State of the art review of integrated urban water models

Etat de l'art des modèles intégrés de gestion des eaux urbaines

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RESUME

La gestion intégrée des eaux urbaines est plus avancée que la capacité et la fonctionnalité des modèles qui sont utilisés par l'industrie de la gestion d'eau en Australie. Nous avons donc fait un bilan de l'état de l'art de la modélisation de la gestion intégrée de l'eau, afin d'identifier les besoins pour la recherche. Les résultats sont présentés ici. Dans le premier temps nous avons évalué 65 modèles. Dans le deuxième, nous en avons choisi sept à évaluer plus rigoureusement. Les plus grands problèmes que nous avons identifiés étaient la représentation des échelles temporelles et spatiales et aussi le besoin de grandes quantités de données pour le développement, calibrage et validation des modèles.

ABSTRACT

Integrated Urban Water Management (IUWM) practice is well ahead of the scope and functionality of the majority of models used by the urban water industry in Australia. It is timely to review the current state of the art in IUWM modelling and identify priority research and development needs. This paper presents the outcomes of such a review, conducted in two stages. Some 65 models were screened in the first stage, while seven were more rigorously assessed in the second stage. Identified priority areas span computational issues such as spatial and temporal resolution and representation of system dynamics through to the collection of data sets to support model development, calibration and verification.

KEYWORDS

Integration ; modelling ; stormwater ; wastewater ; water supply.

1 INTRODUCTION

A new paradigm of Integrated Urban Water Management (IUWM) has emerged recently, 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, which are located within a broader physical landscape. Integrating and diversifying urban water systems increases their complexity, creating new attributes and behaviours.

This leads to questions about how to represent urban water systems within the computer models that are so frequently used in planning, design and operation of urban water systems. Therefore, IUWM requires a significant change in the approach to modelling, moving away from spatially lumped approaches and assumptions about linearity of the systems processes and responses. This poses both technical and practical challenges. For example, Schmitt and Huber (2005) recently stated that integrated urban water system modelling faced the challenges of heterogeneous spatial and temporal scales and dimensionality within the various sub-systems. They go on to state that system complexity, as well as these spatial and temporal challenges prevent simplistic linking of existing sub-models to create a larger model to cover the total urban water cycle.

These technical and practical challenges 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. The review placed a strong emphasis on models whose systems 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. The purpose of this model review was to critique a selection of current IUWM models in light of these questions and to determine the research gaps which must be addressed in order to develop more seamlessly integrated modelling tools for researchers and the water industry.

1.1 Background

Rauch et al. (2002) observed that the idea of integrated modelling was put forward as early as 1976 (attributed to M.B. Beck) and that the first integrated urban drainage model was applied over 20 years ago. The authors also go on to say that it took until the early 1990’s before the concept of integrated urban drainage modelling began to be more widely adopted.

During this period Schütze et al (1996) stated that many of the integrated modelling approaches simulated different components (or sub-systems) in a sequential manner. This sequential (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) pick up on this issue, promoting 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, deciding therefore that there was no other alternative to the tightly coupled modelling approach, through 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 core 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 literature for the coupling of models to represent integrated water systems, it may not ideal for IUWM applications.

2 REVIEW APPROACH

The review was conducted in two stages, briefly described below.

2.1 Stage 1 of the model review

The first stage of the review assessed 65 models from around the world, with the aim of conducting a broad sweep of the models used within the field of IUWM. These models 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.

An assessment questionnaire format was used for this first pass or ‘screening’ review stage, with an emphasis on breadth rather than detail. A purpose built database was used to compile the results and provide an ongoing information resource for the research team.

2.2 Stage 2 of the review

The second stage of the review involved the selection of seven models which most closely complied with the following criteria:

1. covered all aspects of the urban water cycle, being water supply, stormwater, wastewater and groundwater;
2. took an integrated approach to the representation of the urban water system;
3. simulated both quality and quantity;
4. represented non-traditional approaches to urban water service provision such as rainwater tanks, stormwater harvesting, greywater and wastewater reuse as well as water efficiency; and
5. able to represent separate stormwater/wastewater systems (as separate systems are used in Australia).

These seven models were Aquacyle (Mitchell et al 2001), Hydro Planner (Maheepala et al 2005), Krakatoa (Stewardson et al 1995), UrbanCycle (Hardy et al 2005), Mike Urban (www.dhisoftware.com/mikeurban), UVQ (Mitchell and Diaper 2005), and WaterCress (Clark et al 2002). Due to space constraints Aquacycle is not discussed here, as much of its functionality has been incorporated into UVQ, which also models water quality.

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.

Due to this second stage of the review involving 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 fairly structured manner, enabling a balance between rigour and open ended enquiry. The review did not involve the implementation of each model though, so the review is limited to the conclusions that were able to be drawn based on the documentation reviewed. Detail of, or comment on the computational processes contained within the seven models is beyond the scope of this paper.

It is important to note that the review was based in the information available to the review team during the period March to August 2006. During this period Hydro Planner and UrbanCycle were still under development. The decision was made to review them based on their capabilities as of August 2006. It is anticipated that over the next year certain aspects of these models will be enhanced.

There were numerous other models identified in Stage 1 of the review that offered particular features of interest despite not covering the whole urban water cycle. Therefore, a further sixteen models were considered in the second stage of the review, albeit focusing on only one or two components within these models. Due to space limitations these models are not discussed further in this paper.

2.3 Overview of stage 2 models

UVQ simulates the daily water balance of the total urban water cycle using nested lot, cluster, and catchment scales. It accounts for the flux of a range of typical urban pollutants from source to sink throughout the water cycle.

Hydro Planner is a modelling package still under development that links existing resource, distribution, demand, and runoff models. It uses daily/monthly data input, and is attuned mainly to larger scale whole system analysis.

Krakatoa provides a daily or multi-day water and contaminant balance of the total urban water cycle, using a spatially distributed grid layout. It has some capacity to model land use change during a run.

Mike Urban is a modelling package that links existing resource, distribution, demand, and runoff models. It is a detailed tool suitable for the design of essentially conventional urban water systems.

UrbanCycle is a water balance model of the total urban water cycle. Time step is sub-daily, and spatial scale is from single lot to cluster scale. No water quality modelling is included at present, but the model is still under development.

WaterCress is a daily water balance model of the total urban water cycle, which operates at the lot to regional scale. It uses a range of graded quality codes to approximately track water quality.

3 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 which require concerted research effort to adequately address.

The approach to integration differs, ranging from the employment of numerous modules within a framework, to a single, all-encompassing model. By-and-large, 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).

3.1 Summary of key findings

3.1.1 Integration

Two distinct modelling philosophies are represented within the seven models reviewed. One philosophy is that integration is achieved by creating a single computer interface and data exchange functionality to link existing models that simulate separate parts of the water cycle, consistent with the tightly coupled modelling approach recommended by Schmitt and Huber (2005). The other philosophy starts with a central water balance and distribution system and builds 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 first type (as demonstrated by Mike Urban and Hydro Planner) provides more detail of the water streams at the expense of seamless integration, while the second type (the other four) provides superior integration at the expense of peripheral detail.

3.1.2 Spatial and Temporal Representation

The six models cover a good range of spatial scales (Table 1). Spatial resolution increased as spatial scale decreased, with three models – WaterCress, UVQ, and UrbanCycle are all able to disaggregate a single land block into components.

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

Table 1 : Coverage of spatial scales

The majority of the six 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 the lack of ability to simulate sub-daily time steps within IUWM models, 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.

There is also a lack of ability to represent changes in either the water system or the urban area over time. The exceptions to this statement 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.

3.1.3 Climatic input

Hydro Planner, WaterCress and Mike Urban allowed the input of multiple climate files, comprising precipitation and evaporation time series data, whilst UQV, Krakatoa and UrbanCycle are only able to use a single climate input file, thereby assuming rainfall and evaporation were 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.

3.1.4 Water flows

Overall water volumes can be modelled with a reasonable level of accuracy using the daily time step models. But, the review highlighted the 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.

3.1.5 Water quality

Simulation of water quality covers a wide range, from none at all (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, in the models reviewed water quality processes, including treatment, are not modelled in as much detail as water flows.

3.1.6 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 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.

3.1.7 Water supply sources

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

3.1.8 Stormwater

All but one of the models (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).

3.1.9 Groundwater

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

3.1.10 Wastewater treatment

This is perhaps one of the areas in which the models are least satisfactory. Only two of the six 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).

3.1.11 Functionality beyond the simulation of water processes

Several issues are not well covered by the six IUWM models reviewed, either within the model or through linkages to other models, although it is anticipated that these issues will become increasingly important as IUWM analysis becomes increasingly 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 also little in the way of intelligent, context-sensitive decision support for the user in developing a modelling scenario. While this is understandable in some cases, given the original reasons for a particular model to be developed, it is likely to pose a significant limitation in the future as IUWM modelling is becoming increasing complex and therefore onerous for users.

3.2 Discussion

There appears to be a lack of IUWM models which strike a balance between the scope and detail of integrated system representation. At one end of the spectrum are models like Mike Urban which represent the system in a high degree of detail but provide little run-time feedback between the separate water streams. At the other end of the spectrum is the handful of IUWM models which lack the detail to progress beyond volumetrically based feasibility analysis into more detailed design which would require greater accuracy of peak flow rates and water quality (for example UVQ, Krakatoa, Hydro Planner and WaterCress).

Rauch et al (2002) considered that the practical application of integrated urban drainage models was limited more by the lack of data than the lack of suitable models. Given the broader scope of IUWM (encompassing water supply, groundwater, water reuse etc.) the weaknesses in data availability for robust model calibration and verification is likely to be as limiting, if not more so.

The complexity of urban water systems is caused by these systems constantly changing due to demographics, urban renewal, infrastructure aging and replacement etc. Also, they are actively managed by people who make day to day operational decisions. In addition, water restrictions, educational campaigns and policy all exert influence over the way in which the urban water system incrementally evolves over time. All these factors create complexity which is difficult to capture in a simple deterministic representation of urban water system processes. Although, as Rauch et al (2002) eloquently stated ‘it is not the most complex model that is the best one, but the least complex that answers the question reliably’.

4 CONCLUSION

The review team concluded that each of the following was a priority area for further IUWM modelling research and development:

- Assessment of the required temporal and spatial resolution required for accurate representation of sub-daily flow patterns ;
- Improved representation of water quality within the whole of the urban water cycle ;

- Collection and/or compilation of data sets which can be used to develop, calibrate and verify IUWM models ;
- Improved understanding of the appropriate level of simplification/complexity within the IUWM model which reflects the requirements of the different model applications ;
- Improved methods to represent the dynamics inherent in urban water systems, going beyond simple deterministic system behaviour, to capture the complexity of these systems ;
- Exploration of the importance of representing urban water system evolution and change (e.g. system configuration, water demands, land use change, operation, infrastructure capacity…) ; and
- Increasing the functionality of the models beyond water quantity and quality fluxes to include features such as uncertainty analysis, optimisation, guidance on option and technology selection, ecological response of water bodies and non water aspects including energy, economics and social assessment.

LIST OF REFERENCES

Clark, R., Pezzaniti, D. and Cresswell, D. (2002) Watercress - Community Resource Evaluation and Simulation System - A tool for innovative urban water system planning and design, Proc Hydrology and Water Resources Symposium 2002, 20-23 May, Melbourne.

Fletcher, T.D., Wong, T.H.F., Duncan, H.P., Deletic, A.B., Coleman, J. & Jenkins, G.A. 2004, 'Recent Advances in Decision-Support for Stormwater Management: the MUSIC Approach', Novatech 2004, 5th International Conference on Sustainable Techniques and Strategies in Urban Water Management, Lyon, France.

Gregerson, J.B. and Blind, M. (2004) OpenMI: The Essential Concepts and their Implications for Legacy Software, The International Environmental Modelling and Software Society Conference, 14-17 June, University of Osnabrück, Germany.

Hardy, M.J., Kuczera, G. and Coombes, P.J. (2005) Integrated urban water cycle management: the UrbanCycle model, Wat. Sci. & Tech., 52(9), 1-9.

Maheepala, S., B. Leighton, F. Mirza, M. Rahilly & J. Rahman (2005) Hydro Planner - a linked modelling system for water quantity and quality simulation of total water cycle. In Zerger, A. and Argent, R.M. (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 170-176.

Mitchell, V.G. and Diaper, C. (2005) UVQ: A tool for assessing the water and contaminant balance impacts of urban development scenarios, Wat. Sci. & Tech., 52(12), 91-98.

Mitchell, V.G., Mein, R.G., & McMahon, T.A. (2001) Modelling the Urban Water Cycle. Journal of Environmental Modelling & Software, Vol. 16 (7) pp 615-629.

Rauch, W., Bertrand-Krajewski, J.-L., Krebs, P., Mark, O., Schilling, W., Schütze, M. and Vanrolleghem, P.A. (2002) Deterministic modelling of integrated urban drainage systems, Wat. Sci. & Tech., 45(3), 81-94.

Schmitt, T.G. and Huber, W.C. (2005) The scope of integrated modeling – system boundaries, sub-systems, scales and disciplines, 10th International Conference on Urban Drainage, Copenhagen, Denmark, 21-25 August 2005.

Schütze, M., Butler, D. and Beck, M.B. (1996) Development of a framework for the optimisation of runoff, treatment and receiving waters. 7th International Conference on Storm Drainage, Hanover, Germany, 9-13 Sept 1996.

Stewardson, M., McMahon, T. & Spears, M. (1995) Krakatoa: A Model to Assist Integrated Water Resource Management Decision-Making in Urban Areas. AWWA 16th Federal Convention. Sydney.