7th ISE & 8th HIC
Chile, 2009

URBAN WATER MODELLING AND THE DAILY TIME STEP: ISSUES FOR A REALISTIC REPRESENTATION

CHRISTOS MAKROPOULOS

School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 5, Athens, GR-157 80 Greece

EVANGELOS ROZOS, DAVID BUTLER

Centre of Water Systems, University of Exeter, Harrison Building, North Park Road, Exeter, EX4 4QF, UK

Interest in modelling the total Urban Water Cycle is increasing, due to the realisation of the need for (high-level) flow integration to address issues of recycling, re-use and ultimately sustainability. Urban Water Cycle models are generally operating on a daily time step due to the inherent strategic/planning nature of such work. However, the choice of time step implies (more or less hidden) assumptions which may influence significantly the model's performance. One such assumption – the way in which water tanks (e.g. rainwater, greywater, greenwater etc) are operated in terms of the sequence between tank overflow (spill) and water extracted from the tank for use (yield) is investigated in this paper. The two alternative sequences are termed here *Yield After Spill* (YAS) and *Yield Before Spill* (YBS). The Urban Water Optioneering Tool was used and advantages and disadvantages of these sequences were examined. The paper reviews the differences under a series of technological configurations and draws recommendations for modelling practice. It is suggested that YAS/YBS schemes have different impacts depending on the technological configuration of the case study under investigation, but that under normal operating conditions, daily time step simulations with YBS schemes tend to result in tank sizes that are (marginally) closer to sizes obtained by hourly time-steps. It is however suggested that YAS schemes should be preferred when the parameter of interest is runoff.

INTRODUCTION

Numerical models use discrete representations to approximate the solution of the governing equations of a natural phenomenon. This discretisation of the time or space domain is a main source of error in numerical modelling. Another source of error is the sequential simulation (prioritisation) of two naturally concurrent processes that each one modifies the inputs of the other. Even though these processes have in reality the same initial conditions, during the simulation the need for artificial prioritisation results in (artificially) different initial conditions. The smaller the time step, the smaller the difference between the initial conditions of the processes, and hence the smaller the error introduced by the artificial prioritisation (and also by the discretisation approximations). Smaller time steps are desirable because they increase model accuracy but unfortunately result in longer execution times. Execution time becomes particularly relevant when a model is used for optimisation, thus requiring numerous repeated runs. Urban water models, for example, may be used to identify optimum technological configurations that improve the performance of the water cycle against a set of sustainability criteria (Makropoulos et al. [7]). This requires repeated model runs with long simulation periods thus the associated modelling work is usually done using daily time steps (see also Mitchell [9]). Unfortunately the daily time step is not small enough to guarantee that the errors due to approximations and due to prioritisation are negligible. A typical example of artificial prioritisation, related to the daily time step, in urban water modelling, is the representations of a water tank's spill and yield processes. A water tank (e.g. rainwater, greywater, greenwater tank etc) included in an urban development can be modelled as operating under the following two schemes: **Yield After Spill (YAS):** Add all inflows, reduce by the amount of water that overflows (spill) and then calculate the water available for yield (ie for outflows, use by appliances etc within a house or development), **Yield Before Spill (YBS):** Add all inflows, subtract all outflows (yield) and then overflow (spill). Under the YAS assumption, the tank water balance can be computed using equation (1) while under the YBS assumption, the balance is computed by equation (2):

$$V_t = \min\{V_{t\text{-}1} + Q_t - Y_t, V_{\max} - Y_t\} \quad (1)$$

$$V_t = \min\{V_{t\text{-}1} + Q_t - Y_t, V_{\max}\} \quad (2)$$

where: V_t is the water volume in the tank at the end of the current time step, $V_{t\text{-}1}$ is the water volume in the tank at the end of the previous time step, Q_t is the water inflow during the current time step, Y_t the water yield during the current step, and Vmax is the tank capacity (see also Fewkes [5]; Fewkes and Butler [4] and more recently Mitchell [8]). When $V_{t\text{-}1}$ is close to $V_{\max}$ the V_t calculated from (1) and (2) may differ by an amount equal to Y_t. This amount is proportional to the time step so the smaller the time step the smaller the difference between the two assumptions (and hence closer to the "real" situation). This difference increases the uncertainty of the actual water volume available. In this study the Urban Water Optioneering Tool (UWOT, Makropoulos et al. [7]) is used to (a) assess the divergence of modelling outputs between models using the YAS and YBS schemes and (b) assess the divergence of results for the same scheme as a function of time step (daily and hourly). The paper gives a brief description of the tools used (UWOT) and presents a case study. It then presents and discusses results and proposes basic guidelines for modelling practice, when using daily time-steps.

THE URBAN WATER OPTIONEERING TOOL (UWOT)

UWOT is a decision support tool that simulates the urban water cycle by modelling individual units (e.g. toilets, washing machines, treatment units, tanks, reservoirs) and assessing their combined effects at the development scale. UWOT includes dedicated representation for all different urban flows i.e. potable water, greywater, treated greywater (or greenwater – including harvested rainwater), wastewater (or blackwater) and runoff.

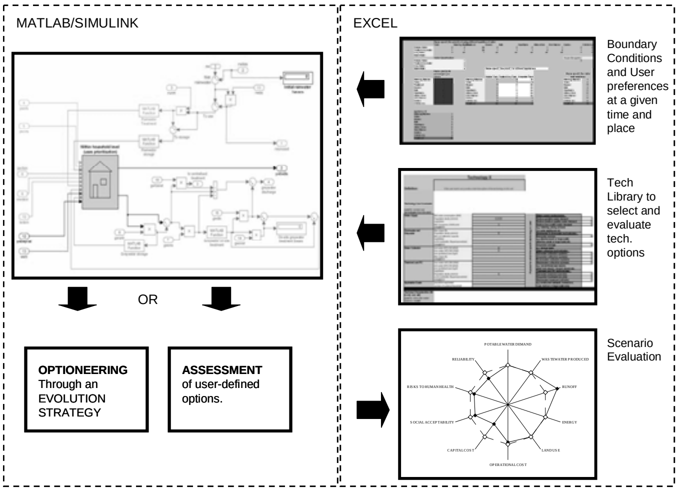


Figure 1: Schematic overview of the UWOT system (Makropoulos et al. [7]).

Previous UWOT versions had a fixed daily time step. The prototype used in this work was modified to allow for simulations with an arbitrary time step. After the choice of time-step is made by the operator, all time-dependent values of the technology library (for example average frequency of use per time step) are multiplied by a conversion factor to make them compatible with the selected time step.

UWOT is linked to a database (hereafter termed the technology library). This database includes technological options (e.g. specific instances of baths, showers, greywater treatment systems etc) and contains data on their major characteristics and performance. The information included in this library is based on environmental, economic, social and technical indicators (Makropoulos et al. [7]). The technology library also contains operational parameters, including technical and operational characteristics for each technology, that are necessary for the calculation of the water balance for the total modelled urban water cycle whenever a specific technology is selected for use (e.g. water use per flush for a specific type of toilet). This selection may be done manually by the user or may be done automatically by an optimisation algorithm. A schematic of the UWOT system can be seen in Figure 1.

YBS AND YAS REPRESENTATION IN UWOT

Equations (1) and (2) contain in fact a circular reference because Y_t depends, apart the water demanded from the tank at time step *t*, on the water available in the tank (V_t), for this demand - which is the output of (1) and (2). For this reason the calculation of V_t is broken into two stages. During the first stage the tank water balance is calculated without taking into account the yield (Y_t). Under the YAS assumption:

$$V_{t+1/2} = \min\{V_{t-1} + Q_t, V_{\max}\} \quad (3)$$

Under the YBS assumption:

$$V_{t+1/2} = \min\{V_{t-1}, V_{\max}\} + Q_t \quad (4)$$

where $V_{t+1/2}$ is the water volume in the tank after any surplus water is spilled and after any incoming water at time step *t* has been calculated. In the second stage the Y_t required to cover the demand is estimated subject to the available water volume $V_{t+1/2}$. Y_t is then abstracted from the stored volume resulting in the available water volume at the beginning of the next time step:

$$V_{t+1} = V_{t+1/2} - Y_t \quad (5)$$

In the YBS prioritisation equation (4) shows that the water level in the tank is allowed to exceed the maximum tank capacity during the intermediate time step *t*+1/2 by an amount of Q_t. If Y_t is larger or equal to Q_t then all the incoming amount of water will be delivered to the household appliances. In this case the water level after the application of (5) will be less than the maximum capacity. If Y_t is not larger than Q_t then any excess amount of water, after the application of (5), will spill over at the beginning of the next time step (comparison between V_{t-1} and $V_{\max}$ in equation (4)). Water spilled, will either go to waste, if the tank in question is the greywater tank or to runoff if the tank in question is the greenwater tank.

CASE STUDY

The case study is a hypothetical development of 500 houses, with an assumed occupancy of four. The development has a combined rainwater harvesting and grey water reuse scheme that includes local grey water treatment (Figure 2). The grey water produced from the household appliances is stored in the local grey water tank. In UWOT, grey water can be used either directly for a few selected uses (e.g. toilet flushing) or treated and then stored in a green water tank (see Figure 2). Rainwater is collected directly in the green water tank.

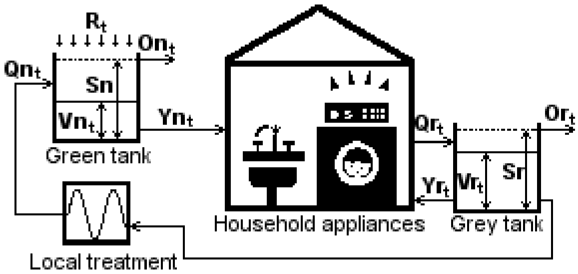


Figure 2: Schematic representation of the water saving and recycling scheme.

In Figure 2: Vn_t:, green water volume in store during time interval *t*, Sn: green tank capacity, Qn_t: green water volume supplied from local treatment during time interval *t*, R_t: harvested rainwater volume during time interval *t*, On_t: green water overflow volume during time interval *t*, Yn_t: green water yield volume during time interval *t*, Qr_t: volume of produced grey water from household appliance during time interval *t*, Or_t: grey water overflow volume during time interval *t*, Yr_t: volume of grey water yield to appliances during time interval *t*, Vr_t: grey water volume in store during time interval *t*, Sr: grey tank capacity. Water demand per household is considered constant for the simulations with daily time step whereas the water demand fluctuation is assumed to follow a pattern derived from EA [3] for simulations with hourly time step.

The stochastic model HYETOS (Koutsoyiannis and Onof [6]) was used to produce synthetic hourly and daily rainfall time series. The produced timeseries were consistent with the statistical characteristics of the daily and hourly rainfall on the meteorological station at Heathrow Airport (approximating typical conditions for the south-east of England), for the period 1981-1990. Optimisation, using the single-objective NSGA-II genetic algorithm (Deb et al. [2]), was performed to identify the optimum green and grey tank sizes, for four different system configurations. The configurations differed in the choice of local grey water treatment technology and the optimisation that proposed tank sizes for each configuration was driven by three metrics (reducing potable water demand, reducing capital cost and reducing residence time for the entire development) which were combined by weighted summation into one objective. A summary of the technological configurations used as an example in this work can be seen in Table 1. As seen from the table, the configurations differ in terms of the capacity of the local treatment plant that processes greywater and turns it into greenwater. The only exception is the 4th configuration, which is in effect only rainwater harvesting without greywater recycling.

Table 1: Configurations under examination (LT: Local Treatment Capacity)

Configuration	Green tank replenishment from:	Grey tank supplies to:
1	Rain + LT(500 l/d)	Toilet + LT
2	Rain + LT(314 l/d)	Toilet + LT
3	Rain + LT(129 l/d)	Toilet + LT
4	Rain	Toilet

Optimum tank sizes were obtained for the YBS/YAS schemes and the daily/hourly time steps. The results of these optimisations indicated that for hourly timesteps, the choice of YBS or YAS scheme is not significant (as was to be expected). The results of the hourly time step were hence used as reference values. The results of the daily time steps (under the YBS and YAS schemes) were compared against the reference values to investigate which of the two schemes delivers more realistic results (ie closer to the hourly time step ones). The comparisons, summarised below, were undertaken using three parameters (the simulation period in each case was 1 year): the Greenwater tank capacity (estimated by the optimisation algorithm); the Greywater tank capacity (estimated by the optimisation algorithm); the Runoff from the development (estimated as an output of the UWOT model run).

RESULTS

A. Influence of YBS/YAS scheme and time step on optimum green water tank capacity

Results of optimum tank capacities (as identified by the optimisation) for 4 different local treatment technologies can be seen in Figure 3 (a). Configuration 1 has the higher capacity local treatment unit, while configuration 4 has the lower capacity local treatment unit (see also Table 1). In Figure 3 (a), tank-sizing results from hourly time step simulations (which are by default a closer representation of the actual phenomenon) are compared to the daily time step simulations using YAS and YBS. The differences between the estimated optimum capacities of local green water tanks with YAS and YBS and hourly time step are displayed in Table 2. YBS estimations tend to be closer to the results obtained by the hourly time step.

The significant deviations that can be observed in the first column of configuration 1, indicate that the simulations with the daily time step were in fact unreliable for this configuration. Although the actual impact of this unreliability in the simulation is minimal, due to the small tank sizes that are involved, this unreliability needs to be highlighted.

Table 2: Differences between optimum tanks capacities with YAS, YBS and HRL.

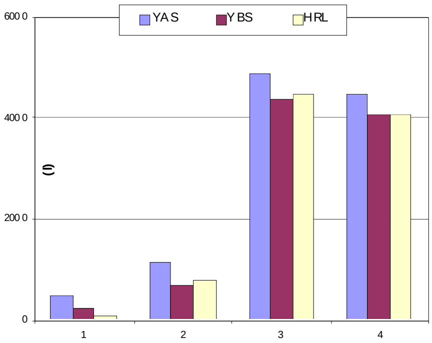
	Config. 1	Config. 2	Config. 3	Config. 4
YAS to YBS (%)	117	66	11	11
YAS to HRL (%)	567	38	9	11
YBS to HRL (%)	207	-16	-1	0

B. Influence of prioritisation and time step on optimum grey water tank capacity

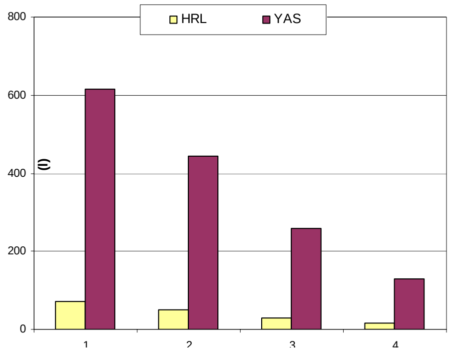
The optimisation with YAS estimated the optimum grey water tank capacity equal to the amount of the produced grey water per time step. The optimisation with YBS estimated the optimum capacity to zero. The comparison between the estimated optimum local grey water tank capacities with YAS and the hourly time step are shown in Figure 3 (b).

C. Influence of the YBS/YAS scheme on the simulated runoff

The runoff from the development was also simulated by UWOT for the range of the scenarios identified and was found that the maximum simulated runoff (peak) from the development over the period of the simulation was consistently lower in the YBS prioritisation by approximately 20%. This difference was noticed with daily, hourly and even finer time steps. A discussion on the significance of this finding is included in the following section.



(a)



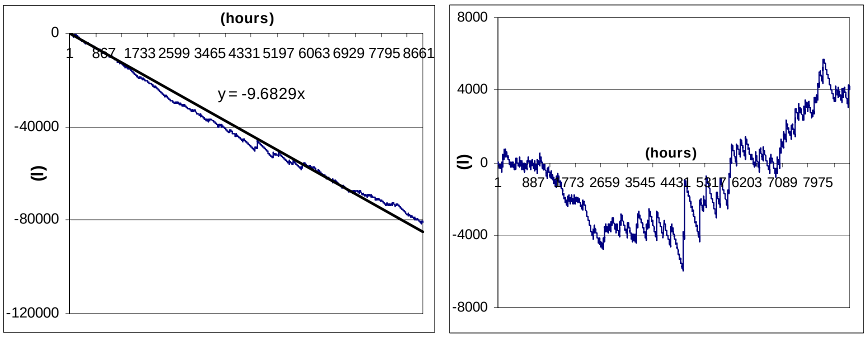
(b)

Figure 3: Estimated optimum local green water tank capacities for 4 different local treatment units (a); estimated optimum local grey water tanks capacities for 4 different local treatment units (b). HRL: hourly time step; YAS: daily time step with YAS prioritisation.

DISCUSSION

A. Influence of prioritisation and time step on optimum green water tank capacity

The analysis shows that estimations of tank sizes using the YBS scheme tend to be closer to the estimations obtained by the hourly time step. It is suggested however that the influence of the YBS/YAS scheme is a function of the specific technological configuration. The deviation is limited in configurations that depend more on rainwater (configurations 3 and 4) and increases in configurations that depend mainly on local treatment. To investigate further this phenomenon the Rippl method was used (ASCE [1]). In Figure 4 (a) the difference between the cumulative harvested rainwater and cumulative green water demand (derived from EA [3]) using an hourly time step is plotted. The constant decline of this graph indicates the need for supply, in addition to the rainwater (in this case treated greywater), to meet the green water demand. The average slope of this graph gives an estimation of the required additional supply, which is 9.68 l/h or 232.39 l/d. Figure 4 (b) depicts the green water deficit and surplus during the simulation period when a constant additional supply of 9.68 l/h is added to the tank budget. According to the Rippl method the optimum capacity of this tank (in the sense of eliminating the overflows and hence maximising available water) is equal to 11667 l, which is the difference between the maximum and minimum values of the deficit-surplus graph. This capacity would ensure availability of green water and elimination of overflows. The estimated optimum capacity with UWOT was much smaller because the capital cost metric that formed part of the objective function that selected the tanks (as discussed above), pushed for a smaller tank size.



(a) **(b)**

Figure 4: Estimation of required replenishment rate (a) and deficit-surplus graph (b) with hourly time step.

Subsequently Rippl was applied using a daily time step. The required additional supply was estimated to be 232.05 l/d and the deficit-surplus graph produced was almost identical to the graph produced with the hourly time step. It is hence suggested that the daily time step is adequate to represent the water level fluctuation of a tank provided that water demand is reliant on rainwater harvesting at least as much as it is reliant on treated greywater. If the role of greywater becomes more prominent, then the daily time step becomes less adequate to represent the process and the influence of the YBS/YAS scheme becomes more important.

B. Influence of the prioritisation and time step on the optimum grey water tank capacity

The optimum grey water tank capacities with YBS prioritisation were zero. This can be explained by equation (4) where even with zero maximum capacity (V_{max}=0) the available grey water volume at the intermediate time step t+1/2 equals the incoming amount of water Q_t. Furthermore since the water consumption is considered to be constant in the daily time step, both Q_t and Y_t are also constant therefore there is no need for storage volume. The optimum capacities of the local grey water tanks estimated with

YAS are equal to the household daily grey water production. This can be explained from equation (3), which suggests that the V_{max} should be at least equal to the incoming amount of water to avoid the overflow. Figure 3 (b) shows that YAS with daily time step overestimated the required capacity of this type of tanks by almost one order of magnitude. The incoming water exhibits a diurnal variability that is lost when daily time step is used resulting in reduced accuracy of the simulations. This is the reason of the unreliable estimations of the local grey water tanks and the green water tanks of configurations 1 and 2.

C. Influence of the YBS/YAS scheme on the simulated runoff

The difference between simulated runoff under YAS and YBS schemes did not diminish with finer time steps. The maximum simulated runoff with YBS prioritisation was consistently lower in all simulations. To explore the reason for this difference and to identify which approach is more accurate, the differences of the YAS and YBS prioritisations were investigated with respect to the runoff generation process. In the YAS any excessive amount of water spills at the beginning of the time step. In the YBS prioritisation the overflow of the excessive amount of water is postponed until the beginning of the next iteration to allow the water appliances to consume the amount. However the high peaks of the runoff hydrograph, which are critical for flood design, are derived from intense rainfall events. During these intense events it is more likely that the harvested rainwater during a time step will exceed, sometimes by orders of magnitude, the corresponding demand. The excessive amount will overflow at the beginning of the next time step introducing an increase to the concentration time and therefore erroneously decreasing the peak of the hydrograph. The time step for simulating runoff generation should be compatible with the hydrological characteristics (concentration time) of the studied area. It is suggested that the YAS/YBS assumption is significant for runoff assessment and YAS is proposed as the safer option. This finding is also consistent with Mitchell [8] who suggests that YAS schemes provide more conservative values.

CONCLUSIONS

Work was carried out to investigate which components of the urban water cycle can be accurately simulated with the daily time step and which components must be simulated with finer time steps. Two alternative schemes of tank operation (the YAS and YBS), were tested to determine their influence in the urban water cycle simulation and the sizing of grey and greenwater tanks. We conclude that:

- The time step used in water tanks simulations should be kept small enough to preserve the statistical characteristics (incl. mean but also the standard deviation) of the most important input and output time series. For the case of rainfall input, as a supplier of water for the household (e.g. through rainwater harvesting), a daily time step is sufficient.
- The tank operation scheme has a different impact depending on the technological configuration of the case study under investigation. The deviation

is limited in configurations that depend more on rainwater and increases on configurations that depend mainly on locally treated greywater.

- In general, YBS tank operation schemes tend to be (marginally) more realistic as a method for sizing water tanks, than YAS, in the sense that they tend to result in tank sizes that are closer to what would have been suggested if finer time steps (in this case hourly time steps) were used.
- On the other hand, the YBS/YAS assumption influences significantly urban runoff simulation. YBS prioritisation was found to (misleadingly) increase the concentration time, thus presenting a more optimistic view, and should therefore be avoided if runoff is of a major concern.

REFERENCES

[1] American Society of Civil Engineers Task Committee on Hydrology Handbook, Hydrology Handbook, New York, NY, (1996), pp. 401.

[2] Deb K., Agrawal S., Pratap A. and Meyarivan T., A Fast Elitist Non-Dominated Sorting Genetic Algorithm for Multi-Objective Optimization: NSGA-II. Report No 200001, Indian Institute of Technology, Kanpur Genetic Algorithms Laboratory, Kanpur, India, (2000).

[3] EA, Less water to waste, Impact of reductions in water demand on wastewater collection and treatment systems, (2008), pp. 13.

[4] Fewkes A. and Butler D., Simulating the performance of rainwater collection and reuse systems using behavioural models. Building Services Engineering Research and Technology 21:22, (2000), pp. 99-106.

[5] Fewkes A., Modelling the performance of rainwater collection systems: towards a generalised approach, Urban Water 1, (1999), pp. 323-333,

[6] Koutsoyiannis D. and Onof C., Rainfall disaggregation using adjusting procedures on a Poisson cluster model, Journal of Hydrology, 246, (2001), pp. 109–122.

[7] Makropoulos C. K., Natsis K., Liu S., Mittas K., and Butler D., Decision Support for Sustainable Option Selection in Integrated Urban Water Management. Environmental Modelling and Software, 23 (12), (2008), pp. 1448-1460.

[8] Mitchell G., How important is the selection of computational analysis method to the accuracy of rainwater tank behaviour modelling? Hydrological Processes, 21(21), (2007), pp. 2850-2861.

[9] Mitchell G., Mein R. G., McMahon T. A., Modelling the urban water cycle, Environmental Modelling and Software 16 (7): (2001), pp. 615-629.