UVQ: A tool for assessing the water and contaminant balance impacts of urban development scenarios

V G Mitchell*, C Diaper*

*CSIRO Urban Water, PO Box 56, Highett, Vic 3190, Australia

Abstract This paper presents the water and contaminant daily simulation model of the total water cycle, called UVQ. The model has been developed to provide a means for rapidly assessing conventional and non-conventional approaches to providing water supply, stormwater and wastewater services to urban allotments, neighbourhoods and study areas. The model is placed the context of other such models developed internationally through a brief literature review. This is followed by a description of the model and output examples, which is used to illustrate the utility of the model. UVQ is an effective preliminary assessment tool for determining the impacts of urban development options on the total water cycle, as well as the performance of a wide range of non-conventional demand and supply side management techniques. It compliments other aspects of an environmental assessment of options, along with more traditional aspects such as infrastructure costing.

Keywords Urban water cycle, water and contaminant balance, mass budget

INTRODUCTION

The emergent paradigm of integrated urban water management promotes the concept of the total urban water cycle, that is, the holistic view of water supply, stormwater and wastewater. The most important benefit of a total water cycle view of the urban water system is increased range of opportunities available to develop more sustainable systems. Just as the robustness of ecological systems is improved through increased diversity, so too will be the sustainability of urban water systems if an increased range of options deriving from a more holistic view of the urban water cycle is made available. This will enable solutions to be tailored to local circumstances.

Quantifying the urban water and contaminant balance (or budget), and detailing the flow paths and contaminant concentrations within the urban water system, is a way of moving towards the goal of more sustainable systems. Developing a software tool for this task can provide a greater understanding of the interaction of water with an urban area, highlighting ways in which it is utilised within the urban area and enable "what-if" type scenario modelling (Binder et al, 1997; Mitchell et al, 2002). Urban water balances have increasingly been employed in recent years as water professionals undertake more holistic evaluations of urban water systems (Heaney et al., 2000). Due to the dominance of water in urban materials budgets (Decker et al, 2000), it is a vital component in sustainable urban systems.

UVQ is an urban water balance and contaminant balance analysis tool that was developed to analyse how water and contaminants flow through an urban area, from source to sink, highlight the interconnectedness of the water supply, stormwater and wastewater system and provide a tool to investigate how a wide range of non-traditional practices enhance the urban water cycle.

This paper presents the methodology used to develop UVQ and outlines the model's input requirements and output produced. The utility of this modelling approach is presented, emphasising the ability of the model to assess the practicalities of alternative urban water systems.

Literature Review

Many authors have carried out water and contaminant balance calculations for the urban water system, primarily based of simple average annual or monthly or spreadsheet calculations (Binder et al., 1997; Hermann and Klaus, 1997; Uunk and van der Ven, 1984) Few utilise more detailed analysis tools of both water and contaminants although there are several models devoted to urban water cycle modelling (see Mitchell et al, 2003). However, typical representations of the urban water cycle either consider the man-made and natural systems as separate entities or the modelling approach only concentrates on one aspect of the water cycle (Table 1). For example, MUSIC (Wong et al, 2002) provides detailed information on the water flow and contaminant loads within the stormwater system but does not integrate these flows with water flow and contaminant loads within the imported water supply and wastewater systems.

Table 1 Examples of existing urban water and contaminant models

Model name or reference	Primary function	Time step	Scale	Comments
Graham (1976)	Generic water balance	Monthly	Catchment	
Grimmond et al. (1986)	Generic water balance for traditional water servicing	Daily to annual	Catchment	Detailed urban evapo-transpiration subroutine
Krakatoa (Stewardson et al., 1995)	Screening tool for alternative water servicing options	Daily	Catchment	Not publicly available
WaterCress (Clark et al., 2002)	Screening tool for alternative water infrastructure options	Daily	Multiple catchment	Water quality ranking and salinity tracking
Aquacycle (Mitchell et al., 1997 & 2001)	Screening tool for alternative water servicing options	Daily	Multiple catchment	Includes stormwater and wastewater reuse options
MUSIC (Wong et al., 2002)	Flows and quality of stormwater for alternative stormwater sensitive urban design options	Daily to 6 minute	Multiple catchment	Reuse options not included
PURRS (Kuczera and Coombes, 2002)	Impact of local stormwater management devices on infrastructure	6 minute	Single house or housing cluster	Water flows only
ICS (Clifforde et al., 1999)	Simulation of urban wastewater, including sewer, treatment plant and receiving water		Catchment	Integration of MIKE™, MOUSE™ and STOAT™

More recent advances in modelling of integrated urban water and contaminant flows, rely on the integration of complex models, with data transfer and handling via a GIS development platform (Clifforde et al., 1999, Burn et al., 2003). This method offers the advantage of the ability to conduct detailed analysis of specific components of the urban water cycle but, to the best of the authors knowledge, no other model is currently available in which stormwater, wastewater, water supply, groundwater and contaminants are simultaneously considered.

Whilst there have been a number of models developed for predicting movement of contaminants within rural areas or from urban areas to sub-surface or open water courses, few have focused on the tracking of water borne contaminants within the existing urban environment in detail. Additionally, none examine the impacts of alternative water servicing options on the flows of contaminants within the urban environment and the effects on discharges to subsurface and open watercourses as well as to existing treatment plants and infrastructure.

With increasing interest in integrated water management and the need for assessment of alternative water servicing approaches in terms of economic and environmental impacts, the development of a model to provide a first cut analysis of water and contaminant flows was required. UVQ was developed to fulfil this need, building on the previously developed Aquacycle model, which focused on the water balance alone.

Model Description

An existing model, Aquacycle (Mitchell et al, 2001), was enhanced by extending the water balance model to include a number of new water flow paths and incorporating contaminant balance modelling, creating UVQ. It was initially developed to support the assessment of alternative urban water system scenarios within the feasibility stage of the CSIRO Urban Water Program. As part of the a major European/Australian project on **A**ssessing and **I**mproving the **S**ustainability of **U**rban **W**ater **R**esources and **S**ystems (AISUWRS), UVQ has turned from an in-house research tool into distributable, documented, stand alone software. It is a stand alone piece of software which runs in a Windows™ environment. It uses Windows™ based screens, and navigational devices such as buttons, drop-down menus and toolbars.

UVQ integrates the water supply, stormwater and wastewater networks into a single framework to provide a holistic view of the water cycle. UVQ uses simplified algorithms and conceptual routines to provide this holistic and integrated view. Figure 1 illustrates the UVQ framework and the water and contaminant flow paths represented by the model.

Climate, land use and existing infrastructure representation are the primary factors determining the water and contaminant balance of an urban area. Bulk water supply and rainfall are the major inflows to the urban water cycle and wastewater, stormwater and evaporation are the main outflows.

The UVQ model has been developed with the objective of maximum applicability to all urban areas in both Australia and Europe and so has undergone modification to include representation of a wider range of system configurations. Incorporating this flexibility into the model allows UVQ to represent:

- A variety of land use types; residential, industrial, commercial and open space.
- Different conventional water infrastructure designs such as combined sewers, septic tanks, separate stormwater systems, and groundwater bores
- Local climatic conditions

Another purpose of UVQ is to represent the multitude of alternative options for water supply, stormwater and wastewater service provision, enabling the assessment of the impact of alternative water servicing approaches on the total water cycle. Options that can be represented in UVQ include:

- At land block scale – water usage efficiency, rain tanks, on-site infiltration of roof runoff, greywater collection and sub-surface irrigation, on-site wastewater collection, treatment and reuse
- At neighbourhood scale – open space irrigation efficiency, aquifer storage and recovery, stormwater infiltration, stormwater collection, treatment and use and local wastewater collection, treatment and use

- At study area/development estate scale - stormwater collection, treatment and use and wastewater collection, treatment and use

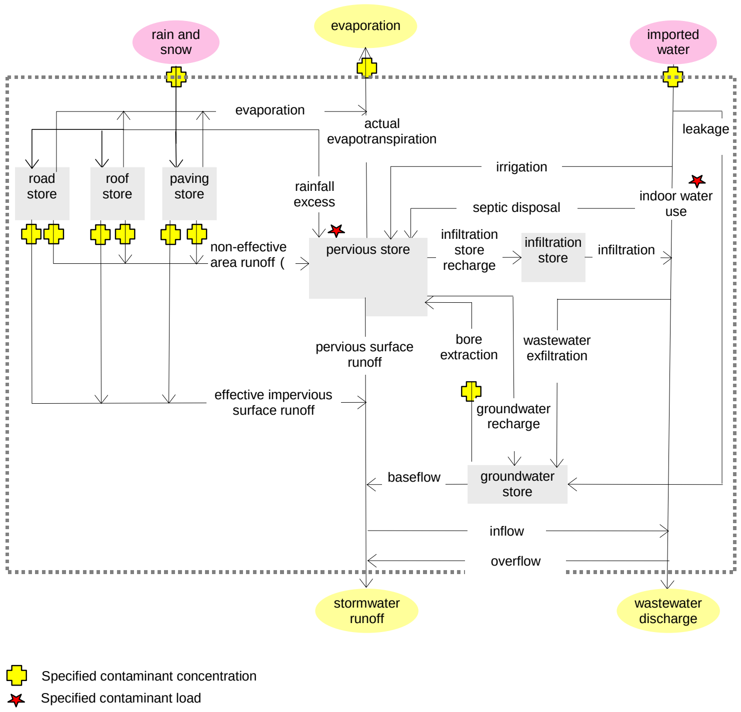

Figure 1 UVQ representation of a conventional urban water system with separate sewers

Three nested spatial scales are used in UVQ to describe the components of an urban area (Figure 2). The single allotment represents a building and associated paved and pervious areas such as paths, driveways and gardens. The proportion of these areas are specified by the user, allowing a range of allotment types such as flats, commercial premises and industry to be represented as well as detached dwellings. A land block containing an industrial property, for example, may only contain a factory building and car parking areas.

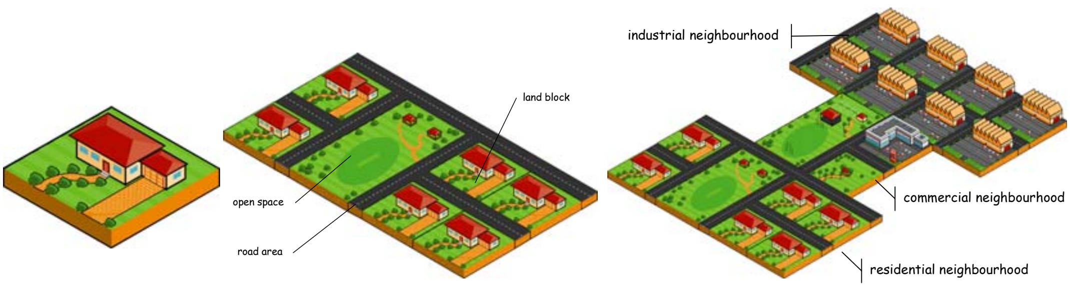

Figure 2 UVQ's spatial representations: land block, neighbourhood and study area

The neighbourhood comprises number of identical land blocks as well as roads and public open space (Figure 2). The configuration of a neighbourhood components may change based on how land blocks within a neighbourhood are used. A common example of a neighbourhood is a group of residential land blocks, with a shared open space and roads.

Alternatively, the land blocks in the neighbourhood could be used for commercial, industrial or institutional purposes. A neighbourhood that simulates an industrial area may only contain industrial land blocks and roads. While a neighbourhood that simulates an area used for institutional purposes such as large university campus' may contain the institutional land blocks, a number of open spaces and roads. Alternatively, a neighbourhood may contain solely open space or solely roads or solely land blocks.

The study area represents the grouping of one or more neighbourhoods that may or may not have the same land use (Figure 2). Modelling a study area allows you to investigate the accumulative affect of different water management strategies within the neighbourhoods within a study area or to explore the feasibility of having different water systems within neighbourhoods that have different characteristics. The order in which stormwater and wastewater flows from one neighbourhood to another can be specified by the user, providing the ability to represent how these streams actually flow through a study area.

A daily computational time step is used, with the model output also summed to monthly, seasonal, and annual totals. The period of simulation is determined by the climate input time series, with an upper limit of 100 years set within the model. In order to gain an understanding of the importance of seasonal and annual variations in climate, which drives the urban water budget, simulation periods of years to decades are recommended.

Contaminant inputs are represented as loads within the home, garden and open spaces or as concentrations in input streams. The mapping of contaminants in the model coincides with the mapping for the water balance, thus directly representing the way in which alterations in the water flows affect the movement and distribution of contaminants. This is a simplification of the processes that occur and does not consider temporal variations in water quality. As UVQ models at a daily time step this approach is applicable and provides detail on sources and flows of contaminants. In addition, as the majority of data collected on temporally varying contaminants flows in the urban environment is expressed as event mean concentrations, this approach is suitable.

Contaminants are all modelled conservatively, with no conversion or degradation within the existing infrastructure. However, the performance of all treatment process from rain tanks through to study area wastewater systems, can be specified in terms of % removal of individual contaminant types or by setting output requirements.

Input requirements

The characteristics of the input data can be highly specific to the study site or generic, depending on the user requirements and data availability. Data input is specified for each neighbourhood (which comprises of allotments, roads and open space) within the case study site. Land use categories that can be represented in UVQ are; urban residential, rural residential, commercial business, commercial horticulture, general light industry, parks and gardens and rural open space. For each of these land use types, the applicable indoor and outdoor water demands, infiltration and exfiltration of pipes and information on occupancy, lot size, garden, roof, paved, road and public open areas is required. For modelling of alternative water management options some knowledge of suitable storage capacity, operation, water sources and uses, uptake rates and routing is required.

Contaminant data on concentrations for all input streams is required. A database of contaminant loads and concentrations derived from international literature can be used to specify input flows where local data is not available. In addition some knowledge of treatment efficiencies of alternative systems is necessary. Any data from case study sites describing outputs flows or concentrations will provide an important basis for model calibration and verification as demonstrated by Rueedi et al (2004).

Model output

The vast array of information and output produced by UVQ is too extensive to record here and so some simple examples of results are provided. In summary, UVQ provides details of water flows and quality from land blocks, neighbourhoods, the entire study area and all associated water reuse alternatives at daily, monthly and yearly time steps. Contaminant balance values are reported on a monthly or yearly basis for the different spatial scales as contaminant input data is usually in the form of mean or Event Mean Concentrations (EMC). It should also be noted that the contaminant loads output by UVQ are a first step in assessing the impact of water systems on the environment, and they should be interpreted in the context of the specific location into which they are discharged and the validity of input data.

The ability to report data for different spatial and temporal scales adds to the utility of UVQ. The model can be used as a preliminary check for the overall viability of an alternative water servicing scenario or for detailed analysis of changes in environmental impacts, potable supply flows and reliability of alternative sources of supply. For example a time series of contaminant concentrations can be viewed and excursions above or below a set point can be tracked (Figure 3). This allows comparison with standards or operating values which need to be met in order for the scenario to be feasible.

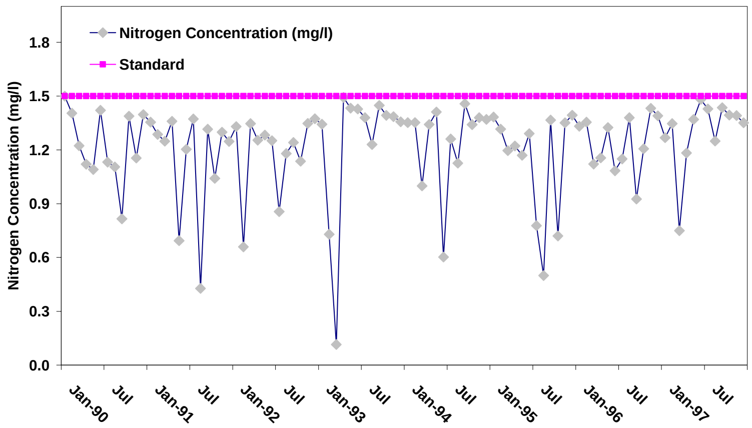

Figure 3 Example of stormwater output concentration results

Alternatively, the reliability of the non-potable reticulation supply sources can be assessed, i.e rain tanks, stormwater ponds and wastewater treatment options, in terms of amount to the demand actually supplied, the occurrence, frequency and length of supply failures (Figure 4).

Preliminary sizing of non-potable reticulated supply storages can be evaluated (Rueedi et al, 2004) and volumes and frequency of overflow calculated. Also, the major sources of contaminants in output streams can be traced, thus aiding the identification of suitable mitigation strategies (Figure 5). In this example the main sources of the contaminant in question originate from the road and land block runoff.

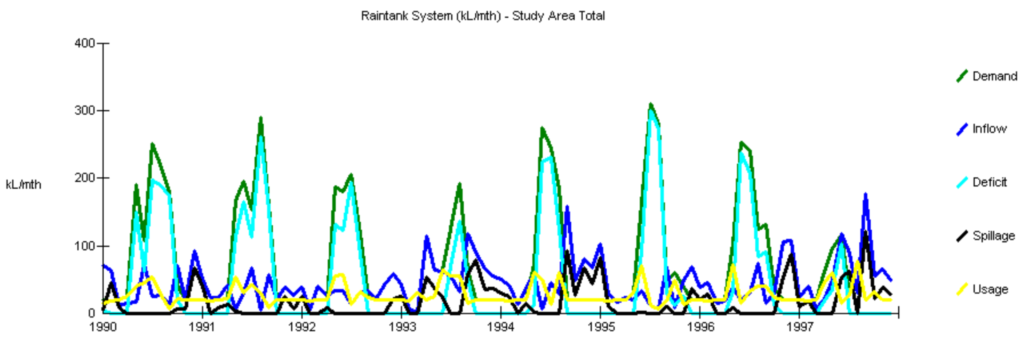

Figure 4 Example of rain tank behaviour output graph

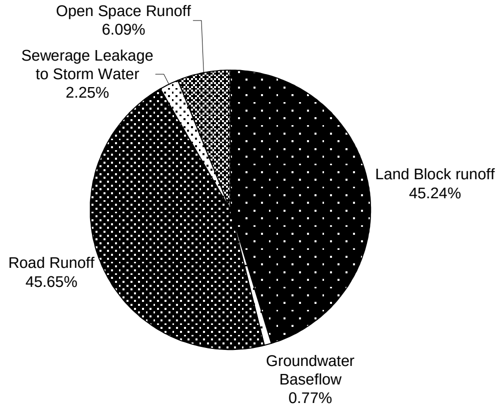

Figure 5 Example of contaminant source output graph

CONCLUSIONS

UVQ has been developed to enable comparison of different water service provision options, from allotment through to study area scale, in terms of water and contaminant flows through the total urban water cycle. The model has been designed with the express intent of representing the uniqueness of each study site. The model provides flexibility with regard to system flow paths and utilises water demand and water quality data that are available to the user.

The output produced by UVQ is a useful component of a broader sustainability assessment of water system options that a user is investigating. Output results from a base case will provide the user with necessary information on which to base the selection of alternative scenarios. The model estimates the impact of a given scenario on the total water cycle and provides contaminant loads at each receiving point, along with the performance of stormwater and wastewater utilisation systems and the impact of demand management. Further application of UVQ by a wider range of users will elucidate its strengths and weaknesses and highlight ways in which the model can be further developed and refined.

ACKNOWLEDGEMENTS

Funding for the enhancement of UVQ was provided by the EU 5FD, grant no. EVK1-CT-2002-00100. The CRC for Catchment Hydrology and Grace Mitchell are acknowledged for allowing CSIRO Urban Water to access the source code of Aquacycle. Acknowledgement also goes to Mike Rahilly, Eric Dell'Oro and Andrew Grant for their work in the UVQ development team.

REFERENCES

Binder, C., Schertenleib, R., Diaz, J., Bader, H.-P. and Baccini, P., (1997) Regional Water Balance as a Tool for Water Management in Developing Countries, *Water Resources Development* **13** (1), 5-20.

Burn, S. DeSilva, D., Tjandraatmadja, G., Mitchell, G., Diaper, C., Dillon, P. and Eiswirth, P. (2003) The role of Urban Infrastructure on groundwater contamination – the EU AISUWRS project, In *PIPES 2003 – Back to Basics: Design and Innovation*, Wagga Wagga (Australia) 21-23 October.

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, In *Hydrology and Water Resources Symposium 2002*, Melbourne 20-23 May.

Clifforde I.T., Tomicic B. and Mark O. (1999) Integrated water management, a European vision for the future, In *Proceeding of The 9th International Conference on Urban Storm Drainage*, Portland, USA 8-13 Sept

Deck, E.H., Elliott, S., Smith, F.A., Blake, D.R. and Rowland, F.S. (1976) Energy and Material Flow Through the Urban Ecosystem, *Annual Review of Energy Environment* **25,** 685-740.

Graham, G.S. (1976) Urban Water Resources Modelling, M.Eng.Sc. Thesis, Monash University.

Grayson, R.B., Argent, R.M., Nathan, R.J., McMahon, T.A. and Mein, R.G. (1996) *Hydrological Recipes Estimation Techniques in Australian Hydrology*, CRC for Catchment Hydrology, Australia.

Grimmond, C.S.B., Oke, T.R. and Steyn, D.G., (1986) Urban Water Balance 1. Model for Daily Totals. *Water Resources Research* **22** (10) 1397-1403.

Kuczera, G and Coombes, P.J. (2002) Towards Continuous Simulation: A Comparative Assessment of Flood Performance of Volume-Sensitive Systems, In *SIA 2002 Conference on Stormwater Management*, 23-24 April, Orange, NSW.

Heaney, J.P., Wright, L. and Sample, D. (2000) Sustainable Urban Water Management, In *Innovative Urban Wet-Weather Flow Management Systems*, Field, R., Heaney, J.P. and Pitt, R. (Ed), Technomic Publishing Company, pp 535, Pennsylvania.

Herrmann, T. and Klaus, U. (1997) Fluxes of Nutrients in Urban Drainage Systems: Assessment of Sources, Pathways and Treatment Techniques, *Water Science and Technology* **36** (8-9), 167-172.

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

Mitchell, V. G., Mein, R. G., & McMahon, T. A. (2002) Utilising Stormwater and Wastewater Resources in Urban Areas. *Australian Journal of Water Resources*. **6** (1) 31-43.

Mitchell, V. G., Diaper, C., Gray, S.R., & Rahilly, M. (2003) UVQ: Modelling the Movement of Water and Contaminants through the Total Urban Water Cycle, In *28th International Hydrology and Water Symposium*, 10-14 November, Wollongong, Australia.

Rueedi, J., Cronin, A. and Moon, B. (2004) Effect of Different Water Supply Strategies on Water and Contaminant Fluxes in Doncaster, United Kingdom, In *IWA World Water Congress*, 19-24 September, Marrakech, Morocco (in this proceedings)

Stewardson, M.J., Clark, R.D.S., Cresswell, D.J. and McMahon, T.A. (1995) Modelling to Assist Integrated Management of Urban Water Resources, In *Second International Symposium on Urban Stormwater Management*, , July 11-13, Melbourne Australia.

Wong, T., Coleman, J., Duncan, H., Fletcher, T., Jenkins, G., Siriwardena, L., Wootton, R. (2002) *Music Model for Urban Stormwater Improvement Conceptualisation*, User Manual, CRC Catchment Hydrology, Australia.