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Developing a New Scoping Model for Urban Water Sustainability

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Abstract

It was an early SWITCH decision to use the water and transport balance concepts underpinning the integrated urban water management scoping model Aquacycle and its successor UVQ as the basis for the development of a rapid urban water sustainability assessment tool. An Excel-based version of the new tool, provisionally referred to as Aquacycle plus, has been implemented and verified against aquacycle at each of the three scales of calculation – dwelling, cluster and city. Currently, a range of options are being investigated and implemented in the new model that reflect the need for better spatial articulation of the natural water systems across a city and the need for additional indicator outputs.

Improved flow and transport representations include the addition of cluster scale groundwater abstraction and groundwater flow, the introduction of canals and rivers and an enhanced sustainable urban drainage (SUDS) capability. A range of SUDS options based on a common model algorithm are being implemented and will include the evolving results from the extensive green roof trials currently taking place in Birmingham UK.

Two additional tools are being added to enable a more complete assessment of sustainability. They will provide indicator values based on whole life cycle energy use and life cycle cost predictions. Initial developments are being based on information collected for the Eastside regeneration scheme, Birmingham, but the model is being formulated to be generally applicable to all cities and all scales.

Keywords: urban water model, scoping model, sustainable

1 Introduction

The SWITCH paradigm shift in water management is from the conventional to the integrated in which all aspects of the urban water system are considered simultaneously by the stakeholder groups to develop a strategy that should be more sustainable. The demand for a more sustainable water system is now growing in the face of several factors including climate change, rising energy costs and rising population: all creating large adjustments to and pressures on the management of the available water reserves globally (notably in Australia and large parts of Africa) (*Lundin*, 2004). Food

production and economic growth place the greatest stress on the water supply of a growing population (*Lundin*, 2004). The pressing need to address current practices to reduce their environmental impacts is also highlighted in the STERN Report (*Stern, N. et al.*, 2006; which addresses the economics of climate change). One estimate is that by the 2080's more than one billion people will suffer water shortages. Several climate models predict an annual runoff reduction of 30% for a temperature increase of 2ºC and 40-50% for a rise of 4 ºC (*Arnell*, 2006). In addition to water scarcity are the effects of increased intensity rainfall events: with a rise of 3-4 ºC the cost of flooding in the UK is estimated to increase from 0.1% GDP to 0.2-0.4% GDP.

The UK's water system is still largely based on designs from the early 1800s when cost-optimised sanitation was the priority and environmental effects were not considered. Health is clearly still the priority in water provision but technology has long been in place to achieve this and so attention has turned to the environmental effects. In order to address these, new designs need to be considered for the water system.

Under Theme 1.2 a new scoping model is being developed for the urban water system that will have the capability of addressing different scenarios (e.g. climate change, population increase) with a variety of sustainable technologies, outputting a suite of sustainability indicators. Fundamental indicators include mains water saved, wastewater emitted, runoff quantity, various contaminant emissions, life cycle energy and life cycle economic cost.

Birmingham, UK, will be used as a demonstration city for the model. Particular focus will be on a 170 hectare site east of the city centre, Eastside. It is currently undergoing physical regeneration which has sustainability as one of it's driving principles.

2 Aquacycle and UVQ

It was a SWITCH decision to use the concepts underpinning the Australian water balance program Aquacycle as a basis for developing the scoping model on a daily time-step (*Mitchell*, 2004). Aquacycle is a good example of a Life Cycle Analysis (LCA) predictive model that outputs a suite of sustainability indicators. It's successor, UVQ (Urban Volume and Quality) adds a contaminant balance to the water balance in addition to improving the interface and adding snow modelling capability.

Aquacycle performs a daily water balance with various water recycling options available to test their effect on the primary indicators – mains water used, stormwater runoff and wastewater emissions. The alternative strategies are raintanks, cluster stormwater systems, catchment stormwater systems, subsurface direct greywater irrigation, aquifer storage and wastewater recycling at unit, cluster and catchment level.

Spatial representation is as follows: the entire study area is called the catchment. Within the catchment are various smaller areas called clusters that are primarily delimited based on land use. Each cluster consists of a number of unit blocks –unit block characteristics are homogeneous within a cluster. The model outputs results at the three spatial levels (catchment, cluster and block) in terms of quantity and, in the case of UVQ, quality.

Aquacycle does not have the capability to address events that require modelling on a sub-daily timestep. For example, it cannot adequately describe flash flooding as it works in daily averages.

3 The new Scoping Model

Aquacycle' and UVQ' concepts and algorithms, based on information in their manuals, have been embedded, initially, in an Excel Workbook using the programming language Visual Basic for Applications (VBA). This programming environment is efficient and user friendly such that additional model capabilities can be developed, tested and demonstrated quickly in the initial stages of the model's construction.

Various steps have been taken to ensure that the new code is correct. Internal consistency has been assured by using mass balance checks for each component of the code (e.g. raintanks, garden area, public open space) and for the total water cycle.. Errors are of the order 10^{-9} m^3 for the whole model for simulations for a small catchment area of 100 ha for one year. Verification of the results against those for Aquacycle using the same input data has also been undertaken. Discrepancies between the models have been noted but these problems cannot be traced to errors in the implementation of the algorithms in the new code.

To find the cause for the discrepancies both models were run with simple test input data whose result could be checked manually. By way of an example a test calculation was performed for a one year time series of constant daily 1mm precipitation and 0.5mm evaporation for a garden area. The values adopted for the required input parameters were set to simplify the manual calculations (Table 1).

Table 1: Input parameters for code verification – Test 1 (Garden area runoff)

Days	365
PS1 capacity (m)	0.05
PS2 capacity (m)	0.5
PS1 proportion	0.5
Garden area (m^2)	100
Roof area (m^2)	100
No. blocks in cluster	10

The garden allows infiltration up to the capacity of it's two stores PS1 (Pervious Store) and PS2, with no interaction between the two. Once the capacity is exceeded there is surface runoff. For the purpose of this verification recharge was set to zero and all roof runoff flows onto the garden without loss. The evaporation algorithm is shown in Figure 1. Since Precipitation is always greater than evaporation the level of the stores will never fall below half and so condition (2) will always apply and the evaporation will be a constant 0.5mm per day.

The simplified garden model yields a total runoff for cluster 1 of 443.75 m^3 (365 m^3 from the roof and 78.75 m^3 from garden runoff once the PS are full) which is the same as the result for the new code. Aquacycle gives a total runoff value of 364 m^3. This suggests either that Aquacycle implements slightly different algorithms to those described in the manual or that there is a possible bug in Aquacycle.

A further example illustrates possible additional discrepancies in the evaporation calculations in Aquacycle. For a fixed 0.5mm evaporation per day for 365 days from a (10 blocks * 100m^2 garden) 1000m^2 area, the resulting evaporation should equal 182.5 m^3/yr but Aquacycle gives 180 m^3/yr unless the soil stores are emptied. For the chosen example this does not arise. A possible explanation is that a fraction of the water cannot return to the atmosphere in aquacycle, but this is not explained in its user manual. While this discrepancy is not particularly large, it is inappropriate for a model to produce results that cannot be explained by the equations that have been apparently employed for its construction. The results for the Scoping model code produce the expected outcome for a fixed evaporation rate.

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(1)     E_actualPS1(j)  =  PS1_unit(j) / PS1_cap(j) * E_trans  (set to 0.007 m)
        E_actualPS2(j)  =  PS2_unit(j) / PS2_cap(j) * E_trans

   Maximum evaporation for day i is the potential, Ep(i):

(2)     If  E_actualPS1(j)  >  Ep(i)  Then
                E_actualPS1(j) = Ep(i) 'units m
        End If
        If  E_actualPS2(j ) >  Ep(i) Then
                E_actualPS2(j) = Ep(i)
        End If

        If  PS1_unit(j)  <  E_actualPS1(j) Then
                E_actualPS1(j) = PS1_unit(j)
        End If
        If  PS2_unit(j)  <  E_actualPS2(j) Then
                E_actualPS2(j) = PS2_unit(j)
        End If


        Where   E_actualPS1(j) is the depth of actual evaporation for pervious store 1,  Cluster j
                PS1_unit(j) is the current storage depth of pervious store 1, Cluster j
                PS1_cap(j) is the maximum storage depth of pervious store 1
                E_trans is the theoretical maximum potential evapotranspiration
                Ep(i) is the potential evaporation for day i
```

Figure 1: Summary of the algorithms used to calculate evaporation from garden areas in the new model, as reproduced from the Aquacycle manual.

4 Developing additional model components

There is considerable scope to develop new facets to the scoping model’s water features that are applicable to the conditions observed in Birmingham, as well as to other cities. Initial additions have incorporated:

- Sustainable Urban Drainage Systems (SUDS) options including green roofs
- Borehole extraction
- Intercluster groundwater flow

- Canal/river option with extraction capability
- spatially heterogeneous aquifer storage
- a more user-friendly indoor usage profile

A generic SUDS option has been programmed at unit, cluster and catchment level. All components are based on a simplified transformed conceptual representation of input, storage compartment(s) and output. The description and functioning of the storage compartments and the outflow behaviour is component dependent The unit level includes options for small swales and infiltration ditches, the cluster level larger swales, ditches and gully pots and the catchment scale infiltration basins, detention basins, lagoons etc. These options allow the user to create a SUDS "treatment train" (*Butler et al.*, 2006).

For a basic Swale, a user specified drain period is applied with the default set as 2 days. The store has a capacity which if exceeded goes to the drains and each day up to (1- 1 / drain period) * capacity can be infiltrated into the pervious store (Figure 2). Once the pervious store is saturated infiltration will cease until space is created by evaporation or drainage. Excess water, that cannot infiltrate, flows to the drains. Work is in progress testing the suitability of Manning's equation for channel flow to better represent storage and flow on a daily time-step.

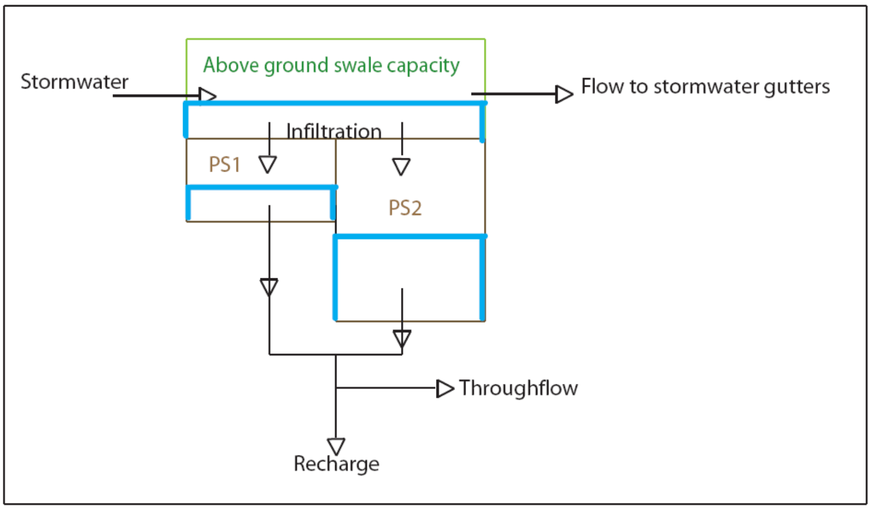

Figure 2 : Flow diagram for the new swale unit in the Scoping model

Groundwater storage is represented at the cluster scale with input from recharge and intercluster flow (baseflow) and loss by baseflow. By modelling at cluster level there is some degree of spatial heterogeneity which is important when assessing groundwater level issues (e.g Birmingham, UK has shallow groundwater which has implications for infrastructure planning). The user can specify which cluster aquifer unit to use for borehole extraction. This can supply other clusters as well. There is the option to use borehole water at the unit level for irrigating the garden or flushing the toilet and at cluster level to irrigate the public open space.

There is the option to model open water (rivers/canals/lakes). The generic water body has a capacity (dimensions – width, depth and length), infiltration rate, interaction with groundwater (gaining or losing river) and flow rate (with the option of setting flow to zero to model static water bodies such as ponds).

The user can choose from five generic indoor usage profiles when running the program. These are domestic, office, hotel, retail and industrial. Default UK values are currently provided. This differs from Aquacycle which has a single usage input profile based on domestic usage split (kitchen, toilet, bathroom, laundry) that the user has to adjust according to his modelling requirements.

The completion of the water cycle components is important and essential for the model's application for quality and energy assessments as well as quantity, the primary goal. However, it is the extension of the aquacycle approach to address life cycle energy usage for a city water system that will be the focus of the research effort in the coming year.

5 Using Eastside as a Demonstrator

Eastside is a 170 hectare site to the east of Birmingham (UK) city centre that is currently undergoing physical regeneration. It is a £6 billion joint public and private venture with best practice sustainability as one of its core principles.

Figure 2. Masshouse in the Eastside - a very different building from the typical unit proposed in Aquacycle and UVQ (*Birmingham City Council*, 2007).

This area will be a pilot study with the aim of applying the model to Birmingham as a whole eventually. It is important to note that the model's design means that it will be generic and applicable to any urban area - not just Birmingham. Unfortunately, the model will not be finished in time to have an effect on the plans for the development of Eastside but application to Eastside provides a framework for testing and refining the model and the underpinning concepts.

Map layers have been prepared with ArcMap commencing with the base ordinance survey layer from Edina Digimap, the proposed building layer from the council website for Eastside, and then additional layers of polygons for canal areas, road area, building areas and general land use areas (Fig. 3). The general land use divisions are based on the proposed land uses. The canal, road and building areas were outlined manually from the proposed map – this was very time consuming and it is likely that supervised pixel selections for the different land uses is a more efficient technique. In this technique a pixel on the map is selected representing a particular land use and the software then identifies all other areas on the map with the same pixel (or to a specified difference in pixel shade e.g. plus or minus 2). Once the selection has been made shadows or poor map definition may require manual correction. The area calculations from the polygons are a dominant input to the water balance model.

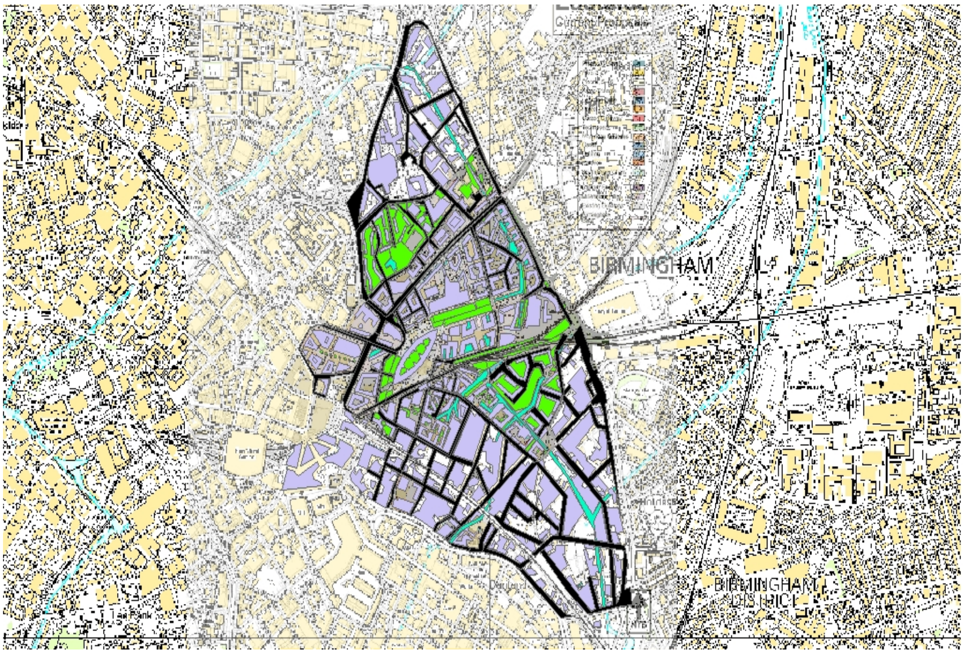

Figure 3: ArcGIS map of Eastside. Green areas are coloured green, buildings are grey, roads are black and canal sections are blue.

6 Preliminary Results

A limited number of alternative water management options have been simulated for Eastside using the water balance model using the best available data available in early 2007. The results are shown in Table 2 and are given for illustration only. The column titled "Mixture with cluster level" shows results for a model run with a mixture of unit block rainwater and wastewater recycling options with the addition of a cluster scale stormwater and wastewater system. Cluster scale alternative water management options can collect water or waste from user specified upstream clusters including the one in which they are situated. They can then supply any cluster with recycled water. All recycling systems use at least 20% less mains water than the conventional system. Reduction in stormwater runoff and wastewater runoff varies from 12-35% but there is some tradeoff between the two. The systems with a mixture of wastewater and rainwater recycling yield the best results.

It is interesting to note that evaporation remains unaltered by the implementation of the different strategies. Simulations were set so that mains water was used to satisfy any outstanding irrigation demand so for all strategies the same volume of water is applied to pervious areas. Consequently the effect of the alternative strategies is not seen as increased evaporation as a result of greater irrigation supplied but rather as a further reduction in the mains water used. Exfiltration from wastewater/stormwater pipes is not currently modeled (it is intended to investigate the inclusion of these in the ongoing model development) and so a reduction in flows has no effect on subsurface moisture levels and as a result no effect on the evaporation volume.

Table 2: Annual catchment equivalent areal depths for precipitation and various indicators for a range of development options.

Annual Areal depth:	Conventional system	Unit block	Unit block wastewater	Mixture RH	Mixture with

		raintanks (RH)	system (WW)	and WW	cluster level
Annual precipitation (mm)	1055.4	1055.4	1055.4	1055.4	1055.4
catchment mains water used (mm)	499.6	390.8	332.7	362.6	364.0
catchment stormwater (mm)	859.8	740.1	849.6	744.0	787.5
catchment wastewater (mm)	480.1	476.6	310.6	443.7	421.6
catchment evaporation (mm)	183.9	183.9	183.9	183.9	183.9

Since this is only a water balance it shows an unrepresentative selection of sustainability indicators. A saving of 20% on “mains water used” for example may cost more in terms of energy use than the conventional or may not be economical. In order to make an informed decision the user needs a suite of indicators covering the “three pillars of sustainability” (Hunt, 2006): environmental, economic and social.

In response to this need it is planned to perform a detailed analysis of energy requirements for the various developments within Eastside. This will inform model development of life cycle energy with the objective of developing a set of generic values for use within the model. Data collection for this is underway. A final additional layer of life-cycle cost will be added using UK data (however the user will have the option to change values for different countries).

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References

Arnell, N.W. 2006. “*Climate change and water resources*” in Avoiding *Dangerous Climate Change*, H.J. Schellnhuber (eds.), Cambridge: Cambridge University Press p167-176.

Birmingham City Council, 2007. Major Developments: Eastside [online]. [Accessed 1st June 2007]. Available from World Wide Web: < http://www.birmingham.gov.uk/eastside.bcc>

Butler, D. & Memon, F.A. 2006. *Water Demand Management*. London: IWA Publishing

Hunt, D.V.L. & Lombardi, D.R. 2006. *Sustainable Water Supplies? A Feasibility Study for Birmingham Eastside.*

Lundin, M. 2004. Indicators for measuring the sustainability of urban water systems – a life cycle approach. *Clean Technologies and Environmental Policy*, **6** (2), pp. 120-127.

Mitchell, G. 2004. *Aquacycle User Manual*

Mitchell, G. & Diaper, C. 2005. *UVQ User Manual*

Stern N. *et al*., 2006. STERN Review: the economics of climate change [online]. [Accessed 2nd June 2007]. Available from World Wide Web:
< http://www.hm-treasury.gov.uk/media/8AC/F7/Executive_Summary.pdf>