Environmental Modelling & Software 54 (2014) 88–107

Contents lists available at ScienceDirect

Environmental Modelling & Software

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

Review

# A critical review of integrated urban water modelling – Urban drainage and beyond

Peter M. Bach [a,*], Wolfgang Rauch [b], Peter S. Mikkelsen [c], David T. McCarthy [a], Ana Deletic [a]

[a] Monash Water for Liveability, Department of Civil Engineering, Building 60, Monash University, Clayton, 3800 VIC, Australia
[b] Unit of Environmental Engineering, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria
[c] Department of Environmental Engineering, DTU Environment, Technical University of Denmark, Miljøvej, Building 113, 2800Kgs., Lyngby, Denmark

ARTICLE INFO

*Article history:*
Received 11 September 2013
Received in revised form
5 December 2013
Accepted 22 December 2013
Available online 19 January 2014

*Keywords:*
Decision support
Integrated urban water management (IUWM)
Inter-disciplinary modelling
Model integration
Uncertainty
Urban water systems

ABSTRACT

Modelling interactions in urban drainage, water supply and broader integrated urban water systems has been conceptually and logistically challenging as evidenced in a diverse body of literature, found to be confusing and intimidating to new researchers. This review consolidates thirty years of research (initially driven by interest in urban drainage modelling) and critically reflects upon integrated modelling in the scope of urban water systems. We propose a typology to classify integrated urban water system models at one of four 'degrees of integration' (followed by its exemplification). Key considerations (e.g. data issues, model structure, computational and integration-related aspects), common methodology for model development (through a systems approach), calibration/optimisation and uncertainty are discussed, placing importance on pragmatism and parsimony. Integrated urban water models should focus more on addressing interplay between social/economical and biophysical/technical issues, while its encompassing software should become more user-friendly. Possible future directions include exploring uncertainties and broader participatory modelling.



## 1. Introduction

Today, more than half of the world's population has migrated to urban areas (United Nations, 2001). The ever-increasing stress that this poses on the urban infrastructure and utility provision has compelled governments and institutions to find new ways to adapt. Researchers and practitioners are beginning to recognise the importance of multiple benefit solutions, multi- and inter-disciplinary work and broad perspectives (e.g. Fratini et al., 2012). Water management paradigms have greatly evolved since the birth of cities, from the most fundamental objective of a secure water supply to sanitation, flood protection and a *Water Cycle City* (Brown et al., 2009). This transition is accompanied by increasing acknowledgement of the inherent complexity of the urban environment. As such, we are moving towards combined management of the various urban water system *components* (i.e. water treatment, distribution, sewerage and storm drainage, wastewater treatment, environmental compartments) and have become considerate of their interactions and feedbacks: the concept known as 'integration'. The principles of Integrated Urban Water Management (IUWM) (Vlachos et al., 2001; Mitchell, 2004) and the vision of a Water Sensitive City (Wong and Brown, 2009) have emerged from recurring dilemmas that we have perceived in previous decades, such as persistent floods and droughts, degradation of natural waterway health at the expense of urban growth, and frequent upgrades and rehabilitation of existing centralised water infrastructure required without end.

Traditional management of urban water systems considers all components independent of each other in a fragmented manner (e.g. Rauch et al., 2005). Due to its ongoing success in delivering water supply and improving public health, there is unwillingness to acknowledge and improve our limited understanding of feedbacks, non-linearity and time delays – all of which alter the nature and state of systems – alongside a diversifying water management agenda and changing societal perceptions (Pahl-Wostl, 2007). Global challenges and the framing of additional water management objectives (e.g. setting water recycling targets or delivering liveable city through stream protection, micro-climate improvements and amenity improvements using green water infrastructure) have now limited the success of single-objective optimisation (Erbe and Schütze, 2005). As such, the need to accept the intrinsic complexity of our environment instead of continuously simplifying

* Corresponding author. Tel.: +61 4 3217 5283.
*E-mail addresses:* peter.bach@monash.edu, peterbach@gmail.com (P.M. Bach).

1364-8152/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2013.12.018

and isolating the problems (Beck, 1976) is slowly being recognised. We now strive to adopt an integrated approach to urban water systems management that: (1) considers all parts, or components, of the system, (2) involves water conservation and diverse fit-for-purpose water supplies, (3) works at a range of scales (both central and decentralised) and (4) allows establishment of links with other environmental cycles (e.g. energy and nutrients) (Mitchell, 2004; Brown et al., 2009).

Modelling the urban water system has progressed along the same path as management. Countless software packages are available for different parts of the urban water system, each developed to the greatest detail, but excluding dynamic interactions with the surrounding environment. The shift towards IUWM has, however, been reflected in model development, with integration seen as necessary to analyse the whole system without neglecting important physical phenomena in each component and their interactions (Gujer et al., 1982; Durchschlag et al., 1992; Holzer and Krebs, 1998; Chocat et al., 2001; Harremoës, 2002; Meirlaen et al., 2002; Muschalla, 2008; Candela et al., 2012). Institutional barriers (Brown, 2008), expensive data requirements (Vanrolleghem et al., 1999; Rauch et al., 2005) and limitations in computational hardware (Vanrolleghem et al., 2005b) have greatly challenged integrated modelling of urban water systems. With rapid advancements in technology, improving collaboration among water management authorities and researchers, the field has gained momentum in recent years. Yet another roadblock has been the shortcomings of traditional single-system modelling approaches, such as those demonstrated by Box and Draper (1987), Wagener et al. (2004). We frequently apply most, if not all, of our pre-conceived and widely accepted modelling principles, which we will henceforth refer to as '*classical modelling*', to integrated models and consequently suffer from repercussions of poor performance and unwieldy models (Ashley et al., 1999; Freni et al., 2008). The urban water system is very complex and whilst integration can simply be accomplished by combining individual model packages, achieving an overall sound system description requires not only knowledge of the sub-models, but also their interactions. Fundamental complexity theory would describe this in terms of the 'big picture' that cannot be seen simply as the sum of its parts (De Haan, 2006; Schmitt and Huber, 2006; Mitchell et al., 2007; Pahl-Wostl, 2007). Consequently, we encounter complexity on two possible fronts: (1) either through the introduction of additional behaviours into the model through interactions between components or (2) new emergent features that result from combining interacting sub-models, which we need to make sense of to ensure that our models are adequate representations of the real system. However, as we do not have a complete understanding of all possible interactions between various processes within the urban water system 'integration' should be regarded as the pathway for achieving model objectives rather than the objective itself. With this comes a suite of new modelling approaches.

Greater focus on interactions between overall system components has been frequently stressed as the primary characteristic of integrated models (Schütze et al., 1999; Meirlaen et al., 2002; Rauch et al., 2002a; Olsson and Jeppsson, 2006). Yet, decades have passed and we still lack sound knowledge on feedback loops in urban water systems. Moreover, we are limited in our choices of suitable algorithms or sub-models for integration due to (1) their excessive complexity (noted by Harremoës and Rauch, 1996; Muschalla, 2008 among others), (2) different aims at their time of development (Rauch et al., 1998) (integrating these models is therefore also an integration of objectives as was highlighted by Schütze et al., 1999) and (3) incompatible parameters and variables (e.g. different primary pollutants between models, different conceptualisation) – an ongoing issue as pointed out by Fronteau et al. (1997) and Erbe et al. (2002). Fortunately, research is addressing these and many other challenges, to make integrated approaches to systems analysis more feasible.

Over the past few decades, a growing and diverse body of integrated urban water modelling literature has emerged, uniquely influenced by historical development in different parts of the world, fraught with linguistic uncertainty (i.e. confusion with semantics due to a lack of transparent terminology as there have been contributions from a variety of academic disciplines) and with localised schools of thought. Consequently, we feel that researchers (particularly those not experienced in this field) delving into this literature may find it lacking clarity and confusing. At the same time, we perceive adoption of integrated models in practice appears to progress slowly. Even though many barriers against adoption have been identified 20 years ago (Lijklema et al., 1993), this perceived slow uptake could be attributed to difficulties of overcoming some of these barriers as well as new emergent challenges, which are documented, yet sprawled across the literature. As such, there is an urgent need for better order in this modelling discipline and an assessment of where these models may find value in practice, so that constructive changes in the current research trends can be made. We aim to clear some of the confusion across the literature in this review by approaching the field from the following aspects: (1) understanding the historical context of integrated modelling of urban water systems, (2) clarifying linguistic uncertainty by looking at how extensive the 'integration' term can be and has been used, (3) making clear distinctions between integrated and classical modelling and where overlaps can be identified, (4) the state of adoption of integrated urban water models (referred to in this review as the entire collection of integrated models of urban water systems regardless of scope and complexity) in research and practice and (5) their likely future role. This review also aims to establish a platform for communication across many disciplines that have been working in this field.

This critical review focuses only on urban water systems. Any mention of 'integration' therefore implies these systems unless otherwise mentioned. A lot of the reviewed literature is, furthermore, centred on the urban drainage systems (e.g. focussing on collection of both sewage and stormwater and their treatment) since it was historically the focal point of 'integrated modelling' in much of the early urban water literature. The authors, however, find many concepts developed in this sector useful for extending the integration principle beyond the urban drainage system, which is reflected in the title of the paper. An attempt will therefore be made to generalise many of these concepts to other parts of the urban water system where required. The authors are aware of the extensive body of literature on integrated river basin modelling and integrated ecological models and will draw upon these in the discussion where deemed relevant.

## 2. Brief historical overview

The first notable study that aimed to develop a combined understanding of several components of an urban water system was conducted in the late 1970s in the Glatt Valley, Switzerland (Gujer et al., 1982). Whilst this study did not specifically report any modelling results, it recognised the impact of wet weather events on secondary wastewater treatment processes and the temporal patterns of pollutant loads at every point of the integrated drainage, treatment and receiving water body systems. Acknowledging the lack of complex studies at the time, the authors promoted widespread adoption of integrated approaches. This statement has had far-reaching impact, evidenced by some of the most influential and highly-cited papers on the topic, e.g. Schütze et al. (1999),