1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

**Article type:  Advanced Review**

**Article title:  Integrated Modelling in Urban Hydrology: Reviewing the role of monitoring technology in overcoming the issue of 'big data' requirements**

**Authors:**

**Full name and affiliation; email address if corresponding author; any conflicts of interest**

| |
|---|
| **First author** <br> Michael G. Hutchins*, Centre for Ecology and Hydrology, Wallingford, UK, OX10 8BB, no conflicts |
| **Second author** <br> Scott J. McGrane, School of Mathematics & Statistics, University of Glasgow, Glasgow, G12 8QQ, no conflicts |
| **Third author** <br> James D. Miller, Centre for Ecology and Hydrology, Wallingford, UK, OX10 8BB, no conflicts |
| **Fourth author** <br> Alex Hagen-Zanker, Department of Civil and Environmental Engineering, University of Surrey, Guildford, Surrey, GU2 7XH, no conflicts |
| **Fifth author** <br> Thomas R. Kjeldsen, Department of Architecture and Civil Engineering, University of Bath, Bath, UK, BA2 7AY, no conflicts |
| **Sixth author** <br> Simon J. Dadson, School of Geography and the Environment, University of Oxford, Oxford, UK, OX1 3QY, no conflicts |
| **Seventh author** <br> Clare S. Rowland, Centre for Ecology and Hydrology, Lancaster Environment Centre, Bailrigg, Lancaster, UK, LA1 4AP, no conflicts |

**Abstract**

Increasingly, the application of models in urban hydrology has undergone a shift toward integrated structures that recognise the interconnected nature of the urban landscape and both the natural and engineered water cycles. Improvements in computational processing during the past few decades have enabled the application of multiple, connected model structures that link previously disparate systems together, incorporating feedbacks and connections. Many applications of integrated models look to

assess the impacts of environmental change on physical dynamics and quality of landscapes. Whilst these integrated structures provide a more robust representation of natural dynamics, they often place considerable data requirements on the user, whereby data is required at contrasting spatial and temporal scales which can often transcend multiple disciplines. Concomitantly, our ability to observe complex, natural phenomena at contrasting scales has improved considerably with the advent of increasingly novel monitoring technologies. This has provided a pathway for reducing model uncertainty and improving our confidence in modelled outputs by implementing suitable monitoring regimes. This commentary assesses how component models of an exemplar integrated model have advanced over the past few decades, with a critical focus on the role of monitoring technologies that have enabled better identification of the key physical process. This reduces the uncertainty of processes at contrasting spatial and temporal scales, through a better characterisation of feedbacks which then enhances the utility of integrated model applications.

## 1. Introduction

Urbanisation is a global trend with more than 55% of the current world population living in urban areas. There are now 394 cities home to over 1 million inhabitants, an increase which represents a doubling of the urban population in a 50 year period[1,2]. As the urban population continues to grow and spread laterally into previously undeveloped areas, a significant stress is placed on natural resources and environmental quality, having a demonstrable impact on atmospheric and hydrological processes as well as the quality of the surrounding environments[3,4,5,6]. The presence of the urban heat island; alterations to air currents and increased particulate matter above urban space result in the emergence of microclimates, which impact on input precipitation and evapotranspiration rates. The creation of impervious surfaces alters dominant runoff-generating processes, flowpaths and infiltration, which can have a profound effect on the overall catchment water balance[7]. The input of freshwater supply and extraction of sewage via large piped networks provide artificial inputs and outputs to the catchment water balance, making it difficult to quantify the components of the water cycle[8].

Urban space also contributes to degradation of water quality, as contaminants and sediment are transferred into urban waterways[4]. Sources of urban pollution fall into two main groups: (i) those transported via the sewerage system and (ii) those such as roads, building sites and atmospheric deposition, which arrive in receiving water bodies via stormwater drains and diffuse pathways[6]. The second group poses greater concern to urban hydrologists and land managers as their pathways remain relatively unknown, hence monitoring and predicting these fluxes remains a considerable challenge[9]. With the emergence of new contaminants such as those found in personal care products, pharmaceuticals and industrial wastes, increasingly advanced monitoring regimes are required to map the spatio-temporal dynamics of their sources and pathways to formulate effective remediation strategies. Novel contaminants (e.g., microbial contaminants and pharmaceuticals) enter into sewer systems, where historically they would not have been targeted for treatment in wastewater treatment works, often resulting in their discharge back into the water environment untreated[10].

Here, we introduce and reprise the development of integrated modelling techniques to assess impacts of urban expansion on the aquatic environment, whilst discussing the central role that advances in monitoring technology (Table 1) has played in enabling their widespread application. We introduce an

example of an integrated model structure to elucidate how such models are developed to tackle real-world problems and assess how the components, as well as the underpinning monitoring technologies have advanced in recent years. We conclude by addressing some of the remaining limitations and assess future priorities for the continued development of urban systems modelling.

## 2. Integrated Modelling and "big data"

### 2.1. Rationale, and definitions of integration

Historically, efforts to model the expansion and impacts of the urban environment on hydrological dynamics and aquatic integrity have relied on a fragmented network of independent model structures that simulate specific processes, often overlooking any connections or feedbacks between linked systems[11,12]. Increasingly, modelling of urban systems has started to adopt an integrated approach whereby complex systems are treated as interconnected rather than disparate, placing an emphasis on the interactions and feedbacks to enable sufficient understanding of the entire system[8,13,14]. Over the past 40 years, integrated modelling has grown concomitantly with improvements in computational power, which has traditionally been a barrier to high-level simulation[15]. In addition, expansive data requirements across multiple model structures have also traditionally precluded widespread application[15].

The role of modelling in urban hydrology has expanded with improvements in computational hardware to become a frequently utilised tool. Models of the urban water environment serve two primary functions: (i) elucidating some of the 'black box' processes that occur within the urban system, such as dominant flow pathways at both the surface and in pipe-systems and their connections, and (ii) predicting future environmental changes (both land-use expansion and climate change) and their subsequent impact on the hydrological cycle. Bach et al. highlight the 1982 study of the Glatt Valley in Switzerland, which sought a combined understanding of multiple components of an urban water system, as the pioneering study into integrated model applications in urban water studies[16]. This study also highlighted a key difficulty in early integrated modelling applications, as it required over 40 people to detect and track contaminants through the wastewater treatment system from rainfall input to the receiving water during a storm. It identified the impacts of stormflow on secondary wastewater treatment dynamics, whilst also tracking the temporal patterns of pollutants within the drainage system, treatment processes and receiving water bodies.

Integrated models are developed at contrasting scales, often to address very specific research questions. These range from assessing the impacts of development on receiving water bodies[17,18], to optimising the treatment steps and processes within a wastewater treatment plant[19,20], to large-scale modelling efforts that are used in decision and policy applications and utilise social and economic variables[21,22,23]. The differing scale and range of research questions posed of models can be viewed as defining the type and extent of "integration". A comprehensive review of model integration in urban environments[12] identifies four tiers of integration which are described graphically (Figure 1) illustrating the increasing breadth of disciplinary coverage and spatial extent from component based models within individual sub-systems (Tier 1) to holistic integrated urban water systems (Tier 4). Historically, integrating activity has predominantly focussed on integrating components of drainage systems (Tier 2); examples of which

enable multi-constituent modelling and the consideration of both acute and chronic impacts at a range of spatial scales.

Increasingly, integrated models have been applied as environmental decision support systems (EDSS), enabling officials and planners to assimilate sufficient information to assess the impacts of particular scenarios or policy implementations accordingly[24]. As with the integrated models themselves, examples of use of EDSS to assess impacts of urban areas cover a wide contextual spectrum, from the urban water cycle itself (UWOT)[25] to basin scale management (e.g. the Elbe-DSS)[26] to appraisal across wider domains as part of ecosystem services assessments (e.g. Envision)[27] As a consequence of the contrasting spatial and temporal scales, integrated models often operate as a balance between parsimony and pragmatism, whereby representation of the overall system is a key outcome, often achieved by representing complexity at local scales[12]. Increasingly, there is an array of 'off-the-shelf' model packages available (e.g., SIMBA[28]; Aquacycle[29] and MIKE toolbox), however these are often limited by their proprietary source-code, meaning users have little flexibility to modify how such models operate, though an increasing number of open-source integrated models are becoming available (e.g., CityDRAIN[30] and TyndallCities/ARCADIA USM[31]).

### 2.2. Integrated Modelling: a generic example and review of the development of component models

We consider an example whereby the role of urban growth on hydrological dynamics and water quality within a large basin is addressed using integrated modelling. Here, the overarching objective is to provide knowledge to inform future development policy that supports sustainable water resources (the POLLCURB project focussing on the Thames basin (southern UK): www.pollcurb.ceh.ac.uk). Such an endeavour requires research teams with diverse modelling and data collection skills. To achieve objectives coverage of the following domains with an array of interconnected models is essential: (i) Land-use change (ii) Urban drainage (iii) Rainfall-runoff (iv) Water quality. In this example modelling the impacts of climate change is also required and in addition, other features, notably population growth and wastewater treatment processes, must be represented. Pragmatism excluded explicit consideration of other relevant domains (e.g. urban air quality, aquatic ecology).  The rationale involves identifying key relationships between land-use, flow and water quality derived at the local scale (< 100 km2) from case-study sub-catchments that have experienced rapid urbanisation in recent decades. By way of upscaling, these relationships would then be employed for predictive purposes at basin scale (> 5000 km2). Therefore, in terms of integration concepts (Figure 1) the overall model philosophy sits in Tier 4. Developments of modelling techniques covering the four key domains are charted below.

#### 2.2.1. Land-Use Change Modelling (LUCM)

Urban growth modelling is primarily concerned with how growing populations and economic development lead to changes in land use. Classical urban models are based on equilibrium theory and the notion that land use will develop to an optimal spatial distribution of activities in terms of access to jobs, markets and labour. The Lowry model[32] is an early and highly influential model of this type whereby for a given employment in the basic sector it estimates the distribution of the population supported by these jobs, as well as the further retail and service jobs meeting local demand. The spatial distributions are based on distance-frequency relationships, known as gravity models. To date, equilibrium-based modelling has developed into two main classes of urban model: land-use transport interaction modelling

(LUTI) and Computational General Equilibrium modelling (CGE). CGE are used for macro-level economic modelling with strong theoretical rigor and minimal assumptions[33], at the cost of remaining relatively abstract in its conclusions. In contrast, LUTI models use a bottom-up approach, taking the behaviour of micro-economic agents as a starting point; these models typically represent the transport network in detail and consider the interactions between industrial sectors and socio-economic groups in spatially refined geographical regions. Being more pragmatic than CGE, LUTI models tend to include some ad-hoc assumptions at the interface between more-or-less established sectorial- or discipline-specific models[34]. In recent years the approaches have converged, with LUTI models adopting more theoretical rigour[35] and CGE models becoming more spatially explicit[36]. Both LUTI and CGE models are primarily economic models and whilst they are suited and used for integrated analysis, it is through the mechanisms of markets. The data required are typically collected by national statistical agencies and census bureaus (information on population and employment detailed by socio-economic groups, industrial section and, importantly, geographical regions). LUTI models in particular rely on fine resolution geographical detail, to realistically incorporate the role of the transport system.

In the late 1970s an important new paradigm was introduced to urban modelling as it was increasingly recognized that the development of urban systems is lagging behind the drivers of change, and urban systems are therefore chronically out of equilibrium. The growth of cities is chaotic, path-dependent and complex mathematically[37,38]. Early models based on this paradigm were no longer finding equilibrium solutions of urban configurations but were simulation models that explored possible trajectories of change[39]. A second development in urban growth modelling that occurred over the same time was the development of 'cellular worlds'[40,41]. These abandoned the use of regions or zone-systems and the thereby implied assumptions about urban boundaries and structure in favour of dynamics based on neutral, fine scale, regular grids. These models simulated growth of urban systems as a bottom-up process, in a petri-dish kind of environment, very well aligned with mathematical[42], and economic[43] understanding of the macro-level manifestations of micro-level processes. These developments gave rise to the cellular automata land use change model[44,45] the dominant form of urban model today which has a more pronounced physical and geographical basis than LUTI or CGE. In addition to transport accessibility, factors determining where urban growth occurs include slope, soil and other factors of physical suitability, zoning (spatial planning) status, and the land uses found in the direct neighbourhood. As such the cellular automata models are highly appropriate for integration with other socio-economical and physical models[46,47].

### 2.2.2. Urban Drainage Modelling

The expansion of urban areas results in extension to subsurface urban drainage infrastructure alongside increased influence of flood storage areas and road drainage. A growing number of urban drainage model packages now exist, and with improvements in computational efficiency these incorporate increasing levels of spatial and temporal detail (Table 2). A common drawback in the early days was that urban models often operated in isolation from the surrounding landscape[14,48]. Urban drainage modelling has evolved markedly in recent decades in response to advances in computing power and an increasing interest from a planning, hazard and management perspective. Whilst underpinning mathematical functions have remained largely unchanged, modelling has been buoyed by the assimilation of GIS software, enabling rapid determination of complex drainage networks, runoff pathways and sewerage catchment areas[49]. The release of CHI's PCSWMM program (an enhanced version of the US EPA SWMM

model) combines GIS, hydraulic modelling and hydrological modelling in one platform. PCSWMM contains a GIS interface that supports Open Street Maps, Bing Maps, Google Maps (including a Google Earth interface) and ESRI OS® mapping products (Table 2) enabling easier identification of subcatchment boundaries, pipe networks and catchment characteristics.

In a perspicacious review, Bach et al., track the move towards integration in urban drainage modelling over the past three decades. Historically considered separately, Wastewater Treatment Plants (WWTPs) have increasingly become recognised as integral parts of urban water systems, particularly in relation to water quality and baseline chemistry[5]. Furthermore, if WWTPs receive large quantities of water from outside catchment boundaries, water balance is no longer explicable in terms of natural rainfall-runoff dynamics[50]. As a result, there has been increasing effort to link natural hydrological dynamics and urban drainage systems with WWTP processes. Sequential treatment processes within WWTPs are increasingly being represented intrinsically to give a 'plant-wide' model of both water fluxes and water quality[12]. Rates of urbanisation typically outstrip increase in WWTP capacity, often resulting in a reduction in the efficiency of some processes[51]. The 'plant-wide' approach to modelling WWTP simulations is successfully used to quantify impacts of urban growth on wastewater loads and thereby on effluent water quality.

### 2.2.3. Rainfall-runoff Modelling

Hydrological models of varying complexity are routinely used for predicting storm runoff volume and peak flow magnitude in urban areas. Several comprehensive reviews of urban runoff modelling have recently been published[52,53,54]. However, most of the recent advances are related to the hydraulic components, routing storm water across urban surfaces to and through sewer systems, and used to predict inundation[55,56]. These advances have capitalised on increasing processing power combined with the emergence of new spatial datasets allowing a more detailed hydraulic description of the urban geometry (e.g. high resolution topographical data such as LiDAR)[57]. When modelling infiltration in urban catchments, land is divided into two portions, one overlain by impervious surfaces (e.g. roads, roofs, pavements) the other characterised as pervious, suggesting soils covered by vegetation. The pervious areas comprise rural land outside the urban area or green-field sites within it, such as parks or gardens. Impervious areas are commonly subdivided into those directly connected to the man-made drainage system (also known as effective urban areas), and those lacking direct hydraulic connection[58]. Using this simplified representation, a number of hydrological models treat runoff generation as two separate systems, which when combined form the total runoff response[59,60,61,62].

A key consideration for urban impacts on runoff response is scale. For example, at very local level, particular features such as local storage ponds and the layout of the sewer system layout are likely to significantly affect runoff. However, further downstream the same urban area might only represent a small fraction of the total catchment, and the localised effects become relatively less important. In terms of land use data there is a strong case for using a scale-dependent level of detail. For example, at large scales a straightforward distinction between urban and non-urban may suffice, whereas in specific cases a detailed classification (e.g. suburban, peri-urban, effective impervious areas, or even down to roofs, roads, gardens, drive ways, pavements etc.) may be necessary. Several studies assess the impact of urban development on catchment runoff across scales, from small[63] to large[64,54]. A coherent view from the literature of the best means to represent urban areas at different scales to ensure appropriate representation of processes is lacking.

*2.2.4. Urban Water Quality Modelling*

A progression has been apparent in water-quality model development, from pathogens and DO[66,67,68]; to nutrients and eutrophication[69,70,71]; to industrial pollution legacies (e.g., toxic organics and metals)[72,73,74,75] and on to the present day where focus is increasingly on emerging contaminants (e.g., synthetic chemicals, pharmaceuticals and microbial contaminants) and nanoparticles, where models are at less advanced stages and remain active fields of research (Table 3). Many of the advances in water quality modelling have been pioneered by increasing access to high quality data, used for both model calibration and parameterisation. Monitoring of water quality is often fuelled by sporadic and seasonally motivated sampling, often driven by events or policies that address specific contaminant problems in a responsive manner. Consequently, datasets are rarely comprehensive, only providing a snapshot in many areas[76]. As novel contaminants continue to emerge, our monitoring ability must keep pace prior to simulating their dynamics in aquatic environments. In addition, the boundary conditions of water quality models for specific contaminants often remain understudied or poorly understood, where a dearth of observed data is available for calibration or parameterisation. For example, a better understanding of contaminant fluxes and interactions from landscapes or facilities (e.g., WWTPs) that input into urban areas is required, to support our understanding of how such dynamics will emerge in urban streams. As technology enhances the resolution and quality of data captured in the field, development of more robust and reliable models that provide a holistic representation of the urban water system become increasingly possible.

In summary, prerequisites for a successful water quality model stem from three key factors: (i) good water quality data for calibration and parameterisation of model structures, (ii) accurately capturing the hydrological dynamics and (iii) ability to determine the sources of pollutants from contrasting landscapes. As a result, efforts to model urban water quality are increasingly turning to an ensemble approach, whereby model structures are coupled with hydraulic, WWTP, surface and atmospheric models, to represent sources and sinks of sediment and contaminants. In terms of biological parameters, representation of autotroph photosynthesis and respiration is commonplace in water quality models as they are fundamental in influencing dissolved oxygen levels. Higher trophic levels, however, are rarely considered beyond their role in acting as a grazing control on autotrophs. Simulation of biological response has largely remained detached from integrated model systems.

*2.3. Integrated Modelling and big data requirements: the monitoring context*

To be effective, integrated models such as POLLCURB require a significant and diverse collection of (often high-resolution) data. In this case the key sources of information are long-term datasets of climate, land use and river water resources (hydrology and water quality). Our ability to access widespread sources of data has expanded considerably in recent decades. High-resolution data (both spatial and temporal) has become an invaluable tool for aiding our understanding and, accordingly, for reduction of predictive uncertainty. Whilst data availability and our scope to access it has improved greatly in recent years, a key barrier that remains to widespread implementation of integrated models is the considerable requirements that such "big-data" impose[15]. Furthermore, it is essential that datasets can be effective in identifying interactions and in the process of calibrating component models within the integrated framework. Consequently, capturing not only the physical processes but also their

connections and feedbacks places considerable strain on modelling practitioners[12]. Taking each of the four key domains in turn, the remainder of this article will critically review how advances in monitoring techniques (summarised in Table 1) have improved integrated model development and applications (Section 3). In particular, we will explore how these advances enable feedbacks and interactions to be better represented. To conclude (in Section 4) we will reflect on how advances in monitoring frame the development of the POLLCURB model application, in particular pinpointing the main aspects needing strong integration.

## 3. A review of advances in monitoring to support integrated model components

Our example of quantifying impacts of urban growth illustrates unique demands imposed on integrated modelling by issues of interconnections, Urbanisation is driven by regional economic development, emergence of new industry, and housing accordingly; a linkage that has been long recognised dating back to Malthus[30]. Planning policy combined with economic growth models can yield detailed insight into how urban areas will expand into the future, both spatially and temporally. Calibration of such growth (to enable future predictions) requires considerable data from multiple sources including economic indices, population metrics, planning policy documents and remotely sensed urban imagery to track urban growth at contrasting spatial and temporal scales[11]. Furthermore, given the iterative nature of development in urban areas within developed countries, changes of land use typically occur across multiple years and in small spatial zones, thereby a reliance on long-term, high-resolution monitoring (often limited in its availability and prohibitively expensive[15]) serves to restrict the skill and utility of land-use change models. As urban growth occurs, infrastructure such as road networks, public transport infrastructure and urban drainage grows concomitantly. Assessing the impacts of growth on rainfall-runoff and urban drainage dynamics requires access to detailed network maps of existing drainage to assess how surface drainage dynamics will change accordingly. Such data can be sensitive and difficult to acquire as water management authorities can often be resistant to disseminate such large spatial datasets. However, accurate representation of urban hydrological dynamics is dependent upon knowledge of water routing, and so acquisition of drainage infrastructure maps is critical in integrated urban modelling[11]. Within urban areas, wastewater treatment facilities contribute considerable artificial inputs to catchment water balances and water quality. Quantifying the role of these plants is crucial to the success of integrated model applications, and as such, acquiring volumetric discharge and effluent water quality is important. Finally, representing the dominant rainfall-runoff dynamics and associated water quality from contrasting landscapes requires high spatial- and temporal-resolution monitoring regimes to connect component models, thereby enabling a sufficiently robust basis for calibration and reduction of uncertainty.

### 3.1. Data Requirements and Monitoring Advances in LUCM

Data informing cellular automata models are often, and increasingly, based on remote sensing, i.e. satellite imagery. Current developments are prominently geared towards containing and unravelling the inherent complexity of cellular automata, through sensitivity analysis and validation[77], and the development of methods for estimation/calibration[78,79,80]. Calibrating land-use change models requires reasonable baseline data, against which model outputs can be trained. The advance in urban remote sensing technologies and post-capture processing computing has enabled the rapid proliferation of land-use data at increasingly high resolutions. The earliest urban remote sensing for quantifying impervious

surfaces made use of aerial photography[81,82]. Archives of aerial photography stretch back over 60 years in some places, however their coverage is often temporally and spatially sparse. Despite this limitation, aerial photographs provide a valuable resource for quantifying urbanisation in selected areas[83]. The upgrade to high-resolution imagery enabled increased accuracy for detecting urban spread[84]. Commercial high-resolution sensors have traditionally been restricted owing to international security concerns. However, such limitations have since been relaxed and high-resolution satellite imagery (e.g., IKONOS-2, ORBIMAGE Inc and Quickbirk-2) are now widely available, providing scope to track real-time changes within urban areas[85, 86, 87, 88].

Most urban applications of remote sensing (RS) have used optical data, although radar and LiDAR are becoming increasingly common. For urban hydrology there are three key types of data set derived from RS, specifically land cover classifications, impervious surface and topography. Land cover classifications provide maps of land cover that typically include at least one urban class. Examples include urban extent from land cover maps which are widely available at a range of scales from country-wide, such as the US National Land Cover Database (NLCD)[89] and the 2007 UK Land Cover Map (LCM2007)[90], to continental and global-level with the Moderate Resolution Imaging Spectroradiometer (MODIS)[91] and GLOBCOVER products. Currently a number of single-class (i.e., urban/non-urban) RS products are in production including the European Urban Atlas and Germany's Space Agency (DLR) global classification of human settlement from TanDEM-X, generating a global urban extent dataset with a spatial resolution of around 30m[92]. Impervious surface mapping contains a number of methods that have been developed for capturing the percentage impervious area from satellite data[87,93,94]. An impervious surface product derived from Landsat data is now part of the United States national land cover data based (NLCD) products[65], including a procedure to update it[96]. Finally, topographical information can be derived from both LiDAR and InSAR data and have an important role to play in urban flood modelling studies[97]. Less research has been conducted on deriving 'effective' or 'directly connected impervious area' (EIA/DCIA), and how impervious such surfaces are in reality[87]. Early efforts to derive EIA/DCIA focused upon using empirical hydrological data or field surveys[98] while more recent research has utilized technology such as RS and GIS to estimate the effective impervious area[99]. With modern urban developments increasingly containing sustainable drainage systems (SuDS) such as permeable paving (that are difficult to distinguish via remote sensing from impervious paving), there is a requirement for more detailed mapping of urban land-use to reflect the diversity of hydrologic-footprint affected by contemporary urban land-use, for which high-resolution sensors provide scope.

### 3.2. Urban Drainage Data and Observation

Given careful processing of remotely sensed imagery or land-use data, GIS techniques permit connections to be made between changes in land-use and extension of drainage networks. In the United Kingdom, following the Pitt review into the 2007 flooding[100], most local authorities and water companies developed digital records of urban drainage infrastructure, enabling an increasingly accurate system-based representation of city drainage dynamics. Therefore, as charted in Section 2.2.2 the increasing widespread availability of digitised drainage data has enabled the development of detailed and powerful urban drainage models.

However, the use of such models has often been hindered by the lack of available observed data for calibration. Information pertaining to the design and operation of various key elements to urban

drainage infrastructure are often being subject to administrative and political barriers to access. In this respect, specific information on diversion structures, treatment units, combined sewer overflows and depression storage areas, important for successful applications of complex process-oriented models are not always readily accessible.

These limitations of data accessibility are perhaps most severely compounded by uncertainty surrounding the integrity of such networks, where defective pipe systems can result in considerable influx or loss of water. Leaking infrastructure has been shown to contribute significantly to groundwater recharge across Europe. For example, Yang et al., estimated that 70% of groundwater recharge from the UK city of Nottingham could be traced to leaking infrastructure[101]. A report by the European Environment Agency demonstrated that leaking infrastructure can range from 3% in Germany to over 50% in Bulgaria[102]. Lerner identified recharge rates of 30% in Lima (Peru), and also attributed 50% of total recharge in Hong Kong to leakage contributions with values ranging from 260mm to 2950mm/yr[103]. Contributions from leaking infrastructure to soil water, and thus groundwater recharge, have long been recognised but quantifying their impacts has proven problematic, often resulting in adoption of environmental tracer techniques and model applications[104,105,106]. Whilst both approaches are valid, these estimates are often time consuming and uncertain. A direct method for measuring loss has thus far proved elusive.

Leakage detection systems (LDS) have advanced substantially in the past few decades as utility companies and governments recognise the economic and resource benefits of identifying and treating inefficient infrastructure[107]. Labour-intensive, costly traditional methods of detection are based on regular schedules or specific failure events[108,109]. Technological advances in Wireless Sensory Networks (WiSN) have resulted in the emergence of portable, inexpensive equipment of low-power requirement for remote real-time monitoring of pipe flow[110]. WiSNs monitor pressure, flow velocity and vibrations (via acoustic sensors) in supply- or sewage-pipe networks, where a change in the respective variable is recorded between sensor nodes and can be integrated into a GIS network, where wireless relays can highlight emergent problems[111]. Experimental applications of WiSN highlight potential to utilise this technology as a method for deriving volumes of water loss from underground transfer systems[112,113]. For example, Li et al., applied a WiSN to the water supply system in Beijing and estimated that it helped detect pipe defects and inform maintenance that reduced leakage volumes by $4*10^6$ m$^3$ of drinking water between 2007 and 2009, representing 80% of China's cumulative water losses ($5*10^6$ m$^3$)[114]. WiSN networks can provide data that quantifies water losses from infrastructure and allows utility providers to repair defective pipelines. However widespread application of such networks has not yet been realised.

### 3.3. Data Supporting Rainfall-Runoff Modelling

#### 3.3.1. Rainfall Monitoring

Conventional rainfall gauging techniques have increasingly been supplemented by widespread radar coverage, which provides greater scope for predictive interpretation of evolving rainfall patterns, although it is accompanied by significant uncertainties. An extensive overview of rainfall-radar methods is beyond the scope of this review but is provided by numerous authors[115,116,117]. Radar has obvious advantages over standard gauges, providing areal averages as opposed to point measurements. Advances in radar-rainfall estimations have been two-fold: (i) in radar sensory systems and (ii) the

processing algorithms that correct against known sources of error[118]. However, it should be stressed that prior to use in hydrological modelling, difficulties of handing large datasets and complications concerned with the calibration of radar data still remain and require pre-processing[119,120]. The recent emergence of X-band technology scales spatial resolution by a factor of 10, resulting in the ability to monitor precipitation data at the hectometre scale, rather than kilometre[121]. As a result, X-band radar has the potential for important applications in the urban environment, providing local authorities with smaller and more affordable infrastructure that has the capacity to generate forecasts and early warnings at the very local scale (e.g. EU funded project, RainGain (http://www.raingain.eu/en/raingain)). The development of X-band polarimetric radar instruments is an encouraging step, as they are capable of detecting ground clutter and enhance the reflection to rainfall relationship through the incorporation of polarimetric parameters and correction for attenuation[5]. The shift towards radar has resulted in increasingly high spatial and temporal resolution rainfall data, which is useful in modelling applications, particularly for the prediction and management of flood events[122,123].

New radar developed in UK measures humidity via a refractivity index, which is then calibrated via synoptic weather stations on the ground[124] This identifies areas where the outbreak of convective storms is likely to occur, thus potentially improving the ability to forecast pluvial flooding in urban areas. Additionally, the measurement of the emission from attenuating objects can now be determined and used to correct signal uncertainty[125] This technique is currently being implemented into the UK radar network and will result in the reduction of real-time estimation uncertainties. Increasingly novel methods are being applied to determine rainfall estimates across urban areas, which could greatly aid in calibration of more conventional monitoring techniques (Table 1). Zinevich et al., (2010) cite a relatively successful means of detecting rainfall fields using microwave tomography from commercial mobile phone networks[126]. This approach relies on the attenuation of microwaves during precipitation events and as terrestrial microwave links are normally within 10m of the ground surface, such a method provides a good basis for estimation of precipitation at the near-surface area[127]. Recent research by Bianchi et al., demonstrated the possibility of combining this information with rain gauges and radar to derive increasingly accurate precipitation estimates[128].

### 3.3.2. Evapotranspiration

Historically, evapotranspiration in urban areas has been the focus of urban climatologists interested in capturing the urban energy budget and quantifying the urban heat island[13,129]. Large buildings and street canyons create local variations in airflow and thermal regimes, which result in the transfer of energy and highly variable eddy currents, affecting the dynamics of evapotranspiration[130]. Furthermore, the patchwork presence of impervious surfaces and vegetated areas create a complex pattern of evapotranspiration, where empirical measurement can often be difficult. However, the varying height of the urban roughness sublayer and inaccurate spatial and temporal scaling laws was demonstrated to create major uncertainties in this method in urban areas[131]. Empirical studies of urban evapotranspiration initially utilised eddy correlation methods, which measure the vertical velocity and moisture content of air parcels[132]. Promising advances in technology, such as eddy covariance[133] and the application of scintillometers[134], are increasingly being employed to derive accurate and reliable measurements of urban heat fluxes and ET.

### 3.3.3. Infiltration Monitoring and Estimation

It is long established that the primary impacts of increase in impervious surface are reduced infiltration rates and travel times[96]. Recently, evidence relating these impacts to increased surface runoff, and reduced baseflow, has been extensive[5,135,136,137,138]. However, incorporation of new knowledge in hydrological models has been slow. In the past some modelling approaches have made the simplified assumption that 100% of the rainfall is converted into runoff transported overland and through stormwater drainage systems in impervious areas, yet this has often been found to be unrealistic. For example, Hollis and Ovenden found that the percentage runoff from a road was 50%[139]. Similarly, Ramier et al., found that between 30%-40% of rainfall on two roads was accounted for by evaporation and infiltration[140]. In a study of runoff from roofs, Ragab et al., found that, depending on pitch and aspect relative to dominant wind-direction, the percentage runoff varied from 61% to 91%[141]. Clearly, the term 'impervious' can be misleading, and runoff from these areas should not automatically be assumed 100% of rainfall. Similar generalisations are made for pervious areas, in which soil infiltration is typically assumed to occur 'naturally'. In reality, compaction and mixing of soil horizons during construction results in reduction in porosity, where saturation excess is reached more quickly than in natural areas, and consequently runoff contributions from pervious areas are often underestimated in model applications.

Assumptions concerning infiltration dynamics in urban space can remain a substantial source of model error. However, increasingly advanced field and laboratory techniques to determine infiltration and percent runoff estimates have been developed and can be widely applied, and thereby be potentially very beneficial for modelling, reducing the reliance on generalised assumptions. Field and laboratory based permeameters provide a hydraulic head to drive water into soil surfaces and directly derive saturated hydraulic conductivity[142,143]. Mini disk portable tension infiltrometers are easily transported and deployed in the field, enabling multiple spatial estimates. However, some of these 'direct' methods remain invariably time consuming and costly; require certain conditions to facilitate their use (e.g., flat surface), and are not always representative of soil infiltration dynamics across wider areas. Electrical resistivity techniques are potentially cost-effective for determining in-situ estimates of soil infiltration capacity[132]. Furthermore, hyperspectral remote sensing techniques can determine soil moisture at the near surface zone with a statistically significant correlation ($R^2 = 0.7$) to simultaneous observations[144]. In urban areas, the applicability of these techniques is limited to pervious zones that permit measurement, often negating the inputs from infrastructure (e.g., septic tanks and ineffective infrastructure) sealed beneath urban surfaces[145]. This can be compounded by traditional assumptions that all rainfall in impervious areas is immediately routed to runoff and that infiltration defaults to zero. Determining the infiltration rates of pervious urban areas remains an important and active area of research which will provide insights on runoff generating mechanisms. It will allow more accurate coupling in models between pervious and connected impervious areas. Furthermore, a concerted effort is required to validate values of infiltration rate used for impervious zones, which currently may be impairing model performance.

### 3.3.4. Urban Runoff Observation

Conventional velocity-area measurements remain the most common technique (c. 90% of gauging sites worldwide)[145] for determining discharge, whereby water velocity is measured at selected intervals across a known channel cross-section. The 2010 World Meteorological Organization (WMO) Manual on Stream

Gauging[145] outlines the advances made in hydrometry since the first version was published in 1980[146]. The emergence of novel techniques such as Acoustic Doppler Current Profilers (ADCPs); Acoustic Doppler Velocity Meters (ADVMs); laser Doppler velocimetry (LDV); electromagnetic channel-width coil and radar gauges have improved the resolution of automated monitoring. Measurements are now possible in uniquely urban locations such as sewer pipes and storm drains that are difficult to access. In such environments monitoring has previously been absent hindering calibration of urban drainage models[12]. Furthermore, the implementation of such technology onto remotely operated platforms (e.g., ARC-Boat®, HR Wallingford) permits monitoring in particularly dangerous or contaminated environments without posing risk to the user. Monitoring flow and bathymetry via remote control[147] enables characterisation of hydrological events, making for better calibration of models. Finally, flow data capture, storage and transfer has been greatly advanced through application of satellite and radio based telemetry methods[148], giving rapid access to data that can be used to provide real-time river level information for flood warnings (e.g. UK Environment Agency, NOAA). For example, Fulton and Ostrowski applied hand-held radar to determine flow velocities from which real-time streamflow were derived and input to existing hydraulic routing models[149]. Furthermore, real-time hydrological data provides early diagnosis of equipment error, thus maintaining continuity and reducing data loss[148].

### 3.4. Water Quality Monitoring

Pollutants found in urban environments can be divided broadly into two main types: (i) those arising from natural processes as a consequence of overstimulation of production and decomposition, and (ii) toxic chemicals originating from manufactured products, including metals and persistent organic compounds. The group arising from natural processes is small and includes macronutrients (N and P), organic waste (usually described in terms of its impact on oxygen levels: Biochemical Oxygen Demand) and pathogens. The problems of these substances are historically well-documented and substantial although the diversity of their sources and transport pathways in the urban environment make prediction of their impacts challenging. With regards to toxic substances, little is known in terms of the detailed composition in the various pathways of diffuse urban pollution. They are often poorly retained in wastewater treatment works, especially the less soluble compounds, and their biotic accumulation and storage in sludge are becoming of increasing concern[150,151]. Increasingly, emerging pollutants such as nanoparticles[152]; pharmaceuticals and endocrine disruptors[153] and microbial bacteria and pathogens[154,155] have resulted in a shift in emphasis in water quality analyses, resulting in increasingly complex monitoring strategies and technologies. The following sections assess the advances in monitoring physical, chemical and emerging priority pollutants in urban river systems.

### 3.4.1. Geomorphic Erosion and Sediment Fluxes

Since the 1960s, substantial advances in understanding of how urbanisation affects geomorphic processes[156] have been made, yet three major challenges remain: first, there is a need to quantify the aggregate impact of urbanisation on sediment transport at spatial and temporal scales greater than those of individual studies[157,158]; second, there is a need to improve understanding of how changes to the downstream river environment may subsequently alter in-stream processes and channel morphology[159,160,161]; and third there is a growing recognition that impacts of urbanisation on aquatic ecology can be understood properly only when the effects of urbanisation on flow and sediment delivery are also taken into account[162]. Establishing the origin of sediment mobilised from urban areas is

particularly important. However, the dynamic nature of sediment transport results in many well-recognised difficulties for field measurements in river systems. Sediment transport is typically divided into three categories, based on size classifications. Of primary concern regarding fluxes of contaminants from urban areas:

(i) Bedload sediment - represents larger material, including gravels and pebbles which will only be mobilised under elevated discharges or steep bed gradients, making for problematic monitoring conditions, and often confined to more upland areas[163]. Conventional measurements of bedload can be separated into four categories: box/basket (sediment traps), trays (or pans), pressure difference samplers (e.g., Helley-Smith) or pit samplers. In addition, grab samples and cores for laboratory analyses can provide insight into the physical and chemical compositions of bedload layers. Measurement entails a range of problems, including capturing of suspended sediment loads in addition to bedload[164].

(ii) Suspended sediment –Acoustic Doppler Current Profilers (ADCPs) are increasingly being explored as a surrogate method for determining suspended sediment concentrations[165]. Guerrero et al., (2011) assessed a dual-frequency ADCP in the laboratory[166] and concluded that acoustic backscatter (ABS) techniques are a robust methodology for determining grain size distribution for suspended sediment columns. Additionally, measures of optical turbidity provide an indirect method of estimating SSC, where strong correlations with discharge are apparent. State-of-the-art turbidity meters are increasingly deployed in conjunction with electrical conductivity probes, as dissolved solids can significantly affect the conductance rates[167]. As suspended sediments provide a viable mechanism for transporting chemical and biological contaminants, physical sampling for post-capture characterisation in the lab is desirable.

### 3.4.2. Chemical and Biological Water Quality Metrics

Chemical and biological indicators remain the dominant focus of policy. Legacies of intensive agriculture and industry resulted in elevated levels of a vast suite of contaminants in freshwater environments including phosphorus, heavy metals and nitrates. As the human footprint continues to expand and agricultural practices continue to intensify, chemical and biological contaminants still remain a dominant threat to water quality from both point and non-point sources.

Autosampling techniques were gradually introduced to enable more frequent and comprehensive sampling without the need for excessive manpower (e.g., programmable ISCO 3700 or flow-triggered Endress and Hauser Liquiport 2000EX samplers). Despite their undoubted utility (particularly for more complex chemical and biological water quality indicators that still require laboratory analysis) autosampling systems are often expensive, particularly where monitoring is spread across multiple areas (Table 1). The emergence of real-time remote monitoring (RTRM) systems have been widely utilised across many sectors providing cheap, accurate and dynamic data capture[168]. RTRM systems incorporate an array of sensors that capture, store and relay meteorological, hydrological and water quality data (Table 1). For water quality, multi-parameter sensors are attached to a bundled device (e.g., YSI 6600ED and RSHydro Manta 2 sondes) and deployed into water bodies, remotely recording and relaying data via radio or satellite telemetry systems. Continual monitoring networks provide an avenue to obtain

accurate and long-term data, which can be used to determine spatial and temporal changes of water quality (including event response), drive policy decisions and inform modelling studies[168]. Furthermore, the introduction of alert systems provides a management tool for local and environmental authorities for responsive action at sites where toxic spills occur or large contaminant concentrations arise. In terms of biological monitoring, chlorophyll (a surrogate for phytoplankton biomass) and cyanobacteria are nowadays routinely captured using fluorescence sensors in RTRM systems, and are also extensively surveyed using airborne hyperspectral remote sensing[169]. When used in conjunction with cell-based characterisation through flow cytometry[170] valuable information is attained on functional composition. In sharp contrast, the highly constraining expense involved in monitoring other biological groups such as macro-invertebrates and fish restricts data availability to, at best, surveys at a seasonal-resolution.

### *3.4.3. Emerging Priority Contaminants*

Increasingly complex contaminants, such as pharmaceuticals, personal care products, endocrine disruptors and nanoparticles are emerging and require novel monitoring techniques. The ecological threats from these contaminants (collectively referred to as Organic Wastewater Contaminants or OWCs) in surface water sources have long been recognised, despite their status as 'emerging priority contaminants'[171]. Their presence in wastewater is almost ubiquitous, presenting a major challenge to treatment plants[172].

Conventional methods for detecting OWCs rely on grab sampling, restricted by both cost and availability of manpower, and also by post-capture processing in the laboratory which requires tandem gas- and liquid chromatography mass spectrometry (GC-MS/MS and LC-MS/MS respectively)[172,173]. Where endocrine disrupting contaminants and pharmaceuticals and personal care products (PPCPs) are present only at trace levels, large volumes of water are required to facilitate sufficient detection, making regular transport of samples increasingly difficult. Some of these limitations can be overcome by autosampling technology, though as discussed in the previous section, this is often expensive and impractical, and such systems are not widely used in extensive sampling regimes[175]. Passive sampling techniques have been successfully applied in environmental monitoring for the best part of four decades for a range of pollutants[174,175]. Continuous submergence of samplers beneath the surface allows time-integrated flow of analyte molecules to pass through a receiving membrane until chemical equilibrium is reached, conceptually replicating absorption rates in aquatic ecology in a given location. For example, the Polar Organic Chemical Integrative Sampler (POCIS) is a highly sensitive device specifically tailored to detect PPCPs and pesticides/herbicides in freshwater systems. The POCIS system samples in the dissolved phase, which enables contaminant bio-availability to be estimated[174] and can be specifically configured to detect drug residues[176]. Passive sampling represents the state-of-the-art means to detect OWCs in water systems although extensive laboratory calibration and analysis is still required to accurately determine trace concentration levels (Table 1). To conclude, an in-situ method for detection that bypasses the need for extensive laboratory analysis and is suitable for real-time monitoring and alert systems remains lacking.

Overall, the ability to monitor contaminants in the urban environment has improved dramatically over the past few decades, greatly aided by the continual improvement in sensor- and communication technology. RTRM technology has enabled a method for identifying and managing high concentrations of contaminants and spills via an alert system. As increasingly complex contaminants such as microbial

pollutants, PPCPs, endocrine disruptors and nanoparticles emerge, new challenges for monitoring fuels further research[177].

## 4. Discussion and Conclusion

### *4.1 Summary*

Despite the advances made in urban hydrology over the past few decades, a holistic understanding of the complexities of the urban environment remains lacking, and is an active area of research. The evolution of monitoring and modelling techniques has advanced our capacity to obtain observations and predictions at increasingly high-resolution spatio-temporal intervals resulting in a paradigm shift toward integrated model applications. As new technologies continue to emerge, the scope for advancing our understanding of urban hydrology increases considerably. Here, we summarise findings from the preceding sections and identify how these advances in monitoring and modelling technologies can be used to drive the future of urban water research.

- Improvements in remote sensing platforms have greatly aided our ability to identify urban landscape at increasing spatial and temporal resolution. As sensor technology, coverage and post-capture analysis techniques continue to improve, there is real scope for remote sensing technologies to drive hydrological research in urban and rural areas alike.
- Whilst performance mismatch is still warranting much attention, the development of novel methods for detecting the spatial and temporal patterns of rainfall (e.g., radar and microwave tomography) have advanced our ability to predict and manage rainfall in urban areas. This is crucial for flood management and drainage design. The move towards now-casting and real-time application remains a current research priority.
- Quantifying evapotranspiration, which is historically the domain of urban meteorologists, has increasingly been recognised by urban hydrologists as crucial to closing the water balance. This remains an active area of research but technology such as eddy flux chambers and scintillometers demonstrate potential for widespread application in networks designed to measure ET for water balance assessment across contrasting urban space.
- Achieving realistic measures of infiltration in pervious and impervious areas alike has been identified as a significant knowledge gap. Overcoming the assumptions that impervious areas prevent any infiltration, whereas parkland areas behave 'as natural' are crucial to understanding rainfall-runoff dynamics. Additionally, the development of wireless sensory networks (WiSN) has greatly aided our ability to quantify leakage from infrastructure and determine infiltration into- and out of pipes. So far, limited applications have highlighted success at reducing water losses. Widespread implementation could reduce urban water loss considerably, whilst providing urban hydrologists with suitable data for parameterising recharge in urban hydrological models.
- The development of novel flow measuring devices has increased our ability to monitor in arduous conditions (e.g., flood events) and challenging locations (e.g., pipes), providing further insights into river bathymetry and velocity mapping. As recording devices become increasingly portable and inexpensive, widespread deployment across urban catchments allows us to understand flows and associated fluxes in increasingly disparate parts of the system, enabling us to trace sources and pathways for water and contaminants.

- A move towards RTRM technologies has greatly improved understanding of water quality dynamics in urban areas. Rapid detection of a suite of water quality contaminants and live telemetric transfer can aid in water quality management during storm events, or detection of spillages from overflows or industrial effluent outputs.
- Efforts to model the urban water balance and water quality have advanced through the move towards an integrated approach, which considers multiple connected systems (e.g., WWTP, surface runoff, pipe flow) as boundary inputs, creating a holistic representation of the urban area. As monitoring data continues to improve and become more readily available, models are becoming increasingly complex as we transition toward spatially distributed, continuous simulation structures in a systems dynamics approach. This is perhaps the most pragmatic way of representing the urban water cycle and more widespread application will improve our ability to represent the system in a more holistic manner, providing a robust baseline for future projection in response to changes in land use, urban expansion and climate.
- The advent of GIS techniques to support for example (i) increasingly high resolution topographic data, (ii) characterisation of urban infrastructure, more detailed land-use observations which better identify contiguous impervious areas has enabled the implementation of more powerful modelling techniques to relate land-use change to water resources.

### 4.2 Remaining Challenges

Remote sensing provides an unparalleled tool for tracking urban growth but as new developments continue to implement sustainable urban drainage features such as permeable paving and road surfaces, and green rooftops, increasingly high-resolution sensors are required to differentiate them from well-understood and conventional land classes. Despite its importance to the urban water balance, empirical derivation of evapotranspiration remains limited and our ability to satisfactorily quantify ET rates in urban areas is lacking. As urban planners continue to restore evapotranspiration as a sustainable management technique for stormwater, an improvement to current methodology is required for deriving ET estimates in urban areas. Although the emergence of radar and microwave tomography has advanced our ability to predict spatio-temporal patterns of rainfall, an important research priority is a move towards shorter-duration prediction and 'now-casting' techniques that will greatly aid in urban flood management. Whilst integrated models provide a mechanism for distilling the wealth of data that can now be attained through monitoring regimes as well as elucidating the potential impacts of environmental and land-use change there are still limitations in their scope, particularly in terms of ecological impacts. The links between water quality and ecology are not well understood. Channel geomorphology, which has been observed to undergo systematic change during urbanisation[156], in particular in terms of artificial modification, is known to influence in-stream biological communities, whereby reductions in in-stream sediment budgets reduce breeding habitats for fish and macroinvertebrates[4,178]. In this regard, taking steps to restore habitats is recognised as being of fundamental importance[179]. In terms of modelling, ecological response is typically represented by empirical statistically-based approaches[180], in part a consequence of the practical restrictions imposed by data collection methods. Any mechanistic representation of ecology is largely absent from integrated models of urban systems, and should be an aspiration for future research.

In spite of these shortcomings, in order to assess urbanisation at the river basin scale, at which water resources are managed for pollution control and for mitigation against extreme events, it is necessary to

distil the impacts of urbanisation into simple yet robust formulations that capture the complex dynamics represented in process-based models. As a step towards achieving this, the overarching objective of the POLLCURB project, we consider that quantification of various essential features must be made, notably the extent of urban and suburban land-use, soil infiltration and rainfall regime, and key thresholds above which sewer infrastructure capacity will be breached. For this reason, we propose that at basin level description of natural water bodies is geographically detailed (an ICBM on Figure 1). Integration at the IUDM level is achieved with meta-modelling approaches, whereby simplified representations of urban infrastructure capture the main features of more-detailed models. In contrast, at the IUWSM level detail must not be compromised in the provision of land-use and climate change drivers

The improvements to monitoring technology and modelling capability present us with renewed ability to assess impacts of urbanisation. Availability of high-resolution remote sensing platforms allows identification of subtle spatial and temporal changes in urban and suburban land cover, hence detailed networks of pervious and impervious surfaces can be supplied to hydrological models. This can be combined with empirical measurements of infiltration capacity and high-resolution rainfall to better determine rainfall-runoff dynamics at increasingly fine scale. In addition, digitised networks of stormwater drainage infrastructure improve the accuracy of runoff routing and simulation of flows to urban channels. RTRM networks can be used in conjunction with rainfall-runoff from specific land uses to determine pollutant loads. This combination of high-resolution monitoring systems and integrated model structures can be used to identify overflow events and quantify their potential water quality and flood implications. As highlighted in Section 2.2, POLLCURB seeks to build on these advances by incorporating high-resolution data into an integrated model to be tested and used to make future projections. It will provide scope for assessing both continuous and event-based impacts of hydrology and water quality under changing land-use, population and climate scenarios. The implementation of robust data from advanced, high-resolution monitoring techniques creates scope to intrinsically link landscapes to their dynamics and assess change over space and time and contrasting scales.

### References

1. United Nations, (2011), World urbanization prospects: the 2011 revision, *United Nations Department of Economic and Social Affairs (Population Division)*, New York, USA

2. United States Census Bureau, (2012), U.S. and World Population Clock, www.census.gov/popclock, *Accessed 03/11/13*

3. Vörösmarty C.J., Green P., Salisbury J. and Lammers R.B., (2000), Global water resources: Vulnerability from climate change and population growth, *Nature*, **289**, 284-288

4. Walsh C.J., Roy A.H.,Feminella J.W., Cottingham P.D., Groffman P.M. And Morgan II R.P., (2005), The urban stream syndrome: current knowledge and the search for a cure, *Journal of the North American Benthological Society*, **24**(3), 706-723

5. Fletcher T.D., Andrieu H. and Hamel P., (2013), Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art, *Advances in Water Resources*, **51**, 261-279

6. McGrane, S.J., (In Press), Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: A review, *Hydrological Sciences*

7. Miller, J.D., Kim, H., Kjeldsen, T.R., Packman, J., Grebby, S. and Dearden, R., (2014), Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover, *Journal of Hydrology*, **515**, 59-70

8. Brown, R.R., Keath, N. and Wong, T.H.F., (2009), Urban water management in cities: historical, current and future regimes, *Water Science and Technology*, **59**(5), 847-855

9. Liu A., Egodawatta, P., Guan, Y. and Goonetilleke, A., (2013), Influence of rainfall and catchment characteristics on urban stormwater quality, *Science of the Total Environment*, **444**, 255-262

10. Ternes, T.A., Joss, A. and Siegrist, H., (2004), Scrutinizing pharmaceuticals and personal care products in wastewater treatment, *Environmental Science and Technology*, **38**(20), 392A-399A

11. Rauch W, Bertrand-Krajewski J.L., Krebs P., Mark O., Schilling W., Schutze M. and Vanrolleghem P.A., (2002), Deterministic modelling of integrated urban drainage systems, *Water Science and Technology*, **45**(3), 81-94

12. Bach P.M., Rauch, W., Mikkelsen P.S., McCarthy D.T. and Deletic, A., (2014), A critical reivew of integrated urban water modelling – urban drainage and beyond, *Environmental Modelling and Software*, **54**, 88-107

13. Mitchell V.G., Cleugh H.A., Grimmond C.S.B. and Xu J., (2007), Linking urban water balance and energy balance models to analyse urban design options, *Hydrological Processes,* **22** (16), 2891–2900

14. Candela A., Freni G., Mannina G. and Viviani G., (2012), Receiving water body quality assessment: An integrated mathematical approach applied to an Italian case study, *Journal of Hydroinformatics*, **14** (1), 30-47

15. Vanrolleghem P.A., Benedetti L. and Meirlaen J., (2005), Modelling and real-time control of the integrated urban wastewater system, *Environmental Modelling and Software*, **20** (4), 427-442

16. Gujer, W., Krejci, V., Schwarzenbach, R., Zobrist, J., (1982). Von der Kanalisation ins Grundwasser e Charakterisierung eines Regenereignisses im Glattal, *GasWasser-Abwasser* **62** (7), 298-311

17. Freni G., Mannina G. and Viviani G., (2008), Catchment-scale modelling approach for a holistic urban water quality management, In *Proceedings of the 11ᵗʰ International Conference on Urban Drainage,* Edinburgh

18. Moglia M., Perez P. and Burn S., (2010), Modelling an urban water system on the edge of chaos, *Environmental Modelling and Software*, **25** (12), 1528-1538

19. Jeppsson U., Pons M.-N., Nopens I., Alex J., Copp J.B., Gernaey K.V., Rosen C., Steyer J.-P., Vanrolleghem P.A., (2007), Benchmark simulation model No. 2: general protocol and exploratory case studies, *Water Science and Technology*, **56** (8), 67-78

20. Regneri, M., K. Klepiszewski, M. Ostrowski and P. A. Vanrolleghem, (2010), Fuzzy Decision Making for Multi-criteria Optimisation in Integrated Wastewater System Management, in: Proceedings of the IWA 6th International Conference on Sewer Processes and Networks, November 11-12, Goldcoast, Australia, 2010

21. Heinz, I., Pulido-Velazquez, M., Lund, J.R. and Andreu, J., (2007), Hydro-economic modelling in river basin management: Implications and applications for the European Water Framework Directive, *Water Resource Management*, **21**, 1103-1125

22. Makropolous C., Natsis K., Liu S., Mittas K. and Butler D., (2008), Decision support for sustainable option selection in integrated urban water management, *Environmental Modelling and Software*, **23**, 1448-1460

23. Doglioni A., Primativo F., Laucelli D., Monno V., Khu S.-T. and Giustolisi O., (2009), An integrated modelling approach for the assessment of land use change effects on wastewater infrastructures, *Environmental Modelling and Software*, **24**, 1522-1528

24. Jakeman, A.J., Letcher, R.A. and Norton, J.P., (2006), Ten iterative steps in development and evaluation of environmental models, *Environmental Modelling and Software*, **21**(5), 602-614

25. Makropoulos C.K., Natsis K., Liu S., Mittas K. and Butler D., (2008), Decision support for sustainable option selection in integrated urban water management, *Environmental Modelling and Software*, **23** (12), 1448-1460

26. Matthies M., Berlekamp J., Lautenbach S., Graf N. and Reimer S., (2006), Systems analysis of water quality management for the Elbe river basin, *Environmental Modelling and Software*, **21** (9), 1309-1318

27. Guzy M. R., Smith C. L., Bolte J. P., Hulse D. W. and Gregory S. V., (2008), Policy research using agent-based modeling to assess future impacts of urban expansion into farmlands and forests. *Ecology and Society* **13**(1): 37

28. IFAK Systems, (2013), SIMBA-6: Simba ® - Simulation of biological wastewater systems, http://www.ifak-system.com/fileadmin/downloads/manual_dt/umwelt/Detailed_information_brochure.pdf, accessed 18/10/13

29. Mitchell V., (2005), Aquacycle, a daily urban water balance model, *User Guide*

30. Achleitner S., Moderl M. and Rauch W., (2007), CITY DRAIN © - An open source approach for simulation of integrated urban drainage systems, *Environmental Modelling Software*, **22**(8), 1184-1195

31. Dawson R.J., Hall J.W., Barr S.L., Batty M., Bristow A.L., Carney S., Dagoumas A., Evans S., Ford A., Harwatt H., Kohler J., Tight M.R., Walsh C.L. and Zanni A.M., (2009), A blueprint for the integrated assessment of climate change in cities, http://www.tyndall.ac.uk/sites/default/files/wp129.pdf, [accessed 23/07/15]

32. Lowry I.S., (1964), A Model of Metropolis, *RAND Memorandum 4025-RC*

33. Bröcker, J., Korzhenevych, A. and Schürmann, C., (2010). Assessing spatial equity and efficiency impacts of transport infrastructure projects. Transportation Research Part B: Methodological 44(7) 795-811

34. Geurs, K.T. and van Wee, B., (2004), Land-use/transport interaction models as tools for sustainability impact assessment of transport investments: review and research perspectives, *European Journal of Transport and Infrastructure Research*, **4**(3) 333-355

35. Jin, Y., Echenique, M., Hargreaves, A., 2013. A recursive spatial equilibrium model for planning large-scale urban change, *Environment and Planning B: Planning and Design*, **40**(6) 1027-1050

36. Anas, A. and Liu, Y., (2007). A regional economy, land-use, and transportation model (RELU-TRAN©): formulation, algorithm, design, and testing, *Journal of Regional Science*, **47**(3) 415-455

37. Allen, P.M. and Sanglier, M., (1979), A dynamic model of growth in a central place system, *Geographical Analysis*, **11**(3) 256-272

38. White, R.W., (1977), Dynamic central place theory: results of a simulation approach, *Geographical Analysis*, **9**(3) 226-243

39. Allen, P.M., (1997), Cities and regions as self-organizing systems : models of complexity. Gordon and Breach, Luxembourg

40. Tobler, W.R., (1970), A computer movie simulating urban growth in the Detroit region, *Economic geography*, 234-240

41. Couclelis, H., (1985), Cellular worlds: a framework for modelling micro-macro dynamics. *Environment and planning A*, **17**(5) 585-596

42. Wolfram, S., (1986), Theory and applications of cellular automata: including selected papers, 1983-1986. World Scientific, Singapore

43. Schelling, T.C., (1971), Dynamic models of segregation. *Journal of mathematical sociology*, **1**(2), 143-186

44. White, R. and Engelen, G., (1993), Cellular-Automata and Fractal Urban Form - a Cellular Modelling Approach to the Evolution of Urban Land-Use Patterns, *Environment and planning A*, **25**(8) 1175-1199

45. Clarke, K.C., Hoppen, S. and Gaydos, L., (1997), A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area, *Environment and Planning B-Planning & Design*, **24**(2) 247-261

46. van Delden, H., Luja, P. and Engelen, G., (2007), Integration of multi-scale dynamic spatial models of socio-economic and physical processes for river basin management, *Environmental Modelling & Software*, **22**(2) 223-238

47. Mahiny, A. and Clarke, K., (2013), Simulating hydrologic impacts of urban growth using SLEUTH, multi criteria evaluation and runoff modelling, *Journal of environmental informatics*, **22**(1) 27-38

48. Han W.S. and Burian S.J., (2009), Determining Effective Impervious Area for Urban Hydrologic Modelling, *Journal of Hydrologic Engineering,* **14**(2), 111–120

49. Chocat B., Krebs P., Marsalek J., Rauch W. and Schilling W., (2001), Urban drainage redefined: from stormwater removal to integrated management, *Water Science and Technology*, **43** (5), 61-68

50. Salvadore E., Bronders J. and Batelaan O., (2015), Hydrological modelling of urbanized catchments: a review and future directions, *Journal of Hydrology*, **529** (1), 62-81

51. Mackay R. and Last E., (2010), SWITCH city water balance: a scoping model for integrated urban water management, *Reviews in Environmental Science and Biotechnology*

52. Chen Q.W., Qu J.H., Liu R.P. and Li W.F., (2008), Rule-based model for aging-induced leakage from water supply pipe network in Beijing city, *China Water and Wastewater*, **24**(11), 52-56

53. Zoppou C., (2001), Review of urban storm water models, *Environmental Modelling & Software*, **16** (3), 195-231

54. Puust R., Kapelan Z., Savic D.A. and Koppel T., (2010), A review of methods for leakage management in pipe networks, *Urban Water Journal*, **7**(1), 25-45

55. Borah D.K., (2011), Hydrologic procedures of storm event watershed models: a comprehensive review and comparison, *Hydrological Processes*, **25**(22), 3472–3489

56. Mark O., Weesakul S., Apirumanekul C., Boonya Aroonnet S., Djordjević S., (2004), Potential and limitations of 1D modelling of urban flooding, *Journal of Hydrology*, **299**(3–4), 284-299

57. Hunter N.M., Bates P.D., Neelz S., Pender G., Villanueva I., Wright N.G., Liang D., Falconer R.A., Lin B., Waller S., Crossley A.J. and Mason D.C., (2008), Benchmarking 2D hydraulic models for urban flooding, *Proceedings of the ICE - Water Management*, 161 (1), 13-30

58. Alley W.M. and Veenhuis J., (1983), Effective Impervious Area in Urban Runoff Modelling, *Journal of Hydraulic Engineering,* **109** (17669), 313–319

59. Braud I., Breil P., Thollet F., Lagouy M., Branger F., Jacqueminet C., Kermadi S. and Michel K., (2013) Evidence of the impact of urbanization on the hydrological regime of a medium-sized periurban catchment in France, *Journal of Hydrology*, **485**, 5-23

60. Aronica G. and Cannarozzo M., (2000), Studying the hydrological response of urban catchments using a semi-distributed linear non-linear model, *Journal of Hydrology*, **238** (1–2), 35-43

61. Crobeddu E., Bennis S., and Rhouzlane S., (2007), Improved rational hydrograph method, *Journal of Hydrology*, **338**(1–2), 63-72

62. Kjeldsen T.R., (2009), Modelling the impact of urbanisation on flood runoff volume, *Proceedings of the ICE - Water Management*, **162**(5), 329 –336

63. Furusho C., Chancibault K. and Andrieu H., (2013), Adapting the coupled hydrological model ISBA-TOPMODEL to the long-term hydrological cycles of suburban rivers: Evaluation and sensitivity analysis, *Journal of Hydrology*, **485**, 139-147

64. Kim H., Noh S.J., Jang C., Kim D. and Hong I., (2005), Monitoring and analysis of hydrological cycle of the Cheonggyecheon watershed in Seoul, Korea: In *Proceedings of the 2005 International Conference on Simulation and Modeling 2005,* 410-417, Nakompathom, Thailand, 17-19 January 2005.

65. Hurkmans, R. T. W. L., Terink, W.,  Uijlenhoet, R., Moors, E. J., Troch, P. A. and Verburg, P. H. (2009) Effects of land use changes on streamflow generation in the Rhine basin, *Water Resour. Res.*, 45, W06405

66. Strangeways I.C., (1990), The telemetry of hydrological data by satellite, Institute of Hydrology Report No.112, http://nora.nerc.ac.uk/6055/1/IH_112.pdf

67. Tyagi B., Gakkher S. and Bhargava D.S., (1999), Mathematical modelling of stream DO-BOD accounting for settleable BOD and periodically varying BOD source, *Environmental Modelling and Software,* **14**, 461-471

68. Babu M.T., Das V.K. and Vethamony P., (2006), BOD-DO modelling and water quality analysis of a waste water outfall off Kochi, west coast of India, *Environmental International*, **32**, 165-173

69. Rustum R., Adeloye A.J. and Sholz M., (2008), Applying Kohonen self-organizing map as a software sensor to predict the biochemical oxygen demand*, Water Environment Research*, **80**(1), 32-40

70. Soranno P.A., Hubler S.L., Carpenter S.R. and Lathrop R.C., (1996), Phosphorus loads to surface waters: A simple model to account for spatial pattern of land use, *Ecological Applications*, **6**(3), 865-878

71. Worrall F., and Burt T.P., (1999), Modelling the impact of land-use change on water quality in lowland catchments: the role of dynamic nitrogen reservoirs. In *Impact of land-use change on nutrient loss from diffuse sources*, Heathwaite (ed.), IAHS **257**, 151-157

72. Dahl M., Wilson D.I. and Hakanson L., (2006), A combined suspended particle and phosphorus water quality model: Application to Lake Vanern, *Ecological Modelling*, **190**(1-2), 55-71

73. Jorgensen S.E., (1990),  A general model for the heavy metal pollution of aquatic ecosystems: Model development, *Environmental Software*, **5**, 136-141

74. Brown J.N. and Peake B.M., (2002), Sources of heavy metals and polycyclic aromatic hydrocarbons in urban stormwater runoff, *Science of the Total Environment*, **359**, 145-155

75. Blanchoud H., Moreau-Guigon E., Farrugia F., Chevreuil M. and Mouchel J.M., (2007), Contribution by urban and agricultural pesticide uses to water contamination at the scale of the Marne watershed. *Science of the Total Environment*, **375**, 168-179

76. Periáñez R., (2009), Environmental modelling in the Gulf of Cadiz: Heavy metal distributions in water and sediments, *Science of the Total Environment*, **407**, 3392-3406

77. Li, X., Liu, X. and Yu, L., (2014), A systematic sensitivity analysis of constrained cellular automata model for urban growth simulation based on different transition rules, *International Journal of Geographical Information Science*, **28**(7) 1317-1335

78. Barreira-González, P., Aguilera-Benavente, F. and Gómez-Delgado, M., (2015), Partial validation of cellular automata based model simulations of urban growth: An approach to assessing factor influence using spatial methods, *Environmental Modelling & Software*, **69**, 77-89

79. Akın, A., Clarke, K.C. and Berberoglu, S., (2014), The impact of historical exclusion on the calibration of the SLEUTH urban growth model, *International Journal of Applied Earth Observation and Geoinformation*, **27**, 156-168

80. Basse, R.M., Omrani, H., Charif, O., Gerber, P. and Bódis, K., (2014), Land use changes modelling using advanced methods: Cellular automata and artificial neural networks. The spatial and explicit representation of land cover dynamics at the cross-border region scale. *Applied Geography*, **53** 160-171

81. Verstegen, J.A., Karssenberg, D., van der Hilst, F. and Faaij, A.P.C., (2015), Detecting systemic change in a land use system by Bayesian data assimilation. *Environmental Modelling & Software*

82. Gluck, W., and McCuen, R.H., (1975), Estimating land use characteristics for hydrologic models, *Water Resources Research*, **11**, 177-179

83. Brabec E., (2002), Impervious surfaces and water quality: a review of current literature and its implications for watershed planning. *Journal of Planning Literature*, **16**(4), 499-514

84. Thomson A. G., Manchester S. J., Swetnam R. D., Smith G. M., Wadsworth R. A., Petit S. and Gerard F.F., (2007),  The use of digital aerial photography and CORINE-derived methodology for monitoring recent and historic changes in land cover near UK Natural 2000 sites for the BIOPRESS project, *International Journal of Remote Sensing*, **28**, 5397-5426

85. Rogan J. and Chen D-M., (2004), Remote sensing technology for mapping and monitoring land-cover and land-use change, *Progress in Planning*, **61**, 301-325

86. Jensen J.R., (2005), Introductory digital image processing: a remote sensing perspective (3$^{rd}$ Edition), *Prentice Hall*, New Jersey

87. Gamba P. and Herold M., (2009), Global mapping of human settlement, *CRC Press*, Berlin

88. Weng Q., (2012), Remote sensing of impervious surfaces in the urban areas: Requirements, methods, and trends, *Remote Sensing of Environment*, **117**, 34-49

89. Aichele S.S. and Andresen J.A., (2013), Spatial and temporal variations in land development and impervious surface creation in Oakland County, Michigan, 1945-2005, *Journal of Hydrology*, **485**, 96-102

90. Homer C., Dewitz J., Fry J., Coan M., Hossain N., Larson C. and Wickham J., (2007), Completion of the 2001 National Land Cover Database for the Conterminous United States, *Photogrammetric Engineering and Remote Sensing*, **73**(4), 337

91. Morton D., Rowland C., Wood C., Meek L., Marston C., Smith G., Wadsworth R. and Simpson I., (2011), Final Report for LCM2007-the new UK land cover map. Countryside Survey Technical Report No 11/07

92. Friedl, M. A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., & Huang, X. (2010). MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sensing of Environment*, *114*(1), 168-182

93. Esch, T., Taubenböck, H., Roth, A., Heldens, W., Felbier, A., Thiel, M., & Dech, S. (2012). TanDEM-X mission—new perspectives for the inventory and monitoring of global settlement patterns. *Journal of Applied Remote Sensing*, *6*(1), 061702-1

94. Ridd, M.K., (1995), Exploring a V-I-S (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities, *International Journal of Remote Sensing*, **16**, 2165-2185

95. Sexton J.O., Song X.-P., Huang C., Channan S., Baker M.E. and Townshend J.R., (2013), Urban growth of the Washington, D.C.–Baltimore, MD metropolitan region from 1984 to 2010 by annual, Landsat-based estimates of impervious cover, *Remote Sensing of Environment*, **129**, 42-53

96. Yang L., Huang C., Homer C.G., Wylie B.K. and Coan M.J., (2003), An approach for mapping large-area impervious surfaces: synergistic use of landsat-7 ETM+ and high spatial resolution imagery, *Canadian Journal of Remote Sensing*, **29**(2), 230-240

97. Xian, G., Homer, C., Dewitz, J., Fry, J., Hossain, N., and Wickham, J., (2011), The change of impervious surface area between 2001 and 2006 in the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, **77** (8), 758-762

98. Mason, D.C., Horritt, M.S., Hunter, N.M. and Bates, P.D., (2007), Use of fused airborne scanning laser altimetry and digital map data for urban flood modelling, *Hydrological Processes*, **21**, 1436-1447

99. Alley W.M. and Veenhuis J., (1983), Effective Impervious Area in Urban Runoff Modelling, *Journal of Hydraulic Engineering,* **109** (17669), 313–319

100. Pitt M., (2007), Lessons learned from the 2007 floods, http://webarchive.nationalarchives.gov.uk/20100807034701/http://archive.cabinetoffice.gov.uk/pittreview/thepittreview/final_report.html, [accessed 14/02/15]

101. ISQ, SMAS Sintra and QUESTOR, (2006), Short guide to improve small WWTP efficiency, http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=WWTREAT_Guide_Efficiency.pdf, [accessed 05/03/15]

102. Yang Y., Lerner D.N., Barrett H.M. and Tellam J.H., (1999), Quantification of groundwater recharge in the city of Nottingham, UK, *Environmental Geology*, **38** (3), 183-198

103. Lallana C., (2003), Indicator fact sheet: (WQ06) water use efficiency (in cities): leakage, *European Environment Agency Factsheet,* http://www.eea.europa.eu/data-and-maps/indicators/water-use-efficiency-in-cities-leakage/water-use-efficiency-in-cities-leakage, accessed 11/10.13

104. Lerner D., (1986), Leaking pipes recharge ground water, *Groundwater*, **24**(5), 654-662

105. Taylor R.G., Cronin A.A., Lerner D.N., Tellam J.H., Bottrell S.H., Rueedi J. and Barrett M.H., (2006), Hydrochemical evidence of the depth of penetration of anthropogenic recharge in sandstone aquifers underlying two mature cities in the UK, *Applied Geochemistry,* **21**(9), 1570-1592

106. Hyer K.E., (2007), A multiple-tracer approach for identifying sewage sources to an urban stream system, U.S. Geological Survey Scientific Investigations Report 2006-5317

107. Jacobson C.R. (2011), Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review, *Journal of Environmental Management*, **92**(6), 1438-1448

108. Al-Kadi T., Al-Tuwaijri Z. and Al-Omran A., (2013), Wireless sensory networks for leakage detection in underground pipelines: A survey paper, *Procedia Computer Science*, **21**, 491-498

109. Shu S.H., He W.J., Zhao M., Gao J.L., Yuan Y.X. and Zhao H.B., (2008), Current application and recent development of leakage detection technologies in water supply networks, *Water and Wastewater Engineering*, **34**(6), 114-116

110. Liu Z. and Kleiner Y., (2013), State of the art review of inspection technologies for condition assessment of water pipes, *Measurement*, **46**(1), 1-15

111. Akyildiz I.F., Su W., Sankarasubramaniam Y. and Cayirci E., (2002), Wireless sensor networks: A survey, *Computer Networks*, **38**, 393-422

112. Li W., Ling W., Lui S., Zhao J., Lui R., Chen Q., Qiang Z. and Qu J., (2011), Development of systems for detection, early warning, and control of pipeline leakage in drinking water distribution: A case study, *Journal of Environmental Sciences*, **23**(11), 1816-1822

113. Christodoulou S., Agathokleous A., Kounoudes A. and Milis M., (2010), Wireless sensor networks for water loss detection, *European Water*, **30**, 41-48

114. Sun Z., Wang P., Vuran M.C., Al-Rodhaan M.A., Al-Dhelaan A.M. and Akyildiz I.F., (2011), MISE-PIPE: Magnetic induction-based wireless sensor networks for underground pipeline monitoring, *Ad Hoc Networks*, **9**, 218-227

115. Petchprayoon P., Blanken P.D., Ekkawatpanit C. and Hussein K., (2010), Hydrological impacts of land use/land cover change in a large river basin in central–northern Thailand, *International Journal of Climatology*, **30**, 1917–1930

116. Battan L.J., (1973), Radar observation of the atmosphere, *University of Chicago Press*, Chicago, USA

117. Sauvageot H., (1991), Radar meteorology, *Artrech House Inc.*, Paris

118. Raghavan S., (2003), Radar Meteorology: 1st Edition, *Springer*, London, UK

119. Cunha L.K., Mandapaka P.V., Krajewski W.F., Mantilla R. and Bradley A.A., (2012), Impact of radar-rainfall error structure on estimated flood management across scales: An investigation based on parsimonious distributed hydrological model, *Water Resources Research*, **48** (10), W10515 DOI:10.1029/2012WR012138

120. Berne A. and Krajewski W.F., (2013), Radar for hydrology: Unfulfilled promise or unrecognized potential, *Advances in Water Resources*, **51**, 357-366

121. Vasiloff S.V., Seo D-J., Howard K.W., Zhang J., Kitzmiller D.H., Mullusky M.G., Krajewski W.F., Brandes E.A., Rabin R.M., Berkowitz D.S., Brooks H.E., McGinley J.A., Kuligowski R.J. and Brown B.G., (2007), Improving QPE and Very Short Term QPF: An Initiative for a Community-Wide Integrated Approach, *Bulletin of the American Meteorological Society*, **88**, 1899–1911

122. Shrestha N.K., Goormans T. and Willems P., (2013), Evaluating the accuracy of C- and X-band weather radars and their application for stream flow simulation, *Journal of Hydroinformatics*, **15**(4), 1121-1136

123. Keller, V.J.D., Tanguy, M., Prosdocimi, I., Terry, J.A., Hitt, O., Cole, S.J., Fry, M., Morris, D.G. and Dixon, H., (2015), CEH-GEAR: 1 km resolution daily and monthly areal rainfall estimates for the UK for hydrological and other applications, *Earth System Science Data*, **7** (1), 143-155

124. Cole, S.J. and Moore, R.J., (2009), Distributed hydrological modelling using weather radar in gauged and ungauged basins, *Advances in Water Resources*, **32** (7). 1107-1120

125. Cranston M.D., Bebbington D.H.O., Cole S.J., Collier C.G., Harrison T., Higginson N., Illingworth A.J., Moore R.J., Neale W., Rennie T., Rico-Ramirez M.A., Sugier J. and Walden C.J., (2012), Inter-agency committee on the hydrological use of weather radar: Eighth report 2010 to 2012, *NERC/Centre for Ecology and Hydrology,* CO4662

126. Zinevich A., Messer H. and Alpert P., (2010), Prediction of heavy rainfall intensity measurement errors using commercial microwave communication links, *Atmospheric Measurement Techniques*, **3**, 1385-1402

127. Thompson R., Illingworth A. and Ovens J., (2011), Emission: a simple new technique to correct rainfall estimates from attenuation due to both the radome and heavy rainfall, *Weather Radar and Hydrology*, Proceedings of the Weather Radar and Hydrology symposium, University of Exeter, 2011

128. Bianchi, B., van Leeuwen, P.J., Hogan R.J. and Berne A., (2013), A variational approach to retrieve rain rate by combining information from rain gauges, radars and microwave links, *Journal of Hydrometeorology*, **14**(6), 1897-1909

129. Shaw E.M., Beven K.J., Chappell N.A. and Lamb R., (2011), Hydrology in practice, *Spon Press*, London

130. Grimmond C.S.B. and Oke T.R., (1999), Aerodynamic properties of urban areas derived from analysis of surface form, *Journal of Applied Meteorology,* **38**(9), 1262-1292

131. Oke T.R., Cleugh H.A., Grimmond S., Schmid H.P. and Roth M., (1989), Evaluation of spatially-averaged fluxes of heat, mass and momentum in the urban boundary layer, *Weather and Climate*, **9**, 14-21

132. Allen R.G., Pereira L.S., Howell T.A. and Jensen M.E., (2011), Evapotranspiration information reporting: 1. Factors governing measurement accuracy, *Agricultural Water Management,* **98**(6), 899-920

133. Ward H.C., Evans J.G. and Grimmond C.S.B., (2013), Multi-season eddy covariance observations of energy, water and carbon fluxes over a suburban area in Swindon, UK. *Atmospheric Chemistry and Physics*, **13**(9), 4645–4666

134. Geli H.M.E., Neale C.M.U., Watts D., Osterberg J., De Bruin H. a. R., Kohsiek, W., and Hipps L. E., (2012), Scintillometer-Based Estimates of Sensible Heat Flux Using Lidar-Derived Surface Roughness, *Journal of Hydrometeorology*, **13**(4), 1317–1331

135. Leopold L.B., (1968), Hydrology for urban land planning – a guidebook on the hydrological effects of urban land use, *US Geological Survey Circular*, **554**

136. Shuster W.D., Bonta J., Thurston H., Warnemuende E. and Smith D.R., (2005), Impacts of impervious surface on watershed hydrology: A review, *Urban Water Journal*, **2**(4), 263-275

137. Sheng J. and Wilson J.P., (2009), Watershed urbanization and changing flood behaviour across the Los Angeles metropolitan region, *Natural Hazards*, **48** (1), 41–57

138. Meierdiercks K.L., Smith J.A., Baeck M.L. and Miller A.J., (2010), Analyses of Urban Drainage Network Structure and its Impact on Hydrologic Response. *JAWRA Journal of the American Water Resources Association*, **46,** 932–943

139. Hollis G.E. and Ovenden J.C., (1988), One year irrigation experiment to assess losses and runoff volume relationships for a residential road in Hertfordshire, England, *Hydrological Processes*, **2**, 61–74

140. Ramier D., Berthier E. and Andrieu H., (2011), The hydrological behaviour of urban streets: long-term observations and modelling of runoff losses and rainfall–runoff transformation, *Hydrological Processes*, **25**, 2161–2178

141. Ragab R., Bromley J., Rosier P., Cooper J.D. and Gash J.H.C., (2003), Experimental study of water fluxes in a residential area: 1. Rainfall, roof runoff and evaporation: the effect of slope and aspect, *Hydrological Processes*, **17**, 2409–2422

142. Muňoz-Carpena R., Regalado C.M., Alvarez-Benedi J. and Bartoli F., (2002), Field evaluation of the new Philip-Dunne permeameter for measuring saturated soil conductivity, *Soil Science*, **167**(1), 9-24

143. Lee L.M., Kassim A. and Gofar N., (2011), Performances of two instrumented laboratory models for the study of rainfall infiltration into unsaturated soils, *Engineering Geology*, **117**(1-2), 78-89

144. Chaplot V., Jewitt G. and Lorentz S., (2011), Predicting plot-scale water infiltration using the correlation between soil apparent electrical resistivity and various soil properties, *Physics and Chemistry of the Earth*, **36**(14-15), 1033-1042

145. Finn M.P., Lewis M.D., Bosch D.D., Giraldo M., Yamamoto K., Sullivan D.G., Kincaid R., Luna R., Allam G.K., Kvien C. and Williams M.S., (2011), Remote sensing of soil moisture using airborne hyperspectral data, *Remote Sensing of Soil Moisture*, **48**(4), 522-540

146. World Meteorological Organization, (2010), Manual on stream gauging: Volume I – Fieldwork, *WMO-No. 1044*, Geneva

147. World Meteorological Organization, (1980), Methods of correction for systematic error in point precipitation measurement for operational use, *Operational Hydrology Report*, **21**, Geneva

148. Glasgow H.B., Burkholder J.M., Reed R.E., Lewitus A.J. and Kleinmann J.E., (2004), Real-time remote monitoring of water quality: A review of current applications, and advancements in sensor, telemetry and computing technologies, *Journal of Experimental Marine Biology and Ecology*, **300**(1-2), 409-448

149. Fulton J. and Ostrowski J., (2008), Measuring real-time streamflow using emerging technologies: Radar, hydroacoustics, and the probability concept, *Journal of Hydrology*, **357**, 1-10

150. Davies P.S., (2005), The biological basis of wastewater treatment, http://bartec-benke.nl/media/1000154/thebiologicalbasisofwastewatertreatment.pdf, accessed 12/12/13

151. Sustrasic M., (2009), Wastewater treatment: Understanding the activated sludge process, *American Institute of Chemical Engineers,* http://www.d.umn.edu/~rdavis/courses/che4601/articles/Activated%20Sludge.pdf, accessed 22/11/13

152. Zhang Y., Chen Y., Westerhoff P., Hristovski, K. and Crittenden J.C., (2008), Stability of commercial metal oxide nanoparticles in water, *Water Research*, **42**, (8-9), 2204-2212

153. Snyder S.A., Westerhoff P., Yoon Y. and Sedlak D., (2003), Pharmaceuticals, personal care products and endocrine disruptors in water: Implications for the water quality industry, *Environmental Engineering Science*, **20**(5), 449-469

154. Kay D, Edwards A.C., McDonald A.T., Stapleton C.M., Wyer M and Crowther J, (2007), Catchment microbial dynamics: the emergence of a research agenda, *Progress in Physical Geography,* **31**, pp59-76

155. McGrane S.J., Soulsby C. and Tetzlaff D., (2014), Application of a linear regression model to assess the influence of urbanised areas and grazing pastures on the microbiological quality of rural streams, *Environmental Monitoring and Assessment*, **186**, 7141-7155

156. Paul M.J. and Meyer J.L., (2001), Streams in the urban landscape, *Annual Review of Ecology and Systematics*, **32**, 333-365

157. Hooke R.L., (1999), Spatial distribution of human geomorphic activity in the United States: comparison with rivers, *Earth Surface Processes and Landforms*, **24**, 687-692

158. Chin A., (2006), Urban transformation of river landscapes in a global context, *Geomorphology*, **79**, 460-487

159. Konrad C.P., Booth D.B. and Burges S.J., (2005), Effects of urban development in the Puget Lowland, Washington, on interannual streamflow patterns: Consequences for channel form and streambed disturbance, *Water Resources Research*, **41**, W07009, 1-15

160. Allmendinger N.E., Pizzuto J.E., Moglen G.E., and Lewicki M., (2007), A sediment budget for an urbanizing watershed, 1951-1996, Montgomery County, Maryland, U. S. A. *Journal of the American Water Resources Association*, **43**, 1483-1498

161. Warrick J.A. and Rubin D.M., (2007), Suspended-sediment rating curve response to urbanization and wildfire, Santa Ana River, California, *Journal of Geophysical Research*, 112, F02018, 1-15

162. Nilsson C., Reidy C.A., Dynesius M. and Revenga C., (2005), Fragmentation and flow regulation of the world's large river systems, *Science*, 308

163. Ongley E., (1996), Chapter 13 – Sediment Measurements, In *Water Quality monitoring – A practical guide to the design and implementation of freshwater quality studies and monitoring programmes,* Bartram J. and Ballance R., (eds), United Nations Environment Programme and the World Health Organization publication

164. Emmett W., (1980), A Field calibration of the sediment-trapping characteristics of the Helley-Smith bedload sampler, *Geological survey professional paper*, 1139

165. Wall G.R., Nystrom E.A. and Litten S., (2006), Use of an ADCP to compute Suspended Sediment Discharge in the tidal Hudson River, New York, *Scientific Investigations Report 2006-5055,* USGS

166. Guerrero M., Szupiany R.N. and Amsler M., (2011), Comparison of acoustic backscattering techniques for suspended sediments investigation, *Flow Measurement and Instrumentation*, 22(5), 392–401

167. Nord G., Gallart F., Gratiot N., Soler M., Reid I., Vachtman D., Latron J., Martin-Vide J.P. and Laronne J.B., (2014), Applicability of acoustic Doppler devices for flow velocity measurements and discharge estimation in flows with sediment transport, *Journal of Hydrology*, **509**, 504-518

168. Glasgow H.B., Burkholder J.M., Reed R.E., Lewitus A.J. and Kleinmann J.E., (2004), Real-time remote monitoring of water quality: A review of current applications, and advancements in sensor, telemetry and computing technologies, *Journal of Experimental Marine Biology and Ecology*, **300**(1-2), 409-448

169. Hunter, P.D., Tyler, A.N., Carvalho, L., Codd, G.A. and Maberly, S.C., (2010), Hyperspectral remote sensing of cyanobacterial pigments as indicators for cell populations and toxins in eutrophic lakes, *Remote Sensing of the Environment*, **114**, 2705-2718

170. Read, D.S., Gweon, H.S., Bowes, M.J., Newbold, L.K., Field, D., Bailey, M.J. and Griffiths, R.I., (2015), Catchment-scale biogeography of riverine bacterioplankton, *The ISME Journal*, **9**, 516-526

171. Stumm-Zollinger E. and Fair G.M., (1965), Biodegradation of steroid hormones, *Journal (Water Pollution Control Federation)*, **37**(11), 1506-1510

172. Viglino L., Aboulfadl K., Mahvelat A.D., Prevost M. and Suave S., (2008), On-line solid phase extraction and liquid chromatography/tandem mass spectrometry to quantify pharmaceuticals, pesticides and some metabolites in wastewater, *Journal of Environmental Monitoring*, **10**(4), 482-489

173. Cahill J.D., Furlong E.T., Burkhardt M.R., Kolpin D. and Anderson L.G., (2004), Determination of pharmaceutical compounds in surface- and ground-water samples by solid phase extraction and high-performance liquid chromatography-electrospray ionization mass spectrometry, *Journal of Chromatography A*, **1041**(1-2), 171-180

174. Vrana B., Allan I.J., Greenwood R., Mills G.A., Dominiak E., Svensson K., Knutsson J. and Morrison G., (2005), Passive sampling techniques for monitoring pollutants in water. *TrAC Trends Analytical Chemistry*, **24**, 845-868

175. Booij K., Smedes F. and van Weerlee E.M., (2002), Spiking of performance reference compounds in low density polyethylene and silicone passive water samplers, *Chemosphere*, **46**(8), 1157-1161

176. Kaserzon S.L., Hawker D.W., Booij K., O'Brien D.S., Kennedy K., Vermeirssen E.L.M. and Mueller J.F., (2014), Passive sampling of perflourinated chemicals in water: in-situ calibration, *Environmental Pollution*, **186**, 98-103

177. Pinto, U. and Maheshwari, B., (2014), A framework for assessing river health in peri-urban landscapes, *Ecohydrology and Hydrobiology*, **14**, 121-131

178. Alvarez D.A., Petty J.D., Huckins J.N., Jones-Lepp T.L., Getting D.T., Goddard J.P. and Manahan S.E., (2004), Development of passive, in-situ, integrative sampler for hydrophilic organic contaminants in aquatic environments, *Environmental Toxicology and Chemistry*, **23**(7), 1640-1648

179. EEA (2012): European waters – assessment of status and pressures. EEA report 8/2012.

180. Birk, S.W., Bonne, A., Borja, S., Brucet, A., Courrat, S., Poikane, A., Solimini A., van de Bund, W., Zampoukas, N. and Hering, D., (2012), Three hundred ways to assess Europe's surface waters: An almost complete overview of biological methods to implement the Water Framework Directive, *Ecological Indicators*, **18**, 31-41

181. Lu D., Moran E. and Hetrick S., (2011), Detection of impervious surface change with multitemporal Landsat images in an urban-rural frontier, *ISPRS Journal of Photogrammetry and Remote Sensing,* **66**(3), 298-306

182. Irons, J.R., Dywer, J.L. and Barsi, J.A., (2012), The next Landsat satellite: The Landsat Data Continuity Mission, *NASA Publications*, **61**

183. Novack T., Esch T., Kux H. and Stilla U., (2011), Machine learned comparison between Worldview-2 and Quickbird-2 simulated imagery regarding object based urban land cover classification, *Remote Sensing*, **3**, 2263-2282

184. Pu R. and Landry S., (2012), A comparative analysis of high spatial resolution IKONOS and Worldview-2 imagery for mapping urban tree species, *Remote Sensing of Environment*, **124**, 516-533

185. GeoDigital©, (2014), LiDAR Maps, http://www.geodigital.com, accessed 08/07/2014

186. Roth A., (2003), TerraSar-X: A new perspective for scientific use of high-resolution spaceborne SAR data, *Proceedings of remote sensing and data fusion over urban areas, 2003, 2ⁿᵈ GRSS/ISPRS Joint Workshop*, Berlin, Germany

187. Krajewski W.F., Villarini G. and Smith J.A., (2010), Radar-rainfall uncertainties: Where are We after Thirty Years of Effort?, *Bulletin of the American Meteorological Society,* **91**(1), 87-94

188. HR Wallingford, (2015), ARC-BOAT, http://www.hrwallingford.com/expertise/arc-boat, [accessed 06/10/15]

189. Bailly E., Levi Y. and Karolak S., (2013), Calibration and field evaluation of polar organic chemical integrative sampler (POCIS) for monitoring pharmaceuticals in hospital wastewater, *Environmental Pollution*, **174**, 100-105

190. Hjelmfelt, A., Jr. (1991). Investigation of Curve Number Procedure. *Journal of Hydraulic Engineering*, **117**(6), 725-737

191. Alley, W.M., and Smith, P.E., (1982), Distributed routing rainfall-runoff model version II: U.S. Geological Survey Open-File, Report 82-344

192. Bicknell, B.R., J.C. Imhoff, J.L. Kittle Jr., T.H. Jobes, and A.S. Donigian, Jr. 2001. Hydrological Simulation Program - Fortran (HSPF). User's Manual for Release 12. U.S. EPA National Exposure Research Laboratory, Athens, GA, in cooperation with U.S. Geological Survey, Water Resources Division, Reston, VA

193. Metcalfe, P., Beven, K. and Freer, J., (2015), Dynamic TOPMODEL: A new implementation into R and its sensitivity to time and space steps, *Environmental Modelling and Software*, **72**, 155-172

194. Huber, W.C. and Dickinson, R.E., (1988), Stormwater Management Model (SWMM) Version 4: User's manual, http://eng.odu.edu/cee/resources/model/mbin/swmm/swmm_1.pdf, [accessed 06/10/15]

195. Mikkelsen, P.S., Madsen, H., Arnbjerg-Nielsen, K., Rosbjerg, D. and Harrmoes, P., (2005), Selection of regional historical rainfall time series as input to urban drainage simulation at ungauged locations, *Atmospheric Research*, **77**(1–4), 4–17

196. Computational Hydraulics International, (2015), PCSWMM: Spatial decision support for EPA SWMM5 stormwater, wastewater and watershed modelling, http://www.chiwater.com/Software/PCSWMM/, [accessed 06/10/15]

197. Streeter H.W. and Phelps E.B., (1925), A study of the pollution and natural purification of the Ohio River, III: Factors concerned in the phenomena of oxidation and reaeration, U.S. Public Health Service, Bulletin 146

198. Thomann R.V., (1965), Recent results from a mathematical model of water pollution control in the Delaware estuary, *Water Resources Research*, **1**(3), 349-359

199. Skaggs R.W., (1977), Evaluation of drainage-water table control systems using a water management model, In *Proceedings of the 3rd National Drainage Symposium*, 61-68. ASAE Publication, St Joseph, Michigan, USA.

200. Ambrose Jr, R.B. and Wool, T.A., (2009), WASP7 stream transport-model theory and user's guide: supplement to water quality analysis simulation program (WASP) user documentation, http://nepis.epa.gov/Adobe/PDF/P1005O7C.PDF, [accessed 06/10/15]

201. Abbott M.B., Bathurst J.C., Cunge J.A., O'Connell P.E. and Rasmussen J., (1986), An introduction to the European Hydrological System – Systeme Hydrologique Europeen, "SHE", 1: History and philosophy of a physically-based, distributed modelling system, *Journal of Hydrology*, **87**(1-2), 45-59

202. Centre for Ecology and Hydrology, (2014), 'The quick guide to QUESTOR', http://www.ceh.ac.uk/products/software/documents/questorguidenew.pdf, accessed 25/06/2014

203. United States Environmental Protection Agency, (2014), http://epa.gov/athens/wwqtsc/QUAL2K.pdf, accessed 25/06/14

**Figure captions**


Figure 1: A typology of integration for urban water models (a concept adopted from Bach et al. (2014)[12]: Figure 2) comprising four tiers of increasingly broad integration: 1. Integrated component based models 2. Integrated urban drainage models/Integrated water supply models 3. Integrated urban water cycle models 4. Integrated urban water system models. The scope of the POLLCURB case-study model is indicated on the diagram with grey ellipses; and the position across these tiers of some of the models/EDSS cited in the text are also indicated in italics

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

**Tables**

**Table 1:** Chronological evolution of monitoring techniques used within urban hydrological studies

| Variable | Decade | Monitoring Advances | Examples/Specification | References |
|---|---|---|---|---|
| **Land Cover/Land Use** | 1910s | Aerial photography | Sub-meter resolution maybe manually or automatically analysed – costly as obtained to request with no regular coverage | 82 |
| | 1970s | Landsat 1-8 (including ETM$^+$) | Broad land cover and change detection up to 15m panchromatic (pan) resolution | 181 & 182 |
| | 2000s | QUICKBIRD-2 | High resolution (up to 0.64m pan resolution) land cover/change to internal urban scale | 183 |
| | 2000s | WORLDVIEW-2 | Highest resolution commercially available (0.5m pan resolution) land cover/change | 184 & 185 |
| **Topography** | Historical | Surveys and Elevation Maps | | |
| | 1980s | Airborne LiDAR | e.g., GeoDigital TerraPoint | 185 |
| **Impervious Fraction (%)** | 1970s | Landsat 1-8 (including ETM$^+$) | % urban pixel for ~30m resolution | 181; 182 |
| | 1980s | Optical and LIDAR | | |
| | 2000s | Interferometric SAR (InSAR) | e.g., TerraSar-X | 186 |
| **Rainfall** | Historical | Collection bucket raingauges | Lumped volumetric measurement | |

| | | | | |
|---|---|---|---|---|
| *Point Measurements* | 1960s | Tipping bucket gauges | e.g., ASOS | |
| | 2000s | Optical and acoustic gauges | e.g. HYDREON RG-11 | |
| *Areal averaging* | 1950s | Radar | Advances from C to X band | 187 |
| | 2010s | Microwave tomography | Signal attenuation – mobile networks | 126 |

**Table 1 (Cont):** Evolution of monitoring techniques applied within hydroclimatic studies in the urban environment

| | | | | |
|---|---|---|---|---|
| **Runoff** | Historical | Velocity-area discharge | Most common technique globally (c.90%) | 135 |
| | 2000s | Ultrasonic and Radar flow gauges | e.g., ADCP and Vegapuls | 146 |
| | 2010s | Remote ADCP monitoring | ArcBOAT® - remote controlled ADCP logger-mounted | 188 |
| **Water Quality** | Historical | Manual sampling and laboratory analysis | Manual Sampling and targeted laboratory analysis | |
| | 1960s | Autosampling chambers | Auto-samplers (e.g., ISCO 4700) | 135 |
| | 2000s | Passive sampling | Passive water quality samplers (e.g., POCIS) | 174 & 189 |
| | 2000s | Real-time remote monitoring (RTRM) | Multiparameter sondes (e.g., YSI 6600; DataSonde IV and HydroLab) and remote telemetry | 146 & 148 |

**Table 2:** Example models that are commonly applied in urban runoff analyses, including both urban drainage and rainfall-runoff models

| Model | Model Type | Description | References |
|---|---|---|---|
| SCS | Simple, empirical urban rainfall-runoff model | Statistical method for calculating runoff based on soil type, antecedent soil moisture conditions and land use for a given area. | 190 |
| DR$_3$M | Distributed hydrologic and hydraulic model | Watershed model that routes water through branched sewer networks and into channels, incorporating soil moisture, overland flow and storages. | 191 |
| HSPF (aka Stanford Watershed Model) | Physically based process model | Uses continuous rainfall and associated meteorological metrics to calculate streamflow hydrographs and water quality with urban parameters. | 192 |
| Dynamic TOPMODEL | Distributed land-surface and hydrologic model | Newest version of TOPMODEL, implemented into R, encompassing land-use processes, rainfall-runoff at distributed scale. | 193 |
| USEPA SWMM5 | Semi-distributed hydrologic and hydraulic model | Dynamic rainfall-runoff model that operates under continuous or event-based simulation of quantity and quality in both surface and pipe network systems. | 194 |
| MIKE-URBAN | Semi-distributed hydrologic and hydraulic model | GIS-based integrated model that incorporates SWMM and EPANET. Includes pipe-flow, rainfall-runoff and water quality transformation and transportation dynamics. | 195 |
| CITYDRAIN | Integrated hydrologic and WWTP model system | CITYDRAIN is a systems dynamic model that represents subsystems of the urban landscape, including sewers, receiving waters and WWTP processes. | 28 |
| SIMBA®6 | Integrated hydrologic and WWTP model system | Complex model that simulates interactions between runoff, WWTP, receiving water quality – includes detailed representation of WWTP. | 26 |
| PCSWMM | Semi-distributed hydrologic and hydraulic model | Couples the powerful USEPA SWMM5 model with GIS software to enable streamlined GUI operation of hydrological, hydraulic and water quality simulation. | 196 |

**Table 3:** Chronological evolution of water quality models commonly applied in the urban landscape

| Model | Model Type | Description | References |
|---|---|---|---|
| Streeter-Phelps Model | BOD/DO | 1D model for simulation of untreated effluent in riverine and estuarine environments. Owing to non-computer operation, the S-P model relied on linear kinetics and was applied to steady-state receiving waters. | 197 |
| Thomann's Expanded Streeter-Phelps Model | BOD/DO | Expansion of Streeter-Phelps model to incorporate multi-segment river systems with multiple contributions to oxygen development and use, including photosynthesis and sludge aeration. | 198 |
| DRAINMOD | In-stream Nutrient (N) Transport | An early nutrient model that sought to simulate transport and transformation of nitrogen in both shallow soils and in-stream environments. | 199 |
| WASP7 | Dynamic in-stream flow and water quality model | Up to 3-D modelling of a suite of contaminants in the river, including metals, nutrients, VOCs, PCBs and sediment. | 200 |
| SHE | In-stream and groundwater flow and water quality | A physically-based, distributed catchment scale model which functions as a valuable decision support tool for a suite of hydrological contaminants. | 201 |
| QUESTOR | In-stream flow and water quality model | A flexible framework that can represent both flow and water quality within river reaches, incorporating multiple point sources and tributaries within a stream network. | 202 |
| QUAL2K | In-stream flow and water quality model | Building on the earlier QUAL2E model, this is a 1D model that simulates nitrogenous and carbonaceous BOD speciation, pH, sediment fluxes and pathogen dynamics. | 203 |

**Related Articles**

| DOI | Article title |
|---|---|
| 10.1002/wat2.1038 | Toward a theoretical framework for integrated modeling of hydrological change |
| 10.1002/wat2.1007 | Urban rivers: novel ecosystems, new challenges |
| 10.1002/wat2.1001 | On the importance of very long-term water quality records |

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

| Water quality | Autosampling | | | Real-time remote monitoring | | **Key monitoring developments** |

Runoff — Ultrasonics and Radar — Acoustic Doppler Current Profile

Landuse — Landsat — Lidar

Advent of dynamic modelling — Integrated urban drainage models — Interdisciplinary integration (e.g. ecology, urban growth) — **Modelling integration**

Geographic Information Systems platforms

Water Framework Directive — **Other key drivers**

1970s   1980s   1990s   2000s   2010s

338x190mm (96 x 96 DPI)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
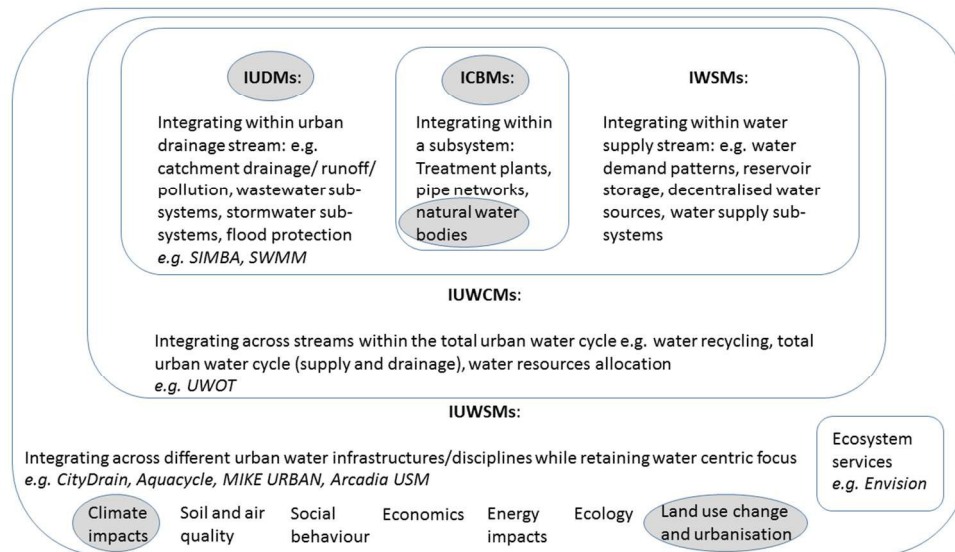51
52
53
54
55
56
57
58
59
60
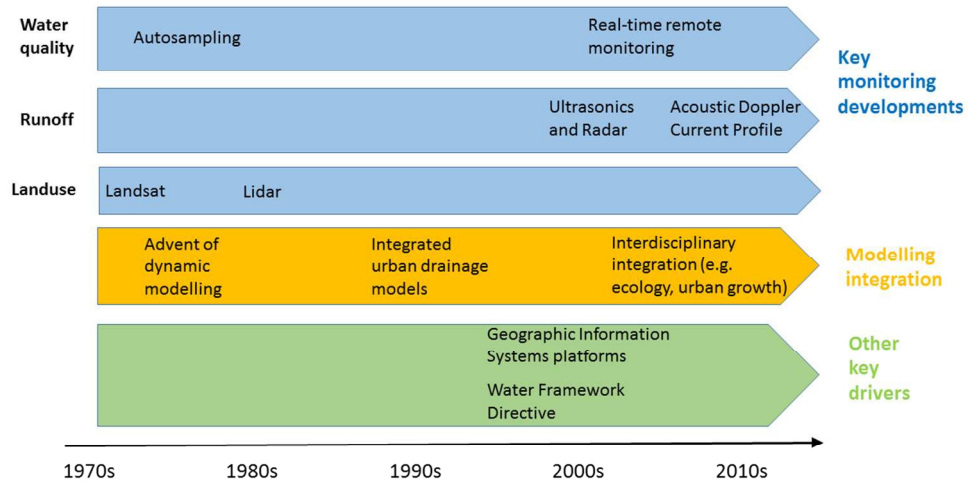
Figure 1: A typology of integration for urban water models (a concept adopted from Bach et al. (2014): Figure 2) comprising four tiers of increasingly broad integration: 1. Integrated component based models 2. Integrated urban drainage models/Integrated water supply models 3. Integrated urban water cycle models 4. Integrated urban water system models. The scope of the POLLCURB case-study model is indicated on the diagram with grey ellipses; and the position across these tiers of some of the models/EDSS cited in the text are also indicated in italics
338x190mm (96 x 96 DPI)