Integrated Urban Water Modelling – Past, Present, and Future

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Abstract

The technical and practical challenges of implementing the Integrated Urban Water Management paradigm provide the setting for the IUWM modelling review presented in this paper, which presents the findings of a review of the current "state-of-the-art" in IUWM modelling. It was found that in recent years there have been significant advances in the development of IUWM modelling tools, and a growing body of knowledge of the scientific and technical challenges of IUWM modelling. However, there are still sizable gaps in modelling capacity and in the knowledge underpinning the models, which require concerted research effort to adequately address. This paper discusses the background, features, and shortcomings of current IUWM modelling, and proposes directions for future research.

Introduction

Recent years have seen greatly increased interest in Integrated Urban Water Management (IUWM), which takes a comprehensive approach to urban water services. This approach views water supply, drainage and sanitation as components of an integrated total water cycle, rather than largely independent hydraulic services. Integrating and diversifying urban water systems increases their complexity, possibly creating new attributes and behaviours. Better understanding of these new and complex systems requires a significant change in the approach to simulation modelling of urban water infrastructure. We need to move away from spatial lumping and time-averaged behaviour towards a more detailed and responsive integrated structure – Integrated Urban Water Modelling. This paper briefly reviews the history of Integrated Urban Water Modelling, presents a recent review of current models, and draws on the findings of the review to discuss future modelling needs and directions.

Background

According to Rauch et al. (2002), the concept of integrated modelling was proposed in the 1970s (Beck, 1976) and the first integrated urban drainage model was applied in the 1980s (Gujer et al., 1982), but it was not until the early 1990's that the concept of integrated modelling began to be more widely adopted. In places such as in Europe the focus was on integrated urban drainage modelling (Schütze et al. 1996). In Australia, integration of urban design and modelling was promoted by numerous people (for example Stewardson et al (1995a & b), Mouritz (1996), Mitchell et al (1998) and Coombes and Kuczera (2002)), with the focus upon simulating the whole urban water system. So, since the 1990's the approach in Australia has largely differed from overseas, extending the scope beyond urban drainage modelling to include wider aspects of the urban water system, particularly urban water supply.

Schütze et al (1996) noted that many of the integrated modelling approaches for urban wastewater systems (sewer system, treatment plant and receiving water) simulated different components (or sub-systems) in a sequential manner. This sequential or loosely coupled modelling approach has a number of shortcomings, including the assumption that the processes being modelled are all unidirectional and flow paths are configured in a tree-like structure, that is, they proceed downstream with no feedback loops of either information or water fluxes (Schütze et al. 1996; Rauch et al. 2002). Schmitt and Huber (2005) promote instead the use of simultaneous modelling, which requires the tight coupling of the sub-system models so that they are synchronized, passing data back and forth at each time step. These authors considered that no single model could cover all the sub-systems adequately, and concluded that there was no alternative to the tightly coupled modelling approach, using IT frameworks that efficiently interface between the various component models. This is the approach which the HarmonIT project took when developing the Open Modelling Interface (OpenMI) for integrated catchment management applications (Gregersen and Blind 2004). Gregersen and Blind (2004) note though that there are "complications in satisfying the needs for iteration, buffering and feedback loops".

The representation of feedback loops is central to the modelling of IUWM systems due to the need to simulate the reuse/recycling of rainwater, stormwater and wastewater at lot, local and regional scale, meaning that flow paths are not configured in a tree structure. Therefore, despite the preference in the European literature for the coupling of models to represent integrated water systems, it may not be ideal for IUWM applications, particularly those which include water supply, such as is the focus in Australia.

Model Review

To assess the current status of IUWM modelling and determine the significant research gaps that are still to be addressed, the Urban Water Management Project of the eWater Cooperative Research Centre carried out an extensive review of available models. The review concentrated on models whose system boundaries represent water supply, stormwater and wastewater services within a single computational framework, either through the coupling of sub-component models or as a single comprehensive model. One of the ultimate objectives of the broader Urban Program in eWater CRC is to develop more seamlessly integrated modelling tools for use by both researchers and the water industry.

The review was conducted in two stages. The first stage located and assessed 65 models from around the world that are used within the field of IUWM. A standard assessment questionnaire format was used for this first pass or 'screening' review stage, with an emphasis on breadth of coverage rather than detail. A purpose built database was used to compile the results and provide an ongoing information resource for the research team. The models reviewed in the first stage were: AISUWRS, Aquacycle, AQUALM, BASINS, BASIX, CANOE, CITY DRAIN, DRAINS, E2, EnviroPro Designer, EPANET 2, FLUX for Septic Trenches, Home Water Investigator, House Water Expert, HSPF - FORTRAN, Hydro Planner, ILSAX, InfoWorks CS, InfoWorks WS, Integrated Waterway Assessment Framework, IQQM, Krakatoa, MEDLI, MIKE URBAN, MODFLOW, MODHMS, MUSIC, PARMS Suite, PURRS, QUAL2E, RAFTS, Rainwater TANK, RAP, REALM, REBEKA, RORB, RRL including SymHyd, SEEPW, SEWSYS, SHETRAN, SMHI - BIOLA model, SLAMM, STORM, StormNET, SWIMv2, StormSHED, Switch (v1 and v2), SWMM, TAWS, TRENCH v3.0, UGROW, UrbanCycle, UVQ, URBS (Australia), URBS (France), URWARE, WARMF, Water CAD, Sewer CAD, StormCAD, WaterCress, WATHNET, WEAP, WSAA SDP, and WUFS.

Table 1: Overview of the models reviewed in Stage 2

Model	Description	Availability	Reference
Mike Urban	A detailed tool using a sub-daily time step suitable for the design of essentially conventional urban water systems using reticulated water. Links existing resource, distribution, demand, and runoff models. Detailed hydraulic design capability.	Purchased from DHI, requiring a licence	www. dhisoftware.com
Hydro Planner	Uses daily/monthly data input and a daily time step, and is attuned mainly to larger scale whole water supply system analysis. Links existing resource, distribution, demand, and runoff models. Can handle any user-defined once-through water source. Limited flow routing and hydraulics. Calculates water quality in stormwater stream. Model still under development.	Contact CSIRO Land and Water	Maheepala et al (2005)
WaterCress	Daily water balance model of the total urban water cycle, operating at the single lot to regional scale. Water sources are reticulated water, rainwater, stormwater, greywater, wastewater, and groundwater. Uses a range of graded quality codes to approximately track water quality. Limited flow routing. Sub-daily time steps under development.	Freeware from www.waterselect. com.au	Clark et al (2002)
Aquacycle	Daily water balance of the total urban water cycle using nested lot, cluster, and catchment scales. Water sources are reticulated water, rainwater, stormwater, greywater, wastewater, and groundwater. No flow routing or hydraulics.	Freeware from www.toolkit.au	Mitchell et al. (2001)
UVQ	Daily water balance of the total urban water cycle using nested lot, cluster, and catchment scales. Water sources are reticulated water, rainwater, stormwater, greywater, wastewater, and groundwater. Accounts for the flux of a range of urban pollutants from source to sink throughout the water cycle. No flow routing or hydraulics. Builds upon the earlier Aquacycle model.	Contact CSIRO Land and Water	Mitchell and Diaper (2005)
Krakatoa	Daily or multi-day water and contaminant balance of the total urban water cycle, using a spatially distributed grid layout. Water sources are reticulated water, rainwater, stormwater, greywater, wastewater, and home delivery. No flow routing or hydraulics. Simple water quality generation, tracking, and treatment. Some capacity to model land use change during a run.	Not publicly available	Stewardson et al (1995a)
UrbanCycle	Water balance model of the total urban water cycle using a sub-daily time step, operating at the single lot to cluster scale. Water sources are reticulated water, rainwater, stormwater, greywater, and wastewater. Limited flow routing and hydraulics. No water quality modelling included at present.	Contact M. Hardy	Hardy et al (2005)

The second stage of the review involved the shortlisting and more detailed examination of those models which most closely complied with the following criteria:

- covered all aspects of the urban water cycle – water supply, rainwater, stormwater, wastewater and groundwater;
- took an integrated approach to the representation of the urban water system;
- simulated both quantity and quality;
- represented non-traditional approaches to urban water service provision such as rainwater tanks, stormwater harvesting, greywater and wastewater reuse as well as water efficiency;
- were able to represent separate stormwater and wastewater systems (as separate systems are used in Australia), and
- had sufficiently detailed documentation publicly accessible at the time of the review.

Seven models were shortlisted, and are summarised in Table 1. The predominance of Australian models in this list is due in part to the greater number of integrated models developed in Australia compared to elsewhere. IUWM modelling and implementation have been high on the agenda in Australia for several years, due to widespread and prolonged drought conditions, and water stress in many urban areas.

Since this second stage involved a significantly smaller number of models, there was greater opportunity to assess the technical basis of each model and compare and contrast them. A more open ended assessment approach was used, although the results were compiled in a consistent format, providing a balance between rigour and open ended enquiry. The review was based largely on the available documentation, although models were run whenever possible to clarify interpretation and to obtain a feel for the user interface.

It is important to note that the review was based on the capabilities of the models during the period March to August 2006. Hydro Planner, UrbanCycle, PURRS, and possibly other models reviewed in Stage 1 were still under development at that time. PURRS now allows reuse of wastewater/greywater, and it is likely that other aspects of various models will be further developed in future.

Several other models were identified in Stage 1 of the review as offering particular features of interest, despite not covering the whole urban water cycle. Since our interest here is in integrated modelling, these models are not discussed further in this paper.

Review Findings

It was found that in recent years there have been significant advances in the development of IUWM modelling tools, and a growing body of knowledge of the scientific and technical challenges of IUWM modelling. However, there are certain areas in which there are sizable knowledge gaps requiring concerted research effort for them to be adequately addressed.

In many cases the models did not cover the full scope of the urban water cycle with a consistent level of detail, usually having an emphasis on more detailed modelling of certain aspects and more simplistic modelling of the rest of the water cycle, if at all. Areas which tended to be poorly considered included: the handling of temporal and spatial scale and resolution, evaluation of predictive (and input data) uncertainty, representation of existing water infrastructure and the dynamics of change within both an urban area and its urban water system over time (i.e. 10 to 100 year horizon).

Integration

The coupled-models and single-model philosophies noted above are both represented within the short-listed models. Mike Urban and Hydro Planner adopt the philosophy that integration is achieved by creating a computer interface and data exchange functionality to link existing models that simulate separate parts of the water cycle, a first step towards the tightly coupled modelling approach recommended by Schmitt and Huber (2005). The other short-listed models start with a central water balance and distribution system and build outwards to the separate water streams, creating a single model which represents all processes in the urban water system. The review team found that the coupled-models approach provides more detail of the water streams at the expense of seamless integration, while the single-model approach provides superior integration at the expense of peripheral detail.

Spatial and Temporal Representation

The models cover a wide range of spatial scales (Table 2). Spatial resolution increased as spatial scale decreased, with four models – WaterCress, Aquacycle, UVQ, and UrbanCycle – able to disaggregate a single land block into components.

The majority of the seven models use a daily time step. There is an association between spatial and temporal scale, with the larger spatial scale models tending to use monthly or even annual data for one or more inputs. The review highlighted a relative lack of IUWM models able to simulate at sub-daily time steps, particularly hourly or less, with only Mike Urban and UrbanCycle able to model at sub-hourly time steps. This limits the ability to simulate peak flow rates within all the water streams.

Table 2: Coverage of spatial scales

Model	Spatial scale				
	Lot	Neighbourhood	Suburb	Town/city	Region
Mike Urban		✓	✓	✓	✓
Hydro Planner				✓	✓
WaterCress	✓	✓	✓	✓	✓
Aquacycle	✓	✓	✓	✓	
UVQ	✓	✓	✓	✓	
Krakatoa		✓	✓	single catchment	
UrbanCycle	✓	✓	✓		

There is also a lack of ability to represent changes in either the water system or the urban area over time. The exceptions are Hydro Planner's ability to represent changes in water demand over time and Krakatoa's ability to represent land use change. The lack of representation of change over time limits the ability to directly analyse long term water management scenarios which typically have planning horizons of 20 to 50 years.

Climatic input

Hydro Planner, WaterCress and Mike Urban allowed the input of multiple climate files, comprising precipitation and evaporation time series data, whilst Aquacycle, UVQ, Krakatoa and UrbanCycle are only able to use a single climate input file, thereby assuming rainfall and evaporation are uniform over the entire study area. UVQ contains a basic representation of snow accumulation and melting, requiring the input of a temperature time series. UrbanCycle differs from the other models in that it calculates evaporation from temperature input data.

Water Flows

Overall water volumes can be modelled with a reasonable level of accuracy using the daily time step models. But the review highlighted a lack of models suitable for modelling flow rates (sub-daily patterns including peaks) across the whole urban water cycle whilst also representing IUWM features such as rainwater tanks and decentralised wastewater reuse. Mike Urban is able to model detailed flow rates in the water supply, stormwater and wastewater flows in a conventional urban water system only. UrbanCycle is able to model stormwater peak flows with considerable detail but it does not model stormwater base flows and represents the water supply and wastewater components of the urban water cycle in less detail than the stormwater wet weather flows.

Water Quality

Simulation of water quality covers a wide range, from none at all (Aquacycle, UrbanCycle), to a scale of relative water quality levels (WaterCress), to more process-based but still basic water quality algorithms (Krakatoa, UVQ, Hydro Planner). In comparison, Mike Urban has more advanced water quality algorithms. Overall, water quality generation and treatment are modelled in less detail than water flows.

Water Demand

The temporal pattern of water demand is limited by the time step of the models. Mike Urban and UrbanCycle are the two models which can represent diurnal variations in demand. To research the impacts of water efficiency and reuse on peak demands (as well as on peak stormwater and wastewater flow rates), the representation of individual end uses at a sub-daily time scale may be required. Projections of water demand and changing scenarios are rarely addressed. Only Hydro Planner has capabilities in this regard.

Water Supply Sources

The models provide a large degree of freedom in selecting water sources and supply priorities, with the exception of Mike Urban.

Stormwater

Most of the models (except Aquacycle and UrbanCycle) represent stormwater pollutant generation and treatment processes. However, the representation of stormwater treatment systems was not as advanced as current Australian Water Sensitive Urban Design industry standards such as MUSIC (Fletcher et al 2004).

Groundwater

Groundwater was represented in a simple manner in five of the models, and not at all in the current versions of Hydro Planner and UrbanCycle.

Wastewater Treatment

This is perhaps one of the areas in which the models are least satisfactory. Only two of the models represented quantitative wastewater treatment processes in which treatment systems produced treated water of user-defined discharge quality (Krakatoa) or used a percentage-contaminant-reduction approach (UVQ).

Functionality beyond the simulation of water processes

Several issues are not well covered by the short-listed IUWM models, either internally or through linkages to other models, although it is anticipated that these issues will become increasingly important as IUWM analysis becomes more complex. Some of these issues are:

- Uncertainty and/or sensitivity analysis;
- System configuration and option optimisation, and technology selection;
- Non-water aspects including energy, economics and social assessment;
- Ecological response of water bodies to flows and contaminant loads.

There are occasional exceptions: Krakatoa and WaterCress include cost functions and Krakatoa also has a tutorial on social issues relating to IUWM.

There is little in the way of context-sensitive decision support for the user in developing a modelling scenario. While this is understandable in some cases given the original reasons for development, it is likely to pose a significant limitation in the future as IUWM modelling is becoming increasing complex and hence more onerous for users.

Discussion

Many IUWM models have been developed, and between them they cover many useful aspects of current interest, yet at the time of this review there is still no IUWM model which satisfactorily meets the current and future needs of the Australian urban water industry.

The ideal model must handle feedback, since so many forms of urban efficiency and reuse depend on feedback, both of information, and of the water itself. In IUWM, closed loops will be the norm rather than the exception. Short-term feedback appears to be considerably more advanced and more effective in the single-model approach than in the coupled-models approach.

The ideal model must handle variability in demand, at a spatial scale and time step appropriate to the task at hand. Considering first the spatial scale, a cluster of diverse demands does not behave in the same way as a cluster of identical demands each showing mean behaviour. Preliminary simulations using a rainwater tank scenario indicate that a cluster of households with variable roof area and tank volume (coefficient of variation 0.5) has a total cluster yield about 8% less than a cluster of households each with mean roof area and tank volume.

Looking now at the time scale, a long time step does not capture the variability which is known to occur at short time intervals. Given the strong diurnal pattern that is observed in domestic water use (see for example Roberts (2005)), a sub-daily time step will almost certainly be required. Furthermore, factors such as total demand, demographic structure and land use may change with time. Such changes may be built into the model, or approximated using a snapshot approach. We note that many models of both single and coupled types currently use a daily time step, and that changing model parameters during a run is very much the exception rather than the rule.

Having achieved all desirable technical features, the ideal model must still be readily usable by its intended audience. It must be approachable by the informed user (user-friendly), run satisfactorily using data that is available at the great majority of sites, and operate within the resources typically available at a computer workstation. Based on our model review, we believe that achieving all these objectives simultaneously still presents substantial technical and programming challenges. We concur with Rauch et al (2002) where they state that 'it is not the most complex model that is the best one, but the least complex that answers the question reliably'. Nevertheless, our review has shown that much work remains before we can assert that we have answered the question reliably.

Conclusions

As a result of the IUWM model review described here, the review team reached the following conclusions.

- There is at present no single IUWM model which satisfactorily meets the current and future needs of the Australian urban water industry.
- Feedback of information and water is integral to IUWM modelling. Feedback is currently handled much better by single models than coupled models.
- Temporal and spatial resolution requirements of models require further assessment. The expectation is that a sub-daily time step will be necessary.

- Improved and consistent modelling of water quality throughout the urban water cycle is required.
- Variations in layout, dimensions, demand, and user behaviour need to be modelled at the household scale and above. Use of mean values tends to overestimate yield.

Further research is required to address the following:

- Modelling of factors that change with time (demand, demographics, land use, system configuration and capacity, etc.) needs to be further explored.
- Further collection and collation of data sets that can be used to develop, calibrate, and verify IUWM models will be necessary.
- Modelling of functions beyond water quantity and quality (uncertainty, optimisation and decision support, energy, economics, ecological response, and social issues) requires further consideration.
- Model simplicity increases usability and reduces demands on data resources, and hence remains a significant goal despite a degree of conflict with other objectives such as model accuracy.

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