equation in order to estimate exfiltration and infiltration. Interactions between soil water and sewer networks have been modelled by Goebel et al. [86] and Endreny and Collins [87], who examined the influence of stormwater infiltration on groundwater, giving recommendations to reduce risks of cross-contamination and groundwater mounding, respectively.

The complexity of subsurface flow processes means that predicting changes due to urbanisation and urban infrastructure remains an important knowledge gap. The development of suitable tools and a common set of indicators is thus a very important area of future research, particularly given the increasing recognition of the role that baseflow processes play in determining the condition of receiving waters [77].

3.3. Urban evapotranspiration

Evapotranspiration is a major part of the water balance, typically making up around 60-95% of mean annual rainfall in forested catchments [88]. In the urban context, the potential contribution of evapotranspiration is affected by changes to infiltration, vegetation cover and the urban microclimate. Quantifying urban evapotranspiration is imperative to closing the urban water balance, and has implications for the design of stormwater retention and infiltration strategies, along with management of irrigation and the urban landscape.

Evapotranspiration in urban areas has up until now been studied primarily by climatologists, interested in the urban energy budget [89]. An overview of this research field was provided by Sailor [90] in a review of methods to estimate anthropogenic heat and moisture emissions in the urban environment. Grimmond et al. [91] presented an international comparison of 32 urban land surface schemes to model the urban surface energy exchange processes, including latent heat exchanges. One such model was proposed by Grimmond and Oke [92], which used a Local Scale Urban Meteorological Parameterisation Scheme (LUMPS) to calculate the surface energy fluxes from routinely measured data. Coutts et al [89] studied alterations of the local climate resulting from modifications to land surface processes (and reductions to evapotranspiration) through land use change.

More recently, there has been increasing interest in urban evapotranspiration from a hydrological perspective, with the motivation of determining how the urban water balance can be influenced by urban design and specifically by stormwater management. Urban evapotranspiration studies have introduced SVAT (Soil Vegetation Atmosphere Transfer) models, adapted to the urban context to estimate urban evapotranspiration and the urban water budget [93–96]. Wang et al. [97] developed a model called UFORE-Hydro (for Urban Forest Effects Hydrology), which simulates water budget components at the catchment scale to study the influence of trees. Gash et al. [98] reported satisfactory results in estimating evaporation from an urban roof with a model designed to determine evaporation from a forest canopy.

Boegh et al. [99] also modelled evapotranspiration and runoff at a range of scales, incorporating agricultural, forested and urban land uses. They found that runoff could be well estimated when evapotranspiration played an important role in the landscape and identified that in the sparsely vegetated situation common in urban landscapes, parameterisation of vegetation characteristics was critical to accurate estimation of evapotranspiration. Mitchell et al. [100], assessed the influence of urban design on the water budget, confirming the pivotal importance of evapotranspiration in evaluating the efficiency of 'best practice' systems in the area of water management. Despite this, the field remains relatively poorly explored, with few studies that have quantified the influence of stormwater management techniques on the complete water budget. One recent study was that of Hamel et al. [101], who assessed the relative contributions of infiltration and evapotranspiration by vegetated infiltration systems, with the aim of assessing landscape water fluxes and impacts on groundwater and baseflows.

Given the significance of evapotranspiration in the urban water balance, it is critical to develop methods to measure evapotranspiration in an urban context as well as to pursue further modelling studies on this process. Novel techniques such as the use of flux chambers (which can measure fluxes of water vapour as well as other gases such as CO_2) are beginning to be explored [102], but remain in their infancy, at least in terms of application to urban areas. This is clearly an area needing increased research effort, having application not only for urban hydrology, having secondary benefits for understanding the way urban hydrology can be managed to improve the urban landscape and microclimate [89].

3.4. Resulting influence of urbanisation on streamflow

The importance of accurately specifying effective impervious area in rainfall–runoff models within urban areas (e.g. [103]) confirms that urbanisation, and particularly the nature and spatial arrangement of the drainage network [104,105], plays a dominant role in determining catchment hydrological behaviour. Both empirical data and modelling approaches have been used to assess the influence of the urbanisation process. Hawley and Bledsoe [106] studied a large sample of 34 catchments displaying a range of urban development from 0% to 23% imperviousness, in the semi-arid climate of Southern California (United States). Each catchment was measured for at least 15 years. The effects of urbanisation on both flow peaks and durations were examined; all geomorphically significant flows were found to happen more often and with greater magnitude, resulting in a greater total duration of such flows. Burns et al. [107] compared three small headwater catchments representative of a range of suburban development levels (i.e. high density residential, medium and undeveloped). Peak magnitudes increased and recession time decreased with increasing urbanisation; higher baseflow occurred in the dry period in the high-density residential catchment. However, the effects of urbanisation on baseflows are much disputed, with both increases and decreases being observed, dependent on catchment-specific circumstances [71,77]. Sheeder et al. [108] examined five hydrographs from three watersheds of various levels of urban development, which display multiple peaks for a single rain peak, thus clearly separating urban from rural signals. Huang et al. [109] confirmed the consequent changes in model parameters, assessing Curve Number CN and n-cascade linear reservoir respectively as a function of urbanisation rate during a 36 year long observation period.

Total imperviousness of a catchment is a commonly used predictor of hydrologic impacts of urbanisation [110,111]. However, not all studies distinguish the impervious area which is directly connected to receiving waters via the drainage network from those which drain to adjacent pervious land, despite the studies showing the importance of this distinction [64]. Few of studies consider the combined influence of urbanisation and climate change on the flow regime [112–114]; both of these current gaps appear to be important topics future research. Mejia and Moglen [115,116] studied the relationship between the spatial distribution of imperviousness and the space-time variability of the rainfall in determining the nature and timing of the hydrologic of response. Both factors were found to be important.

Few studies address the study of peri-urban and suburban catchments and there are thus no specific models for these catchments, which often experience a rapid land-use evolution and changes in their hydrologic functioning. A special issue of the *Journal of Hydrology* is in preparation and should contribute to a better understanding of peri-urban catchments. Among the most important remaining knowledge gaps is the development of reliable tools to quantify connected imperviousness (rather than total imperviousness) and to incorporate its spatial arrangements into readily applicable hydrologic models.

4. Impacts of urban hydrology on receiving waters

It is not surprising, given the extensive changes to both hydrology induced by urbanisation and its consequences for the water quality and hydraulic regime, that receiving waters in catchments that contain even small areas of urbanisation, end up highly degraded. There have been several very thorough reviews of the 'urban stream syndrome', as it is often known [70,117–119]. We summarise briefly here the key impacts of urban hydrology on receiving water ecosystems, Understanding these impacts has become an integral requirement for management of urban hydrology.

4.1. Urban hydrology as a master variable driving ecological degradation

In their review of the urban stream syndrome, Walsh et al. [117] describe a number of ecological consequences of urbanisation which are consistently observed, including loss of sensitive species, increases in nutrients and toxicants, and a loss of organic matter. Perhaps one of the most critical observations in the study of urbanisation impacts on the ecology of receiving waters has been the extremely low levels of urbanisation at which such impacts can be detected. Early studies suggested that significant degradation of receiving waters could be expected when the total catchment imperviousness exceeds 10% [120], although others proposed a linear decline [70]. More recently, degradation at much lower levels of imperviousness has been observed, with a noticeable decline in species richness measured at even 0.5% catchment imperviousness [121]. The differences in these observations appear to come about as a result of the use of *total imperviousness* as a predictor of decline. As previously discussed, the effective imperviousness (the proportion of the catchment made up of impervious surfaces which are directly connected via constructed drainage to the receiving water) provides much clearer prediction of receiving water state [117], because it is those surfaces which transmit runoff directly to receiving waters (without the opportunity for infiltration, treatment or attenuation), which most affect the hydrology and water quality of the receiving water [122,123].

Understanding the mechanisms by which urban stormwater impacts receiving waters is a prerequisite to developing strategies to protect waterways from degradation. Wenger et al. [118] identify eight primary symptoms underpinning the 'urban stream syndrome' (Fig. 1) and identify the causes of each of these symptoms. It is apparent that a multitude of stressors therefore impact on urban streams. While considerable effort has often been spent trying to separate out the various impacts (water quality, hydrology, geomorphology, physical habitat), the reality is that there are very strong interactions between them. For example, changes to flow impact on the mobilisation and transport of pollutants, which influences water chemistry. Importantly, many causes of degradation are ultimately driven by hydrological changes [118]. It is for this reason that hydrology is often described as the master variable controlling the degradation of urban waterways [124], influencing changes to both water quality and geomorphology.

4.2. Water quality

Water quality in receiving waters subject to catchment urbanisation is degraded as a result of two primary mechanisms (i) in-

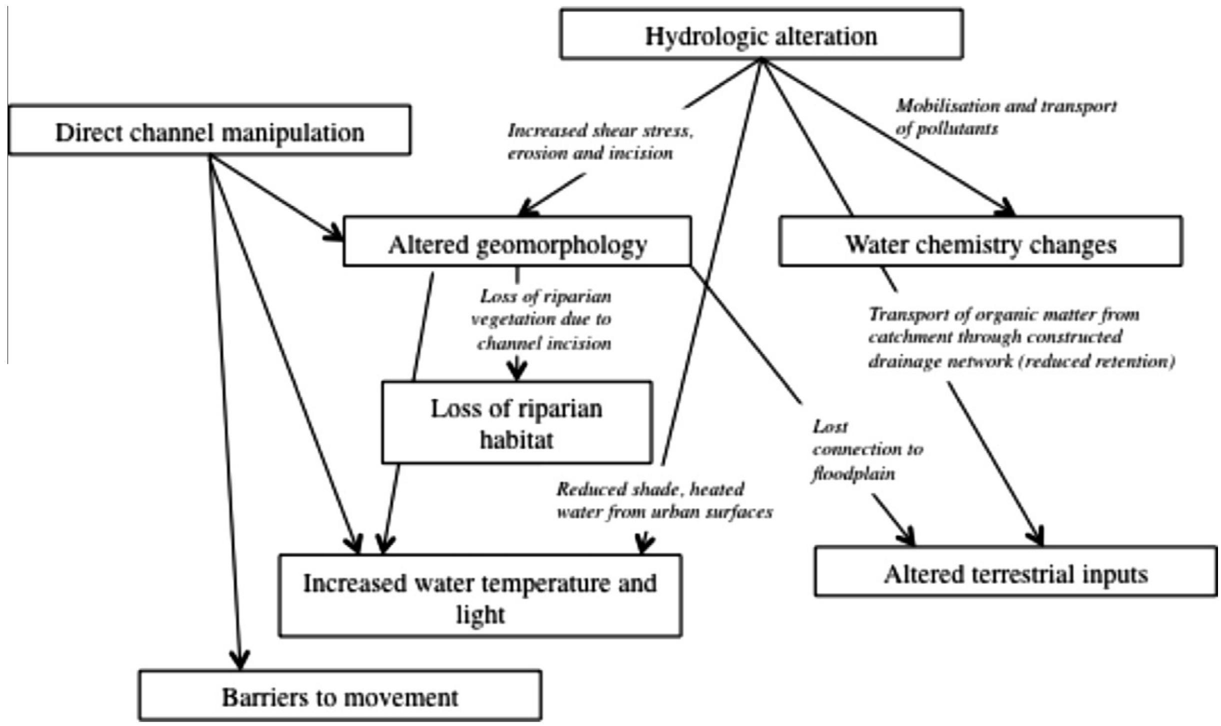

Fig. 1. Illustration of some of the principal mechanisms by which urbanisation degrades aquatic ecosystems (the principal 'symptoms' of urbanisation, listed in the boxes, are derived from the review of Wenger et al. [118]. The role of hydrology as a 'master variable' is illustrated with examples (*in italics*) given to show the relationship between symptoms (e.g. total runoff volume, peak flows, baseflows, lag time).

creased generation of pollutants, through land use and human activity and (ii) increased mobilisation and transport as a result of increased surface runoff and hydraulic efficiency of the network. Pollutants in urban stormwater have been a topic of quite extensive research since the 1970s and even before (e.g. [125–126]). Duncan published in the late 1990s a series of documents outlining stormwater quality relative to land use and examined the processes leading to the generation and mobilisation of pollutants in catchments [127–129] and another thorough review was undertaken by Makepeace [130]. Typically, pollutants have been categorised based on their physical and chemical properties, their typical sources and their impacts. The nature of the pollutant – particularly the extent to which it is present in the dissolved or particulate form [131] – determines the facility with which the pollutant can be mobilised from the catchment surface and transported through the stormwater network, and the techniques necessary for its removal [132–134].

In general, the primary focus on stormwater quality over the last 20 years has been around sediments and organic matter, nutrients and heavy metals, but there is an increasing interest in both pathogens and in the so-called 'emerging priority pollutants', which include industrially derived components, PAHs and herbicides [135]. For example, the European Water Framework Directive lists 33 priority substances and 8 other pollutants under Annex II of the 2008/105/EC Directive [136], with the US EPA maintaining a similar list [137]. The move towards measurements of such pollutants has created a requirement for more sophisticated sampling, storage and analytical methods, because many of these pollutants are found in trace or ultra-trace concentrations [138]. Over the next few years there is thus likely to be substantial development in the ability to detect and quantify micropollutants, which may well lead to an evolution in the priority-setting and source-identification elements of stormwater management, as well as the development of new treatment technologies [139,140].

Predicting pollutant concentrations and loads has been one of the greatest challenges in urban hydrology over the last 20 years. Researchers have attempted to relate stormwater pollutant concentrations to land use classification (e.g. residential, commercial, roads, and roofs) [129,141–148], but commonly observe that the variability in pollutant concentrations within a given land use is of a similar order to the variation between land uses. Others have tried to predict urban stormwater quality as a function of more physically based land use indicators. Soranno et al. [149] developed a simple model predicting pollutant concentrations and loads from a spatial database of topography, impervious surfaces and physical descriptions of land use, including features such as the presence of riparian zones. Hatt et al. [123] found that the percentage of the catchment made up of impervious areas *directly connected* to the receiving water via a constructed drainage system gave a better prediction than did simple total imperviousness frequently used [150–152].

The third approach to predicting stormwater quality – and the one that has received by far the most attention – has been the so-called deterministic models which attempt to model water quality as a direct function of hydrologic and hydraulic phenomena. Deterministic approaches involve an attempt to explain the physical mechanisms responsible for pollutant generation, mobilisation and transport. For example, such models attempt to explain the buildup of pollutants on the catchment surface (as a function of factors such as time, antecedent weather conditions), the washoff from the surface (as a function of factors such as rainfall intensity and duration and the depth of runoff) and the pollutant characteristics (e.g. particle size) [153–155]. Many such approaches also include models of the transport of pollutants within the stormwater sewer system. These models are well reviewed by Obropta and Karbos [153], Vaze and Chiew [156] and Zoppou [157].

4.3. Geomorphology

Hydrologic changes due to connected impervious surfaces also lead to significant geomorphic changes, including habitat simplification, scouring of sediments and the creation of larger, deeper channels [158]. The mechanisms of such disturbance are multi-faceted. Firstly, the increase in the frequency and magnitude of high flows (and thus shear stress) results in an increase in the mobilisation and transport of sediments [159,160]. Secondly, the creation of impervious surfaces in the catchment (and often in the channel itself, as a result of channel lining) results in a reduction in the supply of *coarse sediments* [161], although a temporary increase in coarse sediments may occur as a result of and immediately following construction activities [162]. The result of these processes is a progression towards finer sediments on the channel floor, assisted by the increased concentrations of (fine) suspended sediments in urban stormwater [129], in contrast to the starvation of coarse sediments.

The increased stream power experienced by receiving waters results in an increased potential for channel migration; the response to which is typically the use of lining (with rock, concrete or other durable materials). Such channel modifications, along with the natural loss of channel diversity that happens as a result of reduced coarse mobile sediments (and the loss of other habitat elements such as woody debris) lead to substantially degraded habitat quality [163,164]. The incision of urban streams leads to separation from floodplains, with impacts not only for exchanges between the channel and riparian zones, but potential loss of important ecosystem services delivered by the riparian zone, such as the facilitation of denitrification, particularly during low flows [165,166]. Research into ways of re-engineering interaction between receiving waters and their riparian zones is thus urgently needed.

5. Integrated approaches to managing urban hydrology

5.1. Principles and objectives

Management of urban runoff has evolved along with the understanding of its environmental impacts. This new approach has taken many terms, including *Sustainable Urban Drainage Systems* (SUDS) [167], *Water Sensitive Urban Design* (WSUD) [168,169] and *Low Impact Development* (LID) [170]. Broadly, these approaches share similar objectives:

1. manage the urban water cycle in a sustainable manner (considering both surface water and ground water, along with flooding and impacts on erosion of waterways),
2. maintain or return the flow regime as close as possible to the natural level,
3. protect and where possible restore water quality (of both surface and ground waters),
4. protect and where possible restore the health of receiving waters,
5. conserve water resources (consider stormwater as a resource rather than a nuisance),
6. enhance the urban landscape and amenity by incorporating stormwater management measures which offer multiple benefits into the landscape.

While these approaches focus increasingly on integration of urban stormwater management with the other components of the urban water system, we focus here primarily on trends and technologies which affect the catchment water cycle.

Several authors have attempted to map out conceptual frameworks for protecting receiving waters from urban runoff. Wenger et al. [118] proposed that because the vast number of stressors are caused by only a few sources (Fig. 1) – with change to hydrology being a ‘master variable’ [117] – the impacts can be managed with a relatively small number of tools. They propose among the important as being (i) reduction in areas of directly connected imperviousness and (ii) engineering solutions to retain and treat stormwater. More recently, Burns et al. [171] reviewed various approaches to stormwater management and argued for a new approach that emphasises the protection or restoration of elements of the pre-development flow regime which are shown to be ecologically important. Referred to as the ‘flow-regime management approach’, it relies on identifying hydrologic indicators which affect the ecological and geomorphic condition of receiving waters, and attempting to maintain these as close as possible to their pre-development levels [172,173], recognising of course that the urban drainage system still needs to be able to safely convey peak flows during large storms, to minimise the risk to life and property from flooding. However, the identification of indicators which are both ecologically relevant and applicable to catchments of different scale, physiography and land use remains a challenge.

5.2. Technologies for managing urban runoff

Stormwater management technologies are developed for two main applications (i) treatment of water quality and (ii) mitigation of hydrologic changes. We concentrate here primarily on the evolution of approaches to managing stormwater quantity aspects, given that the principal focus of this article is on urban hydrology. As urbanisation not only increases the frequency and magnitude of peak flows, but often (although not always) results in depletions to baseflow [71], the appropriate technologies will depend on the desired flow regime:

- *Stormwater infiltration-based technologies*: including swales, infiltration trenches, basins, unlined bioretention systems (raingardens), porous pavements; the defining characteristic of this group of techniques is that they assist in the restoration of baseflows through the recharging of subsurface flows and groundwater.
- *Stormwater retention-based technologies*: wetlands, ponds, vegetated roofs, rainwater/stormwater harvesting (tanks, storage basins); the defining characteristic of this group is that they work to retain stormwater, and thus act by either (i) attenuation of outflow or (ii) reductions due to abstraction.

These techniques may be applied close to or at source, or at the end of catchment. Each approach has its advantages and disadvantages (Table 1), with centralised systems often being efficient for peak flow management [174]. However, there is a trend towards more decentralised at-source approaches where a more holistic approach to flow restoration is proposed [171,175]. Indeed, Burns et al. [171] showed that key elements of the natural flow regime could only be successfully achieved by a combination of retention to deal with peaks and overall volume, and infiltration-based techniques to deal with loss of infiltration due to impervious areas (Fig. 2) located throughout the catchment.

5.2.1. Infiltration-based techniques

Performance of infiltration systems depends most strongly on site conditions, particularly soil permeability (Fig. 3), along with the potential evolution of clogging [176–178]. Clogging of infiltration systems may be due to:

1. Poorly specified infiltration media (incorrect particle size distribution).
2. Excess deposition of sediment (particularly fine sediments) or organic matter, forming a clogging layer on the surface [179].
3. Hydraulic compaction (re-arrangement and settling of the infiltration medium due to the weight of water).

Table 1
Advantages and drawbacks of source-control technologies.

	Characteristic of source-control technologies for managing urban runoff
Advantages	– Easier implementation: smaller volumes are often technically easier to manage (for example, groundwater mounding with infiltration is less probable) – Greater private investment: cost of management system relying on source-control will be in part supported by private sector. Techniques at the parcel scale do not involve any land opportunity cost – Greater direct private benefits (e.g. use of water) – Potential microclimate benefits (reduce heat island effect)
Drawbacks	– Limited volume treated (integration with landscape can be restrictive in dense urban context): effects of peak flows (flooding, erosion) are thus weakly mitigated – Complexity of negotiation: implementation on private parcels is subject to public commitment; drivers for a large-scale implementation may be complex – Uncertain maintenance regimes (in private properties)

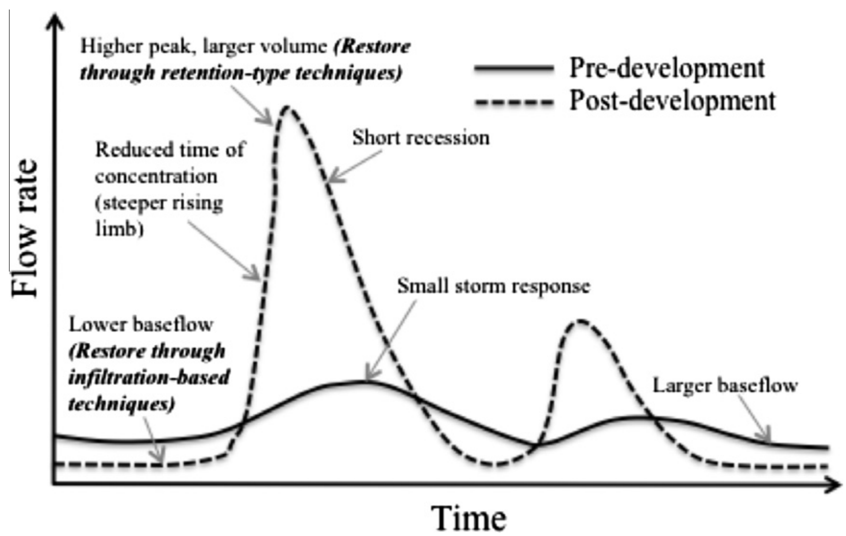

Fig. 2. Schematic illustration of the pertinent impacts of urbanisation on hydrology at the catchment scale (adapted from: [253]).

More recently, the role of vegetation in reducing the likelihood of clogging (thought to be through the creation of macropores) has been demonstrated [178–180]. Given their interaction with site conditions, it is not surprising that the range of performance reported for infiltration-based techniques is very large. Hirschman et al. [181] report reductions in annual runoff of between 40% and 60% for swales and filter strips incorporating an infiltration component, 50–90% for infiltration trenches and basins, 40–80% for unlined bioretention systems (raingardens) and 45–75% for porous pavements. Infiltration-based systems may help to restore groundwater levels and baseflows [87,175]. Whilst concerns exist regarding the potential of infiltration systems to pollute groundwater (e.g. [182,183]), these risks are generally low for most contaminants, although the question of pathogen, salt and thermal pollution to groundwater remains uncertain [184,185]. Guidelines such as those developed by Goebel et al. [86] are necessary to ensure that the development of infiltration-based devices remains consistent with sustainable depths to the groundwater table. There is also a need for models capable of predicting the impact of infiltration techniques on receiving waters and particularly on baseflow processes [77].

5.2.2. Retention-based techniques

Without infiltration or extraction for harvesting, the hydrologic performance of retention-based stormwater systems, such as wetlands, ponds, lined (and drained) bioretention systems, and vegetated roofs, is limited to:

1. Attenuation as a result of their storage-routing properties (ponding volume, detention time and outlet rate).
2. Retention due to evapotranspiration losses, if present.
3. Retention due to stormwater harvesting, if present.

The degree of attenuation will be a function of the storage volume and the detention time, and of the ratio between the catchment area and the size of the system itself (Fig. 4). Hydrologic modelling techniques can be used to estimate the inflows and the outflows and thus assess the potential benefits of a given system in terms of peak flow reduction. Many existing software programs exist for analysing such systems, as described in Section 6.3.

Of the retention systems, *wetlands and ponds* (or basins) have been used extensively for many years (e.g. [186]). Whilst effective for pollutant removal, their ability to reduce overall runoff volumes is limited [181], with their only losses coming from evapotranspiration (or harvesting, where present) Despite this, detention storages can have substantial influences on the flow regime, with both hydrologic and hydraulic consequences. However, there are other consequences of hydrograph attenuation; reducing the peak flow by storage may result in an increase in the duration of flow above a critical discharge, potentially leading to longer periods of ecological damage [171] or geomorphic disturbance [173]. Design of the outlet should thus incorporate hydraulic modelling of the

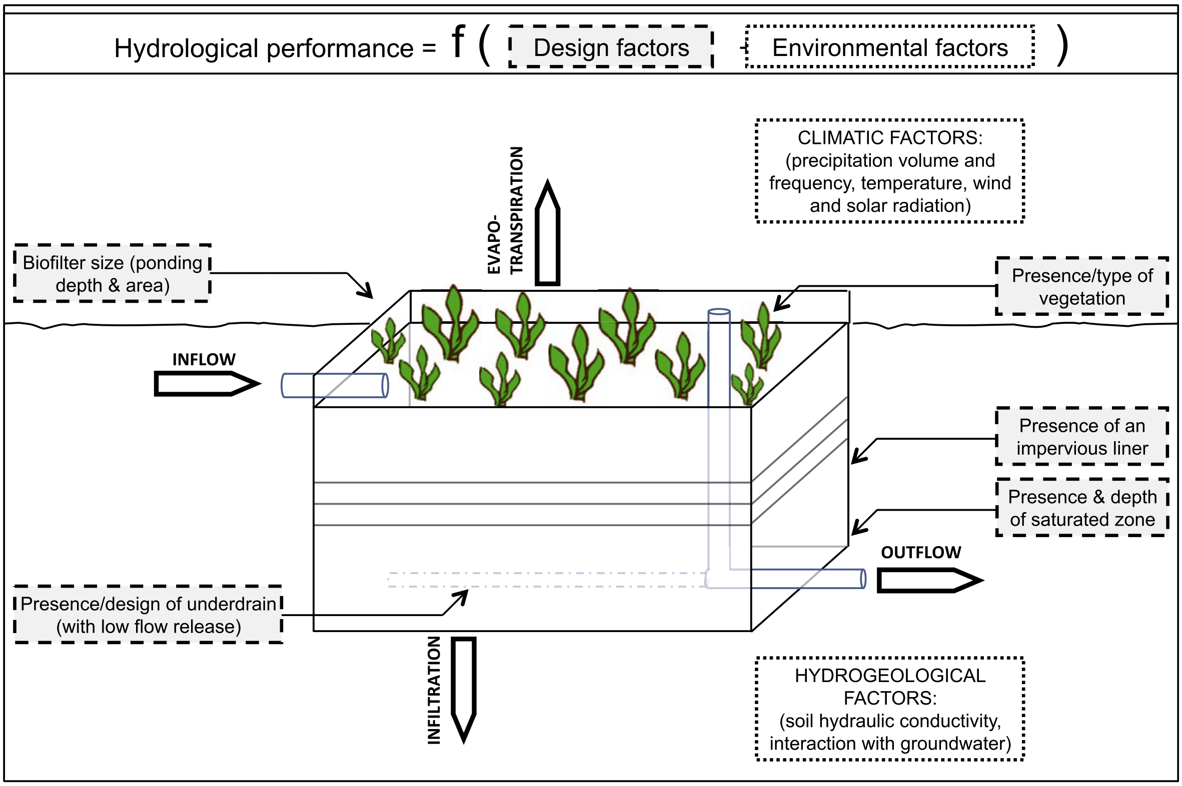

Fig. 3. Conceptual representation of infiltration-based stormwater control measures, showing design factors (in grey long-dashed box) and environmental factors (transparent dotted box) influencing performance and the impacts on catchment hydrology (e.g. total runoff volume, peak flows, baseflows, lag time).

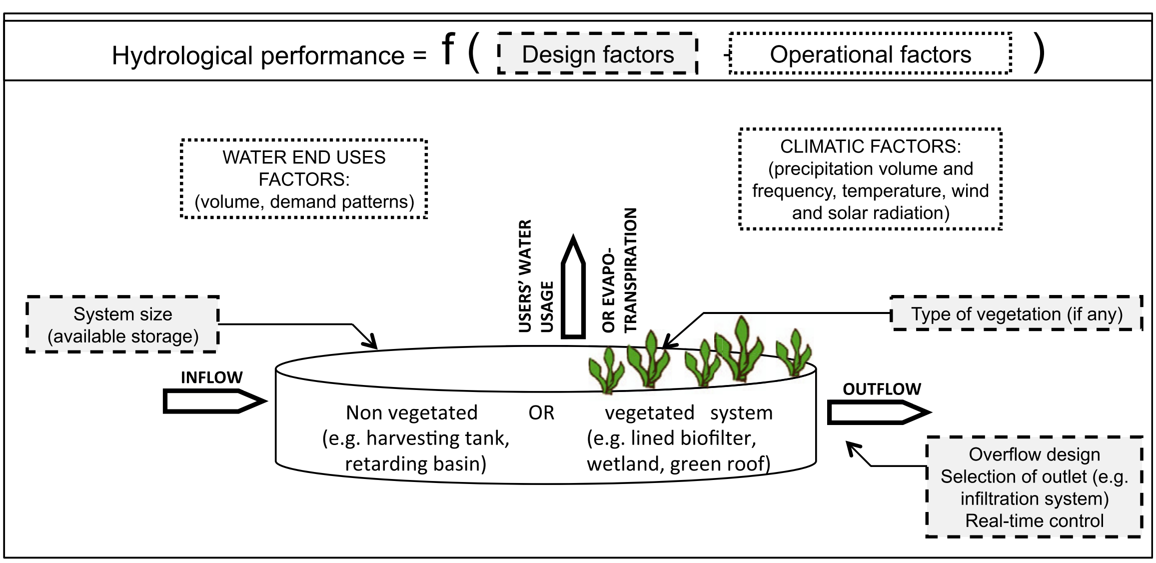

Fig. 4. Conceptual representation of retention-based stormwater control measures, showing design factors (in grey long-dashed box) and environmental factors (transparent dotted box) influencing performance and the impacts on catchment hydrology (e.g. total runoff volume, peak flows, baseflows, lag time).

downstream channel, to ensure that the flow regime does not result in excess work, leading to unnatural levels of erosion. This is an area that is yet to be well developed and will require effective collaboration between hydrologists and geomorphologists.

Bioretention systems that are lined (to prevent infiltration) and drain to the stormwater network are commonly used (e.g. [187,188]). They typically have significant storage, particularly where the underdrain is elevated to create a saturated zone in the base [189]. There are relatively few studies on the water retention and loss within lined rain-gardens. Most studies are of unlined systems, meaning that the evapotranspiration loss is not distinguished from infiltration [190]. In another study in the US [191], a lined bioretention system, making up 4.5% of its catchment area, lost 19% of its inflow volume due to evapotranspiration. Hamel et al. [101] studied an unlined system, but distinguished ET from infiltration and found ET losses of less than 5% of annual inflow, in a system which had an area of around 3% of the upstream catchment. Hatt et al. [178] observed reductions in peak flow of between 14% and 96%, with attenuation significantly influenced by antecedent rainfall. The results show that even systems without infiltration can have significant impacts on peak flow, through the effects of storage and attenuation. Li et al. [191] also showed that appropriately designed bioretention-type systems, even when fully lined, could at least partly emulate low-flow behaviour of pre-development hydrographs.

Vegetated roofs have a major advantage over other stormwater retention systems, because they typically make up 100% of their catchment area. As a result, they may achieve annual retention in the order of reduction of 55–65% of rainfall [192,193]. Climatic parameters are paramount in their performance and explain the great temporal variability in runoff reduction reported in many studies. For example, green roofs in Pennsylvania have shown net retention declining from 95% during summer to approximately 20% during winter [194]. Vegetated roofs enhance the catchment lag time, which may be beneficial to flood mitigation [195]. Important design parameters for vegetated roofs include the depth and type of materials (substrate and drainage cell), vegetation cover, roof geometry (e.g. slope) and position (with regard to wind and sunlight), as summarised by Czemiel Berndtsson [195]. Some recent studies have questioned the importance of vegetation in vegetated roofs [194,196], in part because traditionally plants chosen for vegetated roofs are those with very low evapotranspiration rates, to enhance their survival in dry periods. There is clearly a need to optimise the design of vegetated roofs to improve their retention and evapotranspiration performance, without compromising their survival.

Stormwater harvesting significantly enhances the ability of stormwater retention systems to reduce annual runoff volumes back towards pre-development levels [197]. The annual volume runoff volume reduction of simple household rainwater harvesting systems can easily reach 40% with water being used only for toilet and manual irrigation [198], while Hatt et al. [199] reported reductions in mean annual runoff volumes of between 20% and 100% from larger stormwater harvesting systems. Fletcher et al. [197] showed that under a temperate climate, rainwater harvesting resulted in a substantial restoration of flow regimes (both in terms of volume and frequency), close to pre-development levels.

Stormwater and rainwater harvesting can also reduce peak flows, thus mitigating flood risks [200], although the effect will be limited in the case of rainwater harvesting because only roof-water is retained, leaving runoff from other impervious areas (commonly at least 50% of the total impervious area) unattenuated [201]. Stormwater harvesting systems that supply regular daily demands (rather than seasonal demand, for example for irrigation) are more efficient in terms of the reduction in stormwater runoff. However, the use of harvesting for irrigation should not be ignored, particularly where it can be used in a passive form (for example harvesting into a tank from which drip irrigation is used to restore evapotranspiration and infiltration fluxes within the urban landscape). Further research into the effectiveness of such systems is needed.

Stormwater harvesting can provide an additional water resource for cities; in many cities, the volume of urban stormwater runoff is likely to equal or exceed the total water consumption [202]. It is thus perhaps unsurprising that interest in stormwater harvesting has grown enormously in recent years. For example, in the last 5 years, there have been studies that have examined the ability of stormwater harvesting to reduce flooding impacts [200,203] and to meet human water demands at costs competitive with traditional resources [204], with several studies also examining the modelling of stormwater harvesting systems [205]. More recently, there has been a strong focus on the development of appropriate treatment technologies to meet the water quality requirements for given end uses of harvested water [206]. It thus appears likely that stormwater harvesting will become a significant component of managing urban hydrology, although several important challenges remain, including (i) managing human health risks (ii) developing an economic framework to quantify all lifecycle costs and benefits, including externalities, (iii) cost-effective retrofit technologies and (iv) a lack of data on the nexus between water use and energy consumption [199].

6. Modelling

6.1. Hydrological modelling of urban catchments

Despite the availability of popular and widely used software dedicated to urban hydrology and stormwater drainage, rainfall–runoff modelling still remains an active research topic. Models vary in their temporal resolution, with daily models increasingly being replaced by models running at small timesteps (e.g. 1 or 6 min), which are necessary to represent the fast response typical of urban catchments. In addition to their temporal resolution, urban hydrologic models can be classified according to two general criteria:

1. Spatial resolution: models may be either *lumped* or *spatially distributed*, with lumped models using spatial averaging to represent the overall behaviour of a catchment, while distributed models represent subcatchments components, typically using a node-link structure [207].
2. Event or continuous: event-based models are typically used in the design of drainage infrastructure, and thus used to represent hydrologic (and potentially hydraulic) behaviour for a *design storm* (of a given duration and rainfall intensity). Whilst limited in their use (to event-based analyses), they are particularly useful for delineating catchment processes and contributions. Continuous models use a time-series (either historic or synthesised) to represent long-term behaviour through a variety of rainfall events and dry weather periods, and therefore have broader potential application.

The trend in models of urban hydrology is thus towards models which are better able to represent the spatial and temporal dynamics of the rainfall–runoff response. We review here some of the efforts which have been made towards these two objectives, considering firstly the influence of spatial arrangement on temporal dynamics of the hydrograph and then consider approaches to accounting for longer term variations in rainfall–runoff response.

6.1.1. Accounting for spatial arrangement and its effects on event dynamics

Increasingly, urban hydrology is modelled using spatially distributed approaches that take advantage of the rapidly increasing information on cities through remote sensing and spatial databases. Such information can be helpful to characterise land use, to discriminate impervious from pervious areas [208] and to account for the spatial arrangement of flow paths.

In pursuing a better representation of spatial dynamics of runoff, recent studies have revisited the concept of the unit hydrograph adapted to urban catchments. This event-based concept, which summarises the role of the hydrographic network at the catchment scale, can take advantage of the detailed description of the urban drainage network. Aronica and Canarozzo [209] developed a model that conceptualises the drainage network as a cascade of nonlinear cells and the flood routing as a flux transfer between adjacent cells. Several studies have applied the concept of GIUH (Geomorphologic Instantaneous Unit Hydrograph) to urban catchments. The GIUH approach derives the unit hydrograph from the statistical distribution of travel time along flow paths [210,211]. Gironas et al. [212] proposed the model called U-McIUH (for Urban Morpho-climatic Instantaneous Unit Hydrograph) inspired from that concept. Flow paths are extracted from this specially processed digital elevation model that incorporates hillslopes streets, pipes and channels [213]. Moreover, the travel times of each DTM cell are calculated using the average wave velocity and the U-McIUH is defined as the density probability function of the travel time to the catchment outlet. Cantone and Schmidt [214] developed the IUHM (Illinois Urban Hydrologic Model), which is based on the same concept of GIUH. The same authors [214] proposed to improve the understanding of the hydrologic response of urban catchments by analysing the dispersion mechanisms and the variations of these mechanisms along urban flow paths. Rodriguez et al. [215] derived the unit hydrographs of three urban catchments based on an explicit description of water flow paths from cadastral parcels to the outlet and then compared these hydrographs in order to identify the unit hydrographs from rainfall–runoff data. Rodriguez et al. [216] also compared this method to two alternative methods: including the unit hydrograph derived from observed rainfall and flow data. Rabunal et al. [217] took a statistical approach, determining the unit hydrograph of an urban catchment using artificial neural networks. Similarly, Furusho et al. [75] used a combination of geomorphologic and hydro-meteorological analyses to predict runoff response, testing the predictions using a First-Differenced Transfer Function. Their model demonstrated that during dry weather, impervious areas alone generated runoff, but wetting up of the catchment saw pervious and impervious area contributions to the catchment outlet, resulting in multiple peak responses. An alternative statistical approach consists of building an analytical probabilistic model, as proposed by Chen and Adams [218]; their model consists of deriving the probability density function of event runoff volume from the probability density function (PDF) of total rainfall per event through use of an analytical expression of runoff coefficients.

All these studies considered that the catchment response is highly correlated with the drainage network structure, which tends to be well known in urban areas. They suggest a convergence in approaches to modelling hydrology in natural and urban areas, with spatial arrangement, network structure and sub-area behaviours being increasingly taken into account.

6.1.2. Accounting for temporal variation in runoff response to rainfall

The trend towards continuous simulation has been strong in recent years [207]. While this approach has greater computing and time requirements, it provides more useful information regarding the design of stormwater infrastructure, particularly where understanding of the flow regime is required for treating water quality. For example, one of the best known stormwater models, the Storm Water Management Model (SWMM) [219], was originally, when released in 1971, an event-based model. The model remains widely used today and has evolved to include dynamic continuous simulation, as well as including water quality and treatment processes (see Section 6.2).

The move towards continuous simulation creates the need to track and predict the status of catchment moisture storages, in order to calculate rainfall excess. Most rainfall–runoff models use a similar approach to estimate rainfall excess. In the semi-distributed model proposed by Aronica and Canarozzo [209], the rainfall excess is calculated by a Hortonian infiltration scheme, with depression storage on pervious surfaces and losses being limited to the depression storage on impervious surfaces. The distributed rainfall–runoff model developed by Gironas et al. [212] complements U-McIUH by a rainfall excess value calculated on each grid cell, which combines rainfall on the impervious part of the cell with rainfall exceeding an infiltration capacity and dependent on antecedent moisture for the pervious part of the cell. Cantone and Schmidt [214] enhanced their urban GIUH by introducing a classical rainfall excess scheme: depression storage on impervious surfaces, and depression storage plus a Green-Ampt infiltration model on pervious surfaces. Bennis and Crobeddu [220] presented an urban runoff simulation model that revisits the traditional rational method and used a rainfall excess function similar to existing approaches, to derive the catchment hydrograph and then compared it to SWMM as part of a case study. More sophisticated approaches have attempted to model the behaviour of all moisture stores, including impervious areas, unsaturated soils and groundwater. For example, the water budget approach simulated by Rodriguez et al. [221] on each type of land use (pavements, buildings and natural surfaces) makes it possible to quantify the contribution of vadose storage and groundwater storage to outflow by introducing interflow and groundwater flow components. Rodriguez et al. [222] then proposed the URBS-MO model, which simulates over long time series the various components of rainwater flux, i.e. surface runoff, drainage flow via the sewer, evapotranspiration, and saturation level in the soil from the parcel scale to the catchment scale. This model has been tested on two urban catchments in Nantes (France), of 180 and 5 ha, based on a comparison of observed and simulated flow rates and saturation levels. Khu et al. [223] introduced the physically-based model BEMUS, which regroups the following components: depression storage, infiltration (Green-Ampt method), surface flow and gutter flow, but importantly adds water flows through source control devices and through routing storage within the sewer network (using the Muskingum-Cunge method). Increasingly, such approaches considering interactions between impervious areas, pervious areas, infrastructure and groundwater are becoming feasible, allowing the longer-term dynamics to be represented in continuous simulation models, particularly in peri-urban areas.

6.2. Models for integrated management of urban runoff

The paradigm of an integrated urban water management model intended to simultaneously incorporate water supply, drainage and wastewater as components of an integrated total water cycle has emerged during the past decade. This integrated approach aims to optimise between the different objectives assigned to the drainage system: to maintain public hygiene, prevent flooding, preserve the receiving ecosystem and finally to reduce the influence of urbanisation on the water cycle. It needs models able to simulate all the components of the urban water system in a combined/coupled way, at a wide range of scales.

As noted in Section 6.1, the earliest stormwater models were focussed only on hydrology, hydraulics and only later on water quality. In his review paper, Zoppou [157] presented the main principles of such integrated urban stormwater models. These principles remain valid today and were recently updated by Jacobson [208]. 'Traditional' urban stormwater models covered the main *hydrological* processes occurring in catchments: interception and depression storage, infiltration into unsaturated soils and percolation into groundwater, interflow between groundwater and sewer system, and routing of surface runoff. They also represent hydraulic processes in the drainage network (including storage, diversion and overflow devices) by means of kinematic wave or full dynamic wave flow routing methods. However, these models historically ignored water quality.

More recently, there has been an increased focus on the ability of urban stormwater models to consider water quality aspects, both in terms of pollutant production [157] (see also Section 4.2) and in terms of treatment [207]. Thus, stormwater models are used to predict the production of pollution loads during rain events and their retention by stormwater treatment devices. Models such as the Model for Urban Stormwater Improvement Conceptualisation MUSIC [224], along with new versions of SWMM [225], have thus been developed in order to assess the impacts of urban development on stormwater quality and hydrology and to evaluate the effectiveness of various stormwater management strategies to mitigate these impacts. MUSIC, for example, can be used to model treatment and flow through wetlands, ponds and sediment basins, swales and buffer strips, bioretention and infiltration systems [36,226], as well as through stormwater harvesting systems. Models such as MUSIC require significant calibration effort to provide reliable estimates [227,228], but have found widespread application at a wide range of scales, from allotment scale to precinct or suburb scale planning [207].

There remains, however, an important gap between the complex hydraulic-based models such as MIKE-URBAN [229] or CANOE [230] and conceptual models such as MUSIC. The hydraulic models allow assessment at the network level of hydraulic impacts, but often cannot represent at-source stormwater management and retention techniques, while conceptual models often represent these techniques well, but are unable to accurately represent impacts on hydraulic behaviour at the catchment scale [77]. Facilitating the integration of these two scales thus remains a question of significance for future research [231].

In more recent times, a number of more ambitious models have been developed, aimed at the design, assessment and performance prediction of stormwater management strategies integrated within a broader integrated urban water management framework i.e. moving beyond management of urban runoff in isolation from other components of the urban water cycle. Mitchell et al. [229,232] reviewed a large number of models developed to represent the integrated urban water cycle, and identified significant gaps in current approaches. Within these, there are models developed for the integrated modelling of urban drainage systems; such models are commonly applied to the entire sewer system, which encompasses the wastewater and stormwater systems as well as the treatment plant [233,234]. Mitchell et al. [235] proposed a model called "Aquacycle" with the aim of simulating the urban water cycle, including water supply and wastewater disposal, to the rainwater cycle. The following processes were represented with a daily time step and at a spatial resolution of an urban block: runoff and evaporation on impervious surfaces, groundwater storage fed by infiltration on pervious surfaces, evapotranspiration, inflow and infiltration of stormwater into wastewater, and urban irrigation. These processes were supplemented by residential indoor water use, stormwater storage and use, and wastewater treatment and reuse. The model was then applied to a regional grouping of Canberra suburbs (Australia). Hardy et al. [236] introduced their integrated model, named UrbanCycle, which simulates water supply, stormwater and wastewater using allotments as the basic building block. The ideas behind UrbanCycle and Aquacycle have been used by the eWater Cooperative Research Centre in the development of Urban Developer [237], which allows users to improve understanding and management of the various impacts of urban water management options from the lot to the cluster scale. It allows performance assessment of integrated urban water management options across the entire urban water cycle. The same approach has been now adopted as part of the EU SWITCH program [238].

Despite these advances, significant impediments to the development and adoption of integrated urban water models exist. As model complexity grows, so does the need for data, not only to represent single phenomena, but to understand the interactions between components of the urban water cycle [239]. Models that can thus represent feedback mechanisms between the various components, at various scales, are still far from perfect and remain an important research challenge. Perhaps most importantly, as the complexity of the models grows, so does the difficulty in assessing their accuracy.

6.3. Model validation and uncertainty analysis

The application of hydrologic models brings with it several areas of uncertainty, related to the input data (rainfall time series); the model parameters and structure, as well as the calibration and validation data. Model calibration, sensitivity and uncertainty analysis are key issues in assessing the accuracy and robustness of model results, along with the need for model validation. We do not review here the range of techniques available for the collection of validation data, but we note that techniques such as isotope or temperature tracing, already applied in non-urban areas [240], may be more challenging in urban situations, due to the potential interaction of water cycle components.

6.3.1. Rainfall input data

Aronica et al. [241] analysed the influence of temporal resolution of rainfall on the probability distribution of simulated event maximum outflows, based on a 10-year data series in an experimental catchment in Italy. Willems and Berlamont [242] studied the influence of spatial variability of rainfall on flow modelling results and derived correction factors. Using a case study, Quirmbach and Shultz [243] found that radar data should be introduced for rainfall–runoff modelling in urban hydrology if the rain gauge density is less than one gauge per 16 km^2. Vieux and Bedient [244] analysed the magnitude of radar rainfall measurement errors in simulating the hydrographs of five very intense rain events that occurred within the large urbanised catchment of Brays Bayou, France (260 km^2), with the aim of setting up real-time operations. They concluded that correction of rainfall radar data by gauges is needed as a step to obtaining accurate simulated outflows. An important current challenge is to integrate climate change predictions (and their uncertainty) into rainfall predictions, particularly for extreme events [35].

6.3.2. Runoff model calibration

The automatic SWMM calibration, by means of the complex method, has been addressed by Barco et al. [245], who considered four global calibration parameters: imperviousness, depression storage, width, and channel Manning's roughness coefficient. A sensitivity analysis indicated that imperviousness coefficient and depression storage were the most sensitive parameters affecting total runoff and peak flow. Dotto et al. [103] performed a sensitivity analysis and evaluated the performance of the model MUSIC, which requires 13 parameters for the rainfall–runoff component, and then compared it to a simpler model, KAREN (with just three parameters), for the purpose of determining outlet flow. The analysis, performed within a Bayesian framework, involved simulating a large number of runoff series by randomly varying parameter values, with the calibration step performed in applying an MCMC approach. They concluded that: both models were much more sensitive to impervious properties than to pervious area properties, as soon as there was any significant urbanisation in the catchment. They also observed that the total uncertainty is greater than the parameter uncertainty bounds, which suggests that the errors due to input and calibration data, along with model structure, cannot be neglected. Thorndahl et al. [246] calibrated the MOUSE model and ran a sensitivity analysis using the GLUE methodology, which remains very popular among hydrologists. These authors reached a similar conclusion, whereby the most significant parameters are those controlling the runoff from impervious areas. Khu et al. [223] calibrated the BEMUS model via a different technique (the Multi-Objective Genetic Algorithm), but with a similar result. Estimation of the hydraulically effective impervious area, which is important to hydrological modelling, was raised by Han and Burian [247], who proposed an automated method that combines a classification of fine-scale multispectral satellite imagery with the determination of water flow paths in order to classify impervious pixels as either effective or not. After testing this method for rainfall–runoff modelling with SWMM, these authors concluded that readily available (and high-resolution) data are needed to produce correct results. Walsh and Kunapo extended this method, testing the influence of flow attenuation between impervious surfaces and receiving waters [64].

6.3.3. Uncertainty analysis

Model estimates should be provided with an assessment of their uncertainties, so that users of the model predictions can take this into account in their decision-making. Bertrand-Krajewski and Muste [248] provide a very thorough introduction to the concepts of uncertainty. Recognising the need to consider all sources of uncertainty (model parameter values, input and calibration data, along with the structure of the model), Deletic et al. [249] proposed a framework for the global assessment of modelling uncertainties, which they applied to integrated models of rainfall–runoff and urban stormwater quality. The framework, developed under the auspices of the International Water Association and International Association of Hydraulic Research's Joint Committee on Urban Drainage, involves a three-step process, resulting in probability distributions being created for each model parameter and then propagated through the model, allowing alternate models to be objectively compared. Despite the very clear rationale for such an approach, uncertainty analysis remains a challenge for both research and practice, particularly with the highly complex and highly parameterised models becoming increasingly prevalent in integrated models for urban water management. Some such attempts have been made [233,250], but as more elements of the urban water cycle (including not only physical but also social and economic aspects) become integrated into such models, data requirements for such assessments become increasingly difficult. Ideally, models would be validated using physical measurements (e.g. the use of chemical tracers to measure interactions between surface water and groundwater), but for highly complex interactive systems, such physically based approaches may not be viable.

An additional area of complexity and uncertainty is the incorporation of climate change predictions into models of rainfall, urban hydrology, water quality and treatment. Some attempts have been along this path [251,252], but the combination of uncertainties in the magnitude of change (with a nested uncertainty about the scale of human response to climate change signals) means that substantially greater effort is needed. Such attempts will need to ultimately migrate from theory to practice, so that urban stormwater managers can better factor this uncertainty into decisions about infrastructure.

7. Conclusions and perspectives

Advances in the science and practice of urban hydrology have been extensive over the last two decades, both in terms of fundamental understanding and in terms of the approaches to management. New technologies for recording, analysing and predicting rainfall in urban areas have emerged, with the aim of addressing the challenges of small spatial and temporal scales of the urban rainfall–runoff response. The emergence of microwave networks, exploiting existing mobile communications technologies, is particularly exciting, as are the developments of radar for accurate measurement of rainfall intensities. Despite these advances, understanding of the spatial–temporal structures of rainfall is still relatively poor. An important research priority is thus to develop more reliable methods for predicting short-duration rainfall; such an effort requires increased collaborations between urban hydrologists and meteorologists and needs to take into account the impact of urban land use on rainfall patterns.

The variability and complexity of the rainfall–runoff response in urban areas remains an area of active research. Particularly in peri-urban areas with complex mixes of urban and rural land, multiple flow peaks are likely to be experienced, making prediction difficult. While impervious area runoff is relatively predictable, the changes to pervious areas result in changes to both surface and subsurface flow processes that are more complex and catchment-specific. Catchment-specific evaluations of flow changes due to urbanisation are thus required.

Management of the perturbations to the rainfall–runoff response brought by urbanisation has become considerably more sophisticated, with the traditional singular focus on peak flows now making way for a more holistic flow regime approach. However, such an approach is impeded by a lack of agreement on (i) appropriate hydrologic indicators to use and (ii) the impact of urbanisation (not only from stormwater but from water and wastewater infrastructure) on baseflow processes. In addition, stormwater management must deal with the increased generation, mobilisation and transport of pollutants as a result of urbanisation. The emergence of newly identified micropollutants will increase this challenge.

Despite its importance to both flow regimes and the urban landscape, the loss of evapotranspiration as a result of urbanisation is not well quantified and improved tools to measure evapotranspiration are required. There is an emerging interest in the use of techniques for restoring evapotranspiration, as part of a more integrated approach to stormwater management, but knowledge of such practices at this stage is quite primitive. For example, there is a need to understand the influence of a range of stormwater management techniques on infiltration and evapotranspiration fluxes, in order to assess their effectiveness in restoring baseflows as well as landscape soil moisture.

Whilst the increase in runoff by urbanisation creates a threat to humans and receiving waters, it is also an opportunity for urban communities; harvesting this excess water can both help to protecting aquatic ecosystems from degradation and provide an important new water resource to cities and towns. Further research to quantify the economic, social and environmental value of stormwater harvesting is needed, as are new technologies for the capture, treatment and distribution of stormwater.

With an increasing richness of data on cities, the trend of urban hydrologic models is towards application of spatially distributed continuous simulation models. Combined with a move towards integration of all aspects of the urban water cycle (e.g. rainfall–runoff, water supply and wastewater), models are becoming increasingly complex, thus demanding increasingly sophisticated approaches for assessing their uncertainties. This field is developing rapidly, but unfortunately, the validation and uncertainty assessment of such models lags behind their application.

An important emerging issue is the impact of climate change on urban hydrology. There is thus an urgent need to better understand how rainfall behaviour will change at urban scales and to assess the impacts of such changes on the performance and reliability of stormwater management systems for flood control, hygiene and environmental protection. With uncertainty in the extent and timing of such changes, there is also an imperative to examine ways in which the urban stormwater system – and the urban water system more generally – can be designed to be adaptable to unforeseen changes.

In conclusion, there is a clear trend towards more integrated management of stormwater within a broader integrated urban water management framework. The recognition that interactions between the components of the urban water cycle are as important as the individual components themselves leads to the requirement to collect new types of data and to develop new types of models. Whilst this requirement for integration does not diminish the need for fundamental understanding in urban rainfall, runoff response and the management of urban stormwater – it does mean that a greater range of disciplines need to participate in addressing the impacts of urbanisation on hydrology and its consequences. Urban hydrology thus remains a driving variable in the management of the urban water system – but optimal outcomes will only be achieved where the interactions between climate, land use, ecosystems and society are taken into account. Future approaches will thus necessarily be more complex, but will better meet the needs of an increasingly urban world.

Acknowledgements

We thank three anonymous reviewers and Andrea Rinaldo for their useful comments and criticisms which helped to substantially improve the manuscript.

References

[1] United Nations. World urbanization prospects: the 2009 revision. New York: United Nations Department of Economic and Social Affairs (Population Division); 2010.
[2] Niemczynowicz J. Urban hydrology and water management: present and future challenges. Urban Water 1999;1:1–14.
[3] Lanza LG, Stagi L. High resolution performance of catching type rain gauges from the laboratory phase of the WMO Field Intercomparison of Rain Intensity Gauges. Atmos Res 2009;94:555–63.
[4] Ciach GJ. Local random errors in tipping-bucket rain gauge measurements. J Ocean Atmos Technol 2003;20:752–9.
[5] Ciach GJ, Krajewski WF. Analysis and modeling of spatial correlation structure in small-scale rainfall in Central Oklahoma. Adv Water Resour 2006;29:1450–63.
[6] Moreau E, Testud J, Le BE. Rainfall spatial variability observed by X-band weather radar and its implication for the accuracy of rainfall estimates. Adv Water Resour 2009;32:1011–9.
[7] Berne A, Delrieu G, Creutin JD, Obled C. Temporal and spatial resolution of rainfall measurements required for urban hydrology. J Hydrol 2004;299:166–79.
[8] Einfalt T, Arnbjerg-Nielsen K, Golz C, Jensen NE, Quirmbach M, Vaes G, et al. Towards a roadmap for use of radar rainfall data in urban drainage. J Hydrol 2004;299:186–202.
[9] Emmanuel I, Andrieu H, Tabary P. Evaluation of the new French operational weather radar product for the field of urban hydrology. Atmos Res 2011;103:20–32.
[10] Delrieu G, Creutin JD. Weather radar and urban hydrology: advantages and limitations of X-band light configuration systems. Atmos Res 1991;27:159–68.
[11] Pedersen L, Einar JN, Madsen M. Calibration of local area weather radar - identifying significant factors affecting the calibration. Atmos Res 2010;97:129–43.
[12] Thorndahl S, Rasmussen MR. Marine X-band weather radar data calibration. Atmos Res 2011;103:33–44.
[13] Emmanuel I, Andrieu H, Leblois E, Flahaut B. Temporal and spatial variability of rainfall at urban hydrological scales. J Hydrol 2012;430–431:162–72.
[14] Diss S, Testud J, Lavabre J, Ribstein P, Moreau E, Parent du Chatelet J. Ability of a dual polarized X-band radar to estimate rainfall. Adv Water Resour 2009;32:975–85.
[15] Smith JA, Baeck ML, Villarini G, Welty C, Miller AJ, Krajewski W. Analyses of a long-term high-resolution radar rainfall data set for the Baltimore metropolitan region. Water Resour Res 2012;48:W04504–18.
[16] Upton GJG, Holt AR, Cummings RJ, Rahimi AR, Goddard JWR. Microwave links: the future for urban rainfall measurement? Atmos Res 2005;77:300–12.
[17] Leijnse H, Uijlenhoet R, Stricker JNM. Hydrometeorological application of a microwave link: 2. Precipitation. Water Resour Res 2007;43:W04417.
[18] Cummings RJ, Upton GJG, Holt AR, Kitchen M. Using microwave links to adjust the radar rainfall field. Adv Water Resour 2009;32:1003–10.
[19] Giuli D, Toccafondi A, Biffi Gentili G, Freni A. Tomographic reconstruction of rainfall fields through microwave attenuation measurements. J Appl Meteorol 1991;30:1323–40.
[20] Zinevich A, Alpert P, Messer H. Estimation of rainfall fields using commercial microwave communication networks of variable density. Adv Water Resour 2008;31:1470–80.
[21] Cuccoli F, Baldini L, Facheris L, Gori S, Gorgucci E. Tomography applied to radiobase network for real time estimation of the rainfall rate fields. Atmos Res; doi: 101016/jatmosres201106024 [in press].
[22] Luk KC, Ball JE, Sharma A. An application of artificial neural networks for rainfall forecasting. Math Comput Model 2001;33:683–93.
[23] Bellon A, Zawadzi I. Forecasting of hourly accumulations of precipitation by optimal extrapolation of radar maps. J Hydrol 1994;157:211–33.
[24] Li L, Schmid W, Joss J. Nowcasting of motion and growth of precipitation with radar over a complex orography. J Appl Meteorol 1995;34:1286–300.
[25] Achleitner S, Fach S, Einfalt T, Rauch W. Nowcasting of rainfall and of combined sewage flow in urban drainage systems. Water Sci Technol 2009;59:1145–51.
[26] Bremaud PJ, Pointin Y. Forecasting heavy rain from cell motion using radar data. J Hydrol 1993;142:373–89.
[27] Einfalt T, Denoeux T, Jacquet G. A radar rainfall forecasting method for hydrological purposes. J Hydrol 1990;114:229–44.
[28] Faure D, Schmitt JP, Auchet P. Limits of radar rainfall forecasting for sewerage management: results and application in Nancy. In: 8th International conference on urban storm drainage. Sydney, Australia; 1999. p. 441–9.
[29] Thielen J, Boudevillain B, Andrieu H. A radar data based short-term rainfall prediction model for urban areas; a simulation using meso-scale meteorological modelling. J Hydrol 2000;239:97–114.
[30] Boudevillain B, Andrieu H, Chaumerliac N. Evaluation of RadVil, a radar-based very short-term rainfall forecasting model. J Hydrometeorol 2006;7:178–89.
[31] Germann U, Berenguer M, Sempere-Torres D, Zappa M. REAL – ensemble radar precipitation estimation for hydrology in a mountainous region. Quart J R Meteorol Soc 2009;135:445–56.
[32] Liguori S, Rico-Ramirez MA, Schellart ANA, Saul AJ. Using probabilistic radar rainfall nowcasts and NWP forecasts for flow prediction in urban catchments. Atmos Res 2012;103:80–95.
[33] Bowler NE, Pierce CE, Seed AW. STEPS: a probabilistic precipitation forecasting scheme which merges an extrapolation nowcast with downscaled NWP. Quart J R Meteorol Soc 2006;132:2127–55.
[34] Vasiloff S, Seo D-J, Howard K, Zhang J, Kitzmiller D, Mullusky M, et al. Improving QPE and very short term QPE. Bull Am Meteorol Soc December 2007;2007:1899–911.
[35] Ekstrom M, Fowler HJ, Kilsby CG, Jones PD. New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 2. Future estimates and use in impact studies. J Hydrol 2005;300:234–51.
[36] Wong THF, Fletcher TD, Duncan HP, Jenkins GA. Modelling urban stormwater treatment – a unified approach. Ecol Eng 2006;27:58–70.
[37] Onof C, Chandler RE, Kakou A, Northrop P, Wheater HS, Isham V. Rainfall modelling using Poisson-cluster processes: a review of developments. Stoch Env Res Risk Assess 2000;14:384–411.
[38] Rodriguez-Iturbe I, Cox DR, Isham V. Some models for rainfall based on stochastic point processes. Proc R Soc Lond A: Math Phys Sci 1987;410:269–88.
[39] Cowpertwait P, Isham V, Onof C. Point process models of rainfall: developments for fine-scale structure. Proc R Soc A: Math Phys Eng Sci 2007;463:2569–87.
[40] Onof C, Arnbjerg-Nielsen K. Quantification of anticipated future changes in high resolution design rainfall for urban areas. Atmos Res 2009;92:350–63.
[41] Schertzer D, Lovejoy S. Physical modeling and analysis of rain and clouds by anisotropic scaling multiplicative processes. J Geophys Res 1987;92:9693–714.
[42] Molnar P, Burlando P. Preservation of rainfall properties in stochastic disaggregation by a simple random cascade model. Atmos Res 2005;77:137–51.
[43] Licznar P, Åomotowski P, Rupp DE. Random cascade driven rainfall disaggregation for urban hydrology: an evaluation of six models and a new generator. Atmos Res 2011;99:563–78.
[44] Onof C, Townend J, Kee R. Comparison of two hourly to 5-min rainfall disaggregators. Atmos Res 2005;77:176–87.
[45] Gaume E, Mouhous N, Andrieu H. Rainfall stochastic disaggregation models: calibration and validation of a multiplicative cascade model. Adv Water Resour 2007;30:1301–19.
[46] Burian SJ, Durran SR. Evaluation of an artificial neural network rainfall disaggregation model. Water Sci Technol 2002;45:99–104.
[47] Jennings SA, Lambert MF, Kuczera G. Generating synthetic high resolution rainfall time series at sites with only daily rainfall using a master-target scaling approach. J Hydrol 2010;393:163–73.
[48] Segond ML, Onof C, Weather HS. Spatial-temporal disaggregation of daily rainfall from a generalized linear model. J Hydrol 2006;331:674–89.
[49] Huff FA, Changnon SAJ. Climatological assessment of urban effects on precipitation at St. Louis. J Appl Meteorol 1972;11:823–42.
[50] Shepherd JM. A Review of current investigations of urban-induced rainfall and recommendations for the future. Earth Interact 2005;9:1–27.
[51] Ntelekos AA, Smith JA, Baeck ML, Krajewski WF, Miller AJ, Goska R. Extreme hydrometeorological events and the urban environment: dissecting the 7 July 2004 thunderstorm over the Baltimore MD Metropolitan Region. Water Resour Res 2008;44:W08446.
[52] Ntelekos AA, Smith JA, Donner L, Fast JD, Gustafson Jr WI, Chapman EG, et al. The effects of aerosols on intense convective precipitation in the northeastern United States. Quar J R Meteorol Soc 2009;135:1367–91.
[53] Burian SJ, Shepherd JM. Effect of urbanization on the diurnal rainfall pattern in Houston. Hydrol Process 2005;19:1089–103.
[54] Krajewski WF, Kruger A, Smith JA, Lawrence R, Gunyon C, Goska R, et al. Towards better utilization of NEXRAD data in hydrology: an overview of hydro-NEXRAD. J Hydroinform 2011;13:255–66.
[55] Niyogi D, Pyle P, Lei M, Arya SP, Kishtawal CM, Shepherd M, et al. Urban modification of thunderstorms: an observational storm climatology and

model case study for the Indianapolis urban region. J Appl Meteorol Climatol 2010;50:1129–44.
[56] Rose L, Stallins JA, Bentley M. Concurrent cloud-to-ground lightning and precipitation enhancement in the Atlanta, Georgia (United States), urban region. Earth Interact 2008;12:1–30.
[57] Miao S, Chen F, Li O, Fan S. Impacts of urban processes and urbanization on summer precipitation: a case study of heavy rainfall in Beijing on 1 August 2006. J Appl Meteorol Climatol 2011;50:806–26.
[58] Shem W, Shepherd M. On the impact of urbanization on summertime thunderstorms in Atlanta: two numerical model case studies. Atmos Res 2009;92:172–89.
[59] Leopold LB. Hydrology for urban land planning: a guidebook on the hydrological effects of urban land use. Washington DC: US Geological Survey; 1968. p. 18.
[60] Ragab R, Bromley J, Rosier P, Cooper JD, Gash JHC. Experimental study of water fluxes in a residential area: 1. Rainfall, roof runoff and evaporation: the effect of slope and aspect. Hydrol Process 2003;17:2409–22.
[61] Ragab R, Rosier P, Dixon A, Bromley J, Cooper JD. Experimental study of water fluxes in a residential area: 2. Road infiltration, runoff and evaporation. Hydrol Process 2003;17:2423–37.
[62] Ramier D, Berthier E, Andrieu H. The hydrological behaviour of urban streets: long-term observations and modelling of runoff losses and rainfall, runoff transformation. Hydrol Process 2011;25:2161–78.
[63] Sutherland RC. Methodology for estimating effective impervious area of urban watersheds. Watershed Protect Tech 1995;2:282–3.
[64] Walsh CJ, Kunapo J. The importance of upland flow paths in determining urban effects on stream ecosystems. J N Am Benthol Soc 2009;28.
[65] Herb WR, Janke B, Mohseni O, Stefan HG. Runoff temperature model for paved surfaces. J Hydrol Eng 2009:1146–55.
[66] Thompson AM, Kim K, Vandermuss AJ. Thermal characteristics of stormwater runoff from asphalt and sod surfaces. J Am Water Resour Assoc 2008;44:1325–36.
[67] Janke BD, Herb WR, Mohseni O, Stefan HG. Simulation of heat export by rainfall–ìrunoff from a paved surface. J Hydrol 2009;365:195–212.
[68] Shuster WD, Pappas E. Laboratory simulation of urban runoff and estimation of runoff hydrographs with experimental curve numbers implemented in USEPA SWMM. J Irrigat Drain Eng 2011;137:343–51.
[69] Gregory JH, Dukes MD, Jones PH, Miller GL. Effect of urban soil compaction on infiltration rate. J Soil Water Conserv 2006;61:117–24.
[70] Booth DB, Jackson CR. Urbanization of aquatic systems - degradation thresholds, stormwater detention, and the limits of mitigation. J Am Water Resour Assoc 1997;33:1077–90.
[71] Price K. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Progress Phys Geogr 2011;35:465–92.
[72] Boyd MJ, Bufill MC, Kness RM. Pervious and impervious runoff in urban catchments. Hydrol Sci 1993;38:463–78.
[73] Ando Y, Musiake K, Takahasi Y. Modelling of hydrologic processes in a small urbanized hillslope basin with comments on the effects of urbanization. J Hydrol 1984;68:61–83.
[74] Price K, Jackson CR, Parker AJ. Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA. J Hydrol 2010;383:256–68.
[75] Furusho C, Chancibault, K, Andrieu A. Runoff generation on a urbanizing river basin. In: Novatech conference 2010. Lyon, France; 2010.
[76] Cuo L, Lettenmaier DP, Mattheussen BV, Storck P, Wiley M. Hydrologic prediction for urban watersheds with the distributed hydrology–soil–vegetation model. Hydrol Process 2008;22:4205–13.
[77] Hamel P, Daly E, Fletcher TD. Source-control stormwater management for mitigating the effects of urbanisation on baseflow. J Hydrol [in review].
[78] Lee JY, Choi MJ, Kim YY, Lee KK. Evaluation of hydrologic data obtained from a local groundwater monitoring network in a metropolitan city, Korea. Hydrol Process 2005;19:2525–37.
[79] Reynolds JH, Barrett MH. A review of the effects of sewer leakage on groundwater quality. Water Environ J 2003;17:34–9.
[80] Belhadj N, Joannis C, Raimbault G. Modelling of rainfall induced infiltration into separate sewerage. Water Sci Technol 1995;32:161–8.
[81] Berther E, Andrieu H, Rodriguez F. The Rezé urban catchments database. Water Resour Res 1999;35:1915–9.
[82] Ruban V, Rodriguez F, Rosant JM, Larrarte F, Joannis C, Mestayer P, et al. Hydrologic and energetic experimental survey of a small urban watershed. Lyon, France: Novatech. GRAIE; 2007.
[83] Berthier E, Andrieu H, Creutin JD. The role of soil in the generation of urban runoff: development and evaluation of a 2D model. J Hydrol 2004;299:252–66.
[84] Karpf C, Krebs P. Quantification of groundwater infiltration and surface water inflows in urban sewer networks based on a multiple model approach. Water Res 2011;45:3129–36.
[85] De Silva D, Burn S, Moglia M, Tjandraamadja G, Gould S, Sadler P. Network exfiltration and infiltration model (NEIMO). In: Wolf L, Morris B, Burn S, editors. Integrating groundwater into water management. London: IWA; 2006. p. 34–50 [chapter 2.2].
[86] Goebel P, Stubbe H, Weinert M, Zimmermann J, Fach S, Dierkes C, et al. Near-natural stormwater management and its effects on the water budget and groundwater surface in urban areas taking account of the hydrogeological conditions. J Hydrol 2004;299:267–83.
[87] Endreny T, Collins V. Implications of bioretention basin spatial arrangements on stormwater recharge and groundwater mounding. Ecol Eng 2009;35:670–7.
[88] Zhang L, Dawes WR, Walker GR. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res 2001;37:701–8.
[89] Coutts AM, Beringer J, Tapper NJ. Impact of increasing urban density on local climate: spatial and temporal variations in the surface energy balance in Melbourne, Australia. J Appl Meteorol 2007;47:477–93.
[90] Sailor DJ. A review of methods for estimating anthopogenic heat and moisture emissions in the urban environment. Int J Climatol 2011;31:189–99.
[91] Grimmond CSB, Blackett M, Best MJ, Barlow J, Baik JJ, Belcher SE, et al. The international urban energy balance models comparison project: first results from phase 1. J Appl Meteorol Climatol 2010;49:1268–92.
[92] Grimmond CSB, Oke T. Turbulent heat fluxes in urban areas: observations and a local-scale urban meteorological parameterization scheme (LUMPS). J Appl Meteorol 2002;41:792–810.
[93] Dupont S, Mestayer PG, Guilloteau E, Berthier E, Andrieu H. Parameterization of the urban water budget with the submesoscale soil model. J Appl Meteorol Climatol 2006;45:624–48.
[94] Noilhan J, Malhouf JF. The ISBA land surface parameterisation scheme. Global Planet Change 1996;13:145–59.
[95] Lemonsu A, Masson V, Berthier E. Improvement of the hydrological component of an urban soil, vegetation, atmosphere, transfer model. Hydrol Process 2007;21:2100–11.
[96] Berthier E, Dupont S, Mestayer PG, Andrieu H. Comparison of two evapotranspiration schemes on a sub-urban site. J Hydrol 2006;328:635–46.
[97] Wang J, Endreny TA, Nowak DJ. Mechanistic simulation of tree effects in an urban water balance model. J Am Water Resour Assoc 2008;44:75–85.
[98] Gash JHC, Rosier PTW, Ragab R. A note on estimating urban roof runoff with a forest evaporation model. Hydrol Process 2007;22:1230–3.
[99] Boegh E, Poulsen RN, Butts M, Abrahamsen P, Dellwik E, Hansen S, et al. Remote sensing based evapotranspiration and runoff modeling of agricultural, forest and urban flux sites in Denmark: from field to macro-scale. J Hydrol 2009;377:300–16.
[100] Mitchell VG, Cleugh HA, Grimmond CSB, Xu J. Linking urban water balance and energy balance models to analyse urban design options. Hydrol Process 2007;22:2891–900.
[101] Hamel P, Fletcher TD, Walsh CJ, Beringer J, Plessis E. Water balance of infiltration systems in relation to their operating environment. In: 12th International conference on urban drainage (ICUD) (Proceedings on CD). Porto Allegre, Brazil; 2011.
[102] Rana G, Katerji N. Measurement and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. Eur J Agron 2000;13:125–53.
[103] Dotto C, Deletic A, Fletcher TD, McCarthy DT. Calibration and sensitivity analysis of urban drainage models: MUSIC rainfall/runoff module and a simple stormwater quality model. Aust J Water Resour 2011;15:85–94.
[104] Smith JA, Baeck ML, Meierdiercks KL, Nelson PA, Miller AJ, Holland EJ. Field studies of the storm event hydrologic response in an urbanizing watershed. Water Resour Res 2005;41:W10413.
[105] Villarini G, Smith JA, Serinaldi F, Bales J, Bates PD, Krajewski WF. Flood frequency analysis for nonstationary annual peak records in an urban drainage basin. Adv Water Resour 2009;32:1255–66.
[106] Hawley RJ, Bledsoe BP. How do flow peaks and durations change in suburbanizing semi-arid watersheds? A southern California case study. J Hydrol 2011;405:69–82.
[107] Burns D, Vitvar T, McDonnell J, Hassett J, Duncan J, Kendall C. Effects of suburban development on runoff generation in the Croton River basin, New York, USA. J Hydrol 2005;311:266–81.
[108] Sheeder SA, Ross JD, Carlson TN. Dual urban and rural hydrograph signals in three small watersheds. J Am Water Resour Assoc 2002;38:1027–40.
[109] Huang H, Cheng S, Wen J, Lee J. Effect of growing watershed imperviousness on hydrograph parameters and peak discharge. Hydrol Process 2008;22:2075–85.
[110] Campana NA, Tucci CEM. Predicting floods from urban development scenarios: case study of the Diluvio Basin, Porto Alegre, Brazil. Urban Water Res 2001;3:113–24.
[111] Choi W, Deal BM. Assessing hydrological impact of potential land use change through hydrological and land use change modeling for the Kishwaukee River basin (USA). J Environ Manage 2008;88:1119–30.
[112] Chung ES, Park K, Lee KS. The relative impacts of climate change and urbanization on the hydrological response of a Korean urban watershed. Hydrol Process 2011;25:544–60.
[113] Franczyk J, Chang H. The effects of climate change and urbanization on the runoff of the Rock Creek basin in the Portland metropolitan area, Oregon, USA. Hydrol Process 2009;23:805–15.
[114] Poelmans L, Rompaey AV, Ntegeka V, Willems P. The relative impact of climate change and urban expansion on peak flows: a case study in central Belgium. Hydrol Process 2011;25:2846–58.
[115] Mejia AI, Mogden GE. Spatial distribution of imperviousness and the space-time variability of rainfall, runoff generation, and routing. Water Resour Res 2010;46:W07509.
[116] Mejia AI, Moglen GE. Impact of the spatial distribution of imperviousness on the hydrologic response of an urbanizing basin. Hydrol Process 2010;24:3353–73.

[117] Walsh CJ, Roy AH, Feminella JW, Cottingham PD, Groffman PM, Morgan RP. The urban stream syndrome: current knowledge and the search for a cure. J N Am Benthol Soc 2005;24:706–23.
[118] Wenger SJ, Roy AH, Jackson CR, Bernhardt ES, Carter TL, Filoso S, et al. Twenty-six key research questions in urban stream ecology: an assessment of the state of the science. J N Am Benthol Soc 2009;28:1080–98.
[119] Meyer JL, Paul MJ, Taulbee WK. Stream ecosystem function in urban landscapes. J N Am Benthol Soc 2005;24:601–12.
[120] Beach D. Coastal sprawl. The effects of urban design on aquatic ecosystems in the United States. Arlington, Virginia: Pews Ocean Commission; 2001. p. 32.
[121] King RS, Baker ME, Kazyak PF, Weller DE. How novel is too novel? Stream community thresholds at exceptionally low levels of catchment urbanization. Ecol Appl 2010;21:1659–78.
[122] Walsh CJ, Fletcher TD, Ladson AR. Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. J N Am Benthol Soc 2005;24:690–705.
[123] Hatt BE, Fletcher TD, Walsh CJ, Taylor SL. The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environ Manage 2004;34:112–24.
[124] Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, et al. The natural flow regime. Bioscience 1997;47:769–84.
[125] Akerlindh G. The quality of storm water flow. Nord Hyg Tidskr 1950;31.
[126] Palmer CL. The pollutional effects of storm-water overflows from combined sewers. Sewage Ind Wastes 1950;22:154–65.
[127] Duncan HP. A bibliography of urban stormwater quality. Cooperative Research Centre for Catchment Hydrology (Report 95/8). Melbourne, Australia; 1995.
[128] Duncan HP. A review of urban stormwater quality processes. Cooperative Research Centre for Catchment Hydrology (Report 95/9). Melbourne; 1995. p. 38.
[129] Duncan HP. Urban stormwater quality: a statistical overview. Melbourne, Australia: Cooperative Research Centre for Catchment Hydrology; 1999.
[130] Makepeace DK, Smith DW, Stanley SJ. Urban stormwater quality: summary of contaminant data. Crit Rev Environ Sci Technol 1995;25:93–139.
[131] Zgheib S, Moilleron R, Saad M, Chebbo G. Partition of pollution between dissolved and particulate phases: what about emerging substances in urban stormwater catchments? Water Res 2011;45:913–25.
[132] Shinya M, Tsuchinaga T, Kitano M, Yamada Y, Ishikawa M. Characterization of heavy metals and polycyclic aromatic hydrocarbons in urban highway runoff. Water Sci Technol 2000;42:201–8.
[133] Pitt R, Field R, Lalor M, Brown M. Urban stormwater toxic pollutants: assessment, sources, and treatability. Water Environ Res 1995;67:260–75.
[134] Vaze J, Chiew FHS. Nutrient loads associated with different sediment sizes in urban stormwater and surface pollutants. J Environ Eng 2004;130:391–6.
[135] Eriksson E, Baun A, Scholes L, Ledin A, Ahlman S, Revitt M, et al. Selected stormwater priority pollutants: a European perspective. Sci Total Environ 2007;383:41–51.
[136] European Commission. Priority substances and certain other pollutants (according to Annex II of the Directive 2008/105/EC). <http://ec.europa.eu/environment/water/water-framework/priority_substances.htm>; 2011 [accessed 05.12.2011].
[137] US environmental Protection Agency. Priority chemicals. 2011.
[138] Becouze C, Wiest L, Baudot R, Bertrand-Krajewski J-L, Cren-Olive C. Optimisation of pressurised liquid extraction for the ultra-trace quantification of 20 priority substances from the European Water Framework Directive in atmospheric particles by GC–MS and LC–FLD–MS/MS. Anal Chim Acta 2011;693:47–53.
[139] Bester K, Schaefer D. Activated soil filters (bio filters) for the elimination of xenobiotics (micro-pollutants) from storm- and waste waters. Water Res 2009;43:2639–46.
[140] Vezzaro L, Eriksson E, Ledin A, Mikkelsen PS. Modelling the fate of organic micropollutants in stormwater ponds. Sci Total Environ 2011;409:2597–606.
[141] Torno HC. The nationwide urban runoff program. In: Balmer P, Malmquist P, Sjoberg A, editors. Proceedings of the third international conference on urban storm drainage. Sweden: Goteborg; 1984. p. 1465–74.
[142] Saget A, Chebbo G. Qastor: the French database about the quality of urban wet weather discharges. In: 7th International conference on urban storm drainage (ICUSD). Hannover, Germany; 1996. p. 1707–13.
[143] Novotny V, Goodrich-Mahoney J. Comparative assessment of pollution loadings from non-point sources in urban land use. Progress Water Technol 1978;10:775–85.
[144] Brown RG. Effects of precipitation and land use on storm runoff. Water Resour Bull 1988;24:421–6.
[145] Brown KB. Housing density and urban land use as indicators of stream quality. Watershed Protect Tech 2000;3:735–9.
[146] Characklis WG, Ward CH, King JM, Roe FL. Rainfall quality, land use, and runoff quality. J Environ Eng Div, Proc Am Soc Civil Eng 1979;105:416–9.
[147] Shertzer RH, Hall DW, Steffy SA, Kime RA. Relationships between land uses and rainwater quality in a south-central Pennsylvania watershed. J Am Water Resour Assoc 1998;34:13–26.
[148] Francey M, Fletcher TD, Deletic A, Duncan HP. New Insights into water quality of urban stormwater in south eastern Australia. J Environ Eng 2010;136:381–90.
[149] Soranno PA, Hubler SL, Carpenter SR, Lathrop RC. Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. Ecol Appl 1996;6:865–78.
[150] McMahon G, Cuffney TF. Quantifying urban intensity in drainage basins for assessing ecological conditions. J Am Water Resour Assoc 2000;36:1247–61.
[151] Arnold Jr CL. C.J. Gibbons. Impervious surface coverage: The emergence of a key environmental indicator. J Am Plan Assoc 1996;62:243–58.
[152] Glick RH. Impacts of impervious cover and other factors on storm-water quality in Austin, Texas. J Hydrol Eng 2009;14:316–23.
[153] Obropta CC, Kardos JS. Review of urban stormwater quality models: deterministic, stochastic, and hybrid approaches. J Am Water Resour Assoc 2007;43:1508–23.
[154] Ahyerre M, Chebbo G, Tassin B, Gaume E. Storm water qulaity modelling, an ambitious objective? Water Sci Technol 1998;37:205–13.
[155] Francey M, Fletcher TD, Deletic A, Duncan HP. The testing and sensitivity of a simple method for predicting urban pollutant loads. J Environ Eng 2011;137:782–9.
[156] Vaze J, Chiew FHS. Comparative evaluation of urban storm water quality models. Water Resour Res 2003;39:1280–305.
[157] Zoppou C. Review of urban storm water models. Environ Model Softw 2001;16:195–231.
[158] Konrad CP, Booth DB, Burges SJ. Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: consequences for channel form and streambed disturbance. Water Resour Res 2005;41:7009. art. no. W07009.
[159] Bledsloe BP. Stream erosion potential and stormwater management strategies. J Water Resour Plan Manage 2002;128:451–5.
[160] Nelson PA, Smith JA, Miller AJ. Evolution of channel morphology and hydrologic response in an urbanizing drainage basin. Earth Surf Proc Land 2006;31:1063–79.
[161] Gurnell A, Lee A, Souch C. Urban rivers: hydrology, geomorphology, ecology and opportunities for change. Geogr Compass 2007;1:1118–37.
[162] Nelson EJ, Booth DB. Sediment sources in an urbanizing, mixed land-use watershed. J Hydrol 2002;264:51–68.
[163] Poff N, Allan J. Functional organisation of stream fish assemblages in relation to hydrological variability. Ecology 1995;76:606–27.
[164] Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, et al. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw Biol 2010;55:147–70.
[165] Groffman PM, Bain DJ, Band LE, Belt KT, Brush GS, Grove JM, et al. Down by the riverside: urban riparian ecology. Front Ecol Environ 2003;1:315–21.
[166] Groffman PM, Crawford MK. Denitrification potential in urban riparian zones. J Environ Qual 2003;32:1144.
[167] CIRIA. Sustainable urban drainage systems – design manual for Scotland and Northern Ireland. CIRIA report no. C521. Dundee, Scotland; 2000.
[168] Whelans C, Maunsell HG, Thompson P. Planning and management guidelines for water sensitive urban (residential) design. Perth, Western Australia: Department of Planning and Urban Development of Western Australia; 1994.
[169] Wong THF. Water sensitive urban design; the journey thus far. Aust J Water Resour 2007;110:213–22.
[170] Coffman LS. Low impact development: Smart technology for clear water – definitions, issues, roadblocks and next steps. In: Strecker EW, Huber WC, editors. 9th International conference on urban drainage. Portland, Oregon, USA: American Society of Civil Engineers; 2002. p. 16.
[171] Burns M, Fletcher TD, Hatt BE, Ladson A, Walsh CJ. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landscape Urban Plan 2012;105:230–40.
[172] Palhegyi GE. Designing storm-water controls to promote sustainable ecosystems: science and application. J Environ Eng 2010;15:504–11.
[173] Tillinghast ED, Hunt WF, Jennings GD. Stormwater control measure (SCM) design standards to limit stream erosion for Piedmont North Carolina. J Hydrol 2011;411:185–96.
[174] Freni G, Mannina G, Viviani G. Urban storm-water quality management: centralized versus source control. J Water Resour Plann Manage 2010;136:268–78.
[175] Shuster WD, Gehring R, Gerken J. Prospects for enhanced groundwater recharge via infiltration of urban storm water runoff: a case study. J Soil Water Conserv 2007;62:129–37.
[176] Le Coustumer S, Fletcher TD, Deletic A, Barraud S, Lewis JF. Hydraulic performance of biofilter systems for stormwater management: influences of design and operation. J Hydrol 2009;376:16–23.
[177] Mikkelsen PS, Jacobsen P, Fujita S. Infiltration practice for control of urban stormwater. J Hydraul Res 1996;34:827–40.
[178] Hatt BE, Fletcher TD, Deletic A. Hydrologic and pollutant removal performance of biofiltration systems at the field scale. J Hydrol 2009;365:310–21.
[179] Gonzalez-Merchan C, Barraud S, Le Coustumer S, Fletcher TD. Suivi de l'évolution de colmatage dans les ouvrages d'infiltration (monitoring of clogging evolution in the infiltration system). In: Chocat B, Bertrand-Krajewski J-L, editors. Novatech. Lyon, France: GRAIE; 2010.
[180] Archer A, Quinton J, Hess T. Below-ground relationships of soil texture, roots and hydraulic conductivity in two-phase mosaic vegetation in South-East Spain. J Arid Environ 2002;52:535–53.
[181] Hirschman D, Collins K, Schueler TR. Technical memorandum: the runoff reduction methods. Center for Watershed Protection; 2008.
[182] Barraud S, Gautier A, Bardin JP, Riou V. The impact of intentional stormwater infiltration on soil and groundwater. Water Sci Technol 1999;39:185–92.

[183] Pitt R, Clark S, Field R. Groundwater contamination potential from stormwater infiltration practices. Urban Water 1999;1:217–36.
[184] Weiss P, LeFevre G, Gulliver JS. Contamination of soil and groundwater due to stormwater infiltration practices. Minnesota: University of Minnesota St. Anthony Falls Laboratory; 2008. p. 38.
[185] Foulquier A, Malard F, Barraud S, Gibert J. Thermal influence of urban groundwater recharge from stormwater infiltration basins. Hydrol Process 2009;23:1701–13.
[186] Maestri B, Lord BN. Guide for mitigation of highway stormwater runoff pollution. Sci Total Environ 1987;59:467–76.
[187] Davis AP, Hunt WF, Traver RG, Clar M. Bioretention technology: overview of current practice and future needs. J Environ Eng 2009;135:109–17.
[188] Bratières K, Fletcher TD, Deletic A, Alcazar L, LeCoustumer S, McCarthy D, et al. Removal of nutrients, heavy metals and pathogens by stormwater biofilters. In: 11th International conference on urban drainage (ICUD). Edinburgh, Scotland: International Water Association; 2008.
[189] FAWB. Guidelines for soil filter media in bioretention systems. Melbourne, Australia: Facility for Advancing Water Biofiltration; 2009.
[190] Hunt WF, Jarrett AR, Smith JT, Sharkey LJ. Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. J Irrigat Drain Eng 2006;132:600–8.
[191] Li HW, Sharkey LJ, Hunt WF, Davis AP. Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland. J Hydrol Eng 2009;14:407–15.
[192] Mitchell VG, Morello C. Quantifying stormwater benefits of extensive vegetated roofs in Melbourne. Towards water sensitive cities and citizens: the 6th international water sensitive urban design conference and hydropolis#3. AWA, Engineers Australia, SIA Western Australia, Perth; 2009.
[193] Berthier E, de Gouvellow B, Archambault F, Gallis D. Bilan hydrique des toitures végétalisées: vers de meilleures compréhension et modélisation. Hydrological budget of green roof: contributions to a better understanding and simulation. In: Chocat B, Bertrand-Krajewski J-L, editors. Novatech. Lyon, France: GRAIE; 2010.
[194] Berghage RD, Beattie D, Jarrett AR, Thuring C, Razaei F. Green roofs for stormwater runoff control. In: US-EPA, editor. National Risk Management Research Laboratory; 2009.
[195] Czemiel Berndtsson J. Green roof performance towards management of runoff water quantity and quality: a review. Ecol Eng 2010;36:351–60.
[196] Voyde E, Fassman E, Simcock R, Wells J. Quantifying evapotranspiration rates for New Zealand green roofs. J Hydrol Eng 2010;15:395–403.
[197] Fletcher TD, Mitchell G, Deletic A, Ladson A, Séven A. Is stormwater harvesting beneficial to urban waterway environmental flows? Water Sci Technol 2007;55:265–72.
[198] Toronto and Region Conservation Authority. LID stormwater management planning and design guide (draft). City of Toronto, Toronto; 2010.
[199] Fletcher TD, Deletic A, Mitchell V, Hatt BE. Reuse of urban runoff – a review of recent Australian advances and remaining challenges. J Environ Qual 2008;37:116–27.
[200] Huang YF, Hashim Z, Shaaban AJ. Potential and effectiveness of rainwater harvesting systems in flash floods reduction in Kuala Lumpur City∗ Malaysia. In: 8th International conference on urban drainage modelling and 2nd international conference on rainwater harvesting and management. Tokyo, Japan: IWA/IAHR; 2009.
[201] Burns M, Fletcher TD, Hatt BE, Ladson A, Walsh CJ. Can allotment-scale rainwater harvesting manage urban flood risk and protect stream health? La récuperation des eaux pluviales à l'echelle de la parcelle: peut-elle protéger contre les inondations et la dégradation des milieux aquatiques? In: Chocat B, Bertrand-Krajewski J-L, editors. Novatech. Lyon, France: GRAIE; 2010.
[202] Mitchell VG, McMahon TA, Mein RG. Components of the total water balance of an urban catchment. Environ Manage 2003;32:735–46.
[203] Gerolin A, Kellagher R, Faram M. Rainwater harvesting systems for stormwater manageme: feasibility and sizing considerations for the UK. In: Chocat B, Bertrand-Krajewski J-L, editors. Novatech. Lyon, France: GRAIE; 2010.
[204] McCardle P, Gleeson J, Hammond T, Heslop E, Holden R, Kuczera G. Centralised urban stormwater harvesting for potable reuse. Water Sci Technol 2011;63:16–24.
[205] Mitchell VG, McCarthy D, Deletic A, Fletcher TD. Sensitivity of urban stormwater harvesting storage capacity–reliability–yield relationships to behaviour analysis method selection. Environ Model Softw 2008;23: 782–93.
[206] Hatt BE, Deletic AB, Fletcher TD. A review of integrated stormwater treatment and re-use in Australia. J Environ Manage 2006;76:102–13.
[207] Elliott AH, Trowsdale SA. A review of models for low impact urban stormwater drainage. Environ Model Softw 2007;22:394–405.
[208] Jacobson CR. Identification and quantification of the hydrological impacts of imperviousness in urban catchments: a review. J Environ Manage 2011;92:1343–8.
[209] Aronica G, Cannarozzo M. Studying the hydrological response of urban catchments using a semi-distributed linear non-linear model. J Hydrol 2000;238:35–43.
[210] Rodriguez-Iturbe I, Valdes JB. The geomorphologic structure of hydrologic response. Water Resour Res 1979;15:1409–20.
[211] Rodriguez-Iturbe I, Rinaldo A. Fractal river networks: chance and self-organization. New York: Cambridge University Press; 1997.
[212] Gironas J, Niemann JD, Roesner LA, Rodriguez F, Andrieu H. A morpho-climatic instantaneous unit hydrograph model for urban catchments based on the kinematic wave approximation. J Hydrol 2009;377:317–34.
[213] Gironas J, Niemann JD, Roesner LA, Rodriguez F, Andrieu H. Evaluation of methods for representing urban terrain in storm-water modeling. J Hydrol Eng 2010;1:1–14.
[214] Cantone J, Schmidt A. Improved understanding and prediction of the hydrologic response of highly urbanized catchments through development of the Illinois urban hydrologic model. Water Resour Res 2011;47:W08538.
[215] Rodriguez F, Andrieu H, Creutin J-D. Surface runoff in urban catchments: morphological identification of unit hydrographs from urban databanks. J Hydrol 2003;283:146–68.
[216] Rodriguez F, Cudennec C, Andrieu H. Application of morphological approaches to determine unit hydrographs of urban catchments. Hydrol Process 2005;19:1021–35.
[217] Rabunal JR, Puertas J, Suarez J, Rivero D. Determination of the unit hydrograph of a typical urban basin using genetic programming and artificial neural networks. Hydrol Process 2007;21:476–85.
[218] Chen J, Adams BJ. Development of analytical models for estimation of urban stormwater runoff. J Hydrol 2007;336:458–69.
[219] Delleur JW. The evolution of urban hydrology: past, present, and future. J Hydrol Eng 2003;129:564–73.
[220] Bennis S, Crobeddu E. Runoff simulation model for small urban catchments. J Hydrol Eng 2007;0:540–4.
[221] Rodriguez F, Andrieu H, Zech Y. Evaluation of a distributed model for urban catchments using a 7-year continuous data series. Hydrol Process 2000;14:899–914.
[222] Rodriguez F, Andrieu H, Morena F. A distributed hydrological model for urbanized areas – model development and application to case studies. J Hydrol 2008;351:268–87.
[223] Khu ST, Di PF, Savic D, Djordjevic S, Walters GA. Incorporating spatial and temporal information for urban drainage model calibration: an approach using preference ordering gensetic algorithm. Adv Water Resour 2006;29:1168–81.
[224] eWater CRC. Model for urban stormwater improvement conceptualisation (MUSIC). 4.0 ed. Canberra: eWater Cooperative Research Centre; 2009.
[225] Jang S, Cho M, Yoon J, Yoon Y, Kim S, Kim G, et al. Using SWMM as a tool for hydrologic impact assessment. Desalination 2007;212:344–56.
[226] Fletcher TD, Wong THF, Duncan HP, Deletic AB, Coleman JR, Jenkins GA. Recent advances in decision-support for stormwater management: the MUSIC approach (avances récentes dans d'aide à la décision pour la gestion de stormwater: l'approche de MUSIC). Novatech 2004. Lyon, France; 2004.
[227] Dotto C, Deletic A, Fletcher TD. Analysis of parameter uncertainty of a flow and quality stormwater model. Water Sci Technol 2009;60:717–25.
[228] Dotto C, Kleidorfer M, Deletic A, Fletcher TD, McCarthy DT, Rauch W. Stormwater quality models: performance and sensitivity analysis. Water Sci Technol 2010;62:837–43.
[229] Mitchell VG, Duncan HP, Inman M, Rahilly M, Stewart J, Vieritz A, et al. Integrated urban water modelling – past, present and future. Rainwater 2007, Sydney, NSW; 2007.
[230] Lhomme J, Bouvier C, Perrin J-L. Applying a GIS-based geomorphological routing model in urban catchments. J Hydrol 2004;299:203–16.
[231] Elliott AH, Trowsdale SA, Wadhwa S. Effect of aggregation of on-site storm-water control devices in an urban catchment model. J Hydrol Eng 2009;14:975–83.
[232] Mitchell VG, Duncan HP, Inman M, Rahilly M, Stewart J, Vieritz A, et al. State of the art in integrated urban water modelling. Novatech (6th international conference on sustainable techniques and strategies in urban water management). Lyon, France; 2007. p. 507–14.
[233] Freni G, Mannima G, Viviani G. Uncertainty assessment of an integrated urban drainage model. J Hydrol 2009;373:392–404.
[234] Rauch W, Seggelke K, Brown R, Krebs P. Integrated approaches in urban storm drainage: where do we stand? Environ Manage 2005;35:39–409.
[235] Mitchell VG, Mein RG, McMahon TA. Modelling the urban water cycle. Environ Model Softw 2001;16:615–29.
[236] Hardy MJ, Kuczera G, Coombes PJ. Integrated urban water cycle management: the UrbanCycle model. Water Sci Technol 2005;52:1–9.
[237] eWater CRC. Urban developer website. eWater Cooperative Research Centre, <http://www.ewater.com.au/products/ewater-toolkit/urban-tools/urban-developer/>; 2011 [accessed 27.12.2011].
[238] Mackay R, Last E. SWITCH city water balance: a scoping model for integrated urban water management. Rev Environ Sci Biotechnol 2010;9:291–6.
[239] Fletcher TD, Mitchell VG. Monitoring to understand interactions between urban water cycle components. In: Fletcher TD, Deletic A, editors. Data requirements for integrated urban water management. Paris: UNESCO Publishing and Taylor & Francis; 2007 [chapter 13].
[240] McGuire KJ, Weiler M, McDonnell JJ. Integrating tracer experiments with modeling to assess runoff processes and water transit times. Adv Water Resour 2007;30:824–37.
[241] Aronica G, Freni G, Oliveri E. Uncertainty analysis of the influence of rainfall time resolution in the modelling of urban drainage systems. Hydrol Process 2005;19:1055–71.
[242] Willems P, Berlamont J. Accounting for the spatial rainfall variability in urban modelling applications. Water Sci Technol 2002;45:105–12.
[243] Quirmbach M, Schultz GA. Comparison of rain gauge and radar data as input to an urban rainfall–runoff model. Water Sci Technol 2002;45:27–33.

[244] Vieux BE, Bedient PB. Assessing urban hydrologic prediction accuracy through event reconstruction. J Hydrol 2004;299:217–36.
[245] Barco J, Wong KM, Stenstrom MK. Automatic calibration of the US EPA SWMM model for a large urban catchment. J Hydraul Eng 2008;134:466–74.
[246] Thorndahl S, Beven KJ, Jensen JB, Schaarup-Jensen K. Event based uncertainty assessment in urban drainage modelling, applying the GLUE methodology. J Hydrol 2008;357:421–37.
[247] Han WS, Burian SJ. Determining effective impervious area for urban hydrologic modeling. J Hydrol Eng 2009;14:111–20.
[248] Bertrand-Krajewski J-L, Muste M. Understanding and managing uncertainty. In: Fletcher TD, Deletic A, editors. Data requirements for integrated urban water management. Paris: UNESCO Publishing and Taylor & Francis; 2007 [chapter 8].
[249] Deletic A, Dotto CBS, McCarthy DT, Kleidorfer M, Freni G, Mannina G, et al. Assessing uncertainties in urban drainage models. Phys Chem Earth 2011;42–44:3–10.
[250] Benedetti L, Bixio D, Claeys F, Vanrolleghem PA. Tools to support a model-based methodology for emission/immission and benefit/cost/risk analysis of wastewater systems that considers uncertainty. Environ Model Softw 2008;23:1082–91.
[251] Semadeni-Davies A, Hernebring C, Svensson G, Gustafsson L-Gr. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: suburban stormwater. J Hydrol 2008;350:114–25.
[252] Denault C, Millar RG, Lence BJ. Assessment of possible impacts of climate change in an urban catchment. J Am Water Resour Assoc 2006;42:685–97.
[253] Marsalek J, Rousseau D, Steen PVd, Bourgues S, Francey M. Ecosensitive approach to managing urban aquatic habitats and their integration with urban infrastructure. In: Marshalek I, Wagner J, Breil P, editors. Aquatic habitats in sustainable urban water management: science, policy and, practice; 2007.