Managing the complete Urban Water Cycle: the Urban Water Optioneering Tool

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Abstract

Conventional urban water management practices aim to meet water demands while conveying wastewater and stormwater away from urban settings. However, increasing water scarcity, caused by either changes in climatic conditions, increasing consumption, or both, has drawn attention to the possibility of re-engineering the urban water cycle to implement water recycling and reuse practices (Makropoulos et al., 2006). Examples of these new practices are the use of treated greywater (or "greenwater") or harvested rainwater for a variety of non-potable water uses in the household. The successful design of water recycling schemes should attempt to minimize (simultaneously) the demands for potable water, the energy and cost, and perform adequately in the longer term – possibly even under changing climatic conditions. This paper describes the Urban Water Optioneering Tool (UWOT; Makropoulos et al., 2008), which is a decision support tool that supports the design of the complete (integrated) urban water cycle and helps to achieve sustainable water management for new and existing urban areas and explores both past applications and future developments within the context of new challenges for water in Europe.

1. UWOT structure

UWOT simulates the urban water cycle by modelling individual water uses and technologies for managing them and assessing their combined effects at development scale. It simulates both "standard" urban water flows (potable water, wastewater and runoff) as well as their integration through recycling schemes (including for example greywater, treated greywater and rainwater). It can also be used in an optimization mode, using multi-objective evolutionary algorithms to propose configurations of technologies that minimize water consumption, costs and energy for specific urban developments. The water system components of the development are represented in UWOT using a three level hierarchical structure:

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1. Lower level. This level includes the individual household water appliances (e.g. toilets, washing machines, local treatment units).
2. Middle level. This level includes the households as well as “central” technologies (i.e. technologies such as centralized greywater treatment, centralized wastewater treatment or a development scale drainage system). Each household includes (a) water using appliances, (b) in-house water infrastructure (greenwater tanks, pipeworks) and (c) a set of characteristics that affect the water budget (occupancy, pervious/impervious area).
3. Higher level. The higher level is the urban development as a whole. An urban development could range from a neighbourhood to a village or small town. It is defined by the number of household types included in the development, the public pervious/impervious areas of the development and the type of the recycling/treatment scheme.

UWOT is linked to a database (referred to as the “technology library”) that contains information on the major characteristics of both in-house and development scale water system components. Information that is contained within the technology library includes:

- Information on Local appliances. The technology library contains operational characteristics that are necessary for the calculation of the water balance of the urban water cycle (e.g. water use per flush for a specific type of toilet and frequency of use). The library also contains the technical characteristics that influence the development of a series of indicators (e.g. required energy, cost). The information on local appliances that is included in the technology library was obtained from market surveys (including technical specifications provided by manufacturers) as well as from research and practitioner manuals.
- Information on Central technologies. The technology library contains the operational and technical characteristics of the technologies operating at the development scale. These technologies differ from the local appliances in the sense that (a) they are large units constructed on site; (b) their specifications are not predefined by industrial standards but are tailored to the requirements of each development. For these technologies the library contains relationships that relate the operational and technical characteristics with their capacity.
- Information on Local tanks and central reservoirs. The cost of local water tanks (used for storing treated and untreated recycled water and rainwater) and central reservoirs is assumed proportional to their volume.
- Information on Household piping. The cost of household pipework required for water recycling is assumed proportional to the household size. This lumped approach reduces the number of required data by relating the pipework cost to a property of the household.

UWOT’s engine, the model core where the simulation of the urban water cycle takes place, is implemented in MATLAB Simulink and compiled into a dynamic link library (dll). The user interface and the technology library are implemented in Microsoft Excel.

2. Example Applications

UWOT was applied to sets of alternative design solutions for two water recycling schemes under three basic climatic categories: Oceanic, Mediterranean and Desert (Rozos and Makropoulos, 2010b). The multi-objective optimization algorithm NSGA-II (Deb et al. 2000) was used to obtain the PF of the “optimal” design variables for each of the two recycling schemes for a range of criteria, under the three climatic conditions. Afterwards, UWOT was used as an assessment tool, where optimization results from the Mediterranean climatic conditions were assessed against a potential reduction of the annual precipitation providing an overview of the influence of changes in climatic conditions on the climate-specific “optimal” solutions.

The results of this study indicated that a local rainwater harvesting scheme can offer only a minor potable water demand reduction (3%) in arid climatic conditions, moderate (20%) in Mediterranean climatic conditions and significant in humid climatic conditions. However, the combination of rainwater harvesting with greywater can reduce the demand for potable water by more than 42% even in arid climatic conditions. An extra advantage of this configuration is that it is hardly influenced by changes in climatic conditions.

UWOT was also applied in a case study of flow-pattern restoration of a disturbed (urban) hydrosystem to attempt to bring it back to its pre-urbanisation form (Rozos and Makropoulos, 2010a). Sustainable, water-aware technologies, like Sustainable Drainage Systems (SUDS) and rainwater harvesting schemes, can be in principle implemented to reduce the adverse effects of urbanization on generated runoff. However, such technologies interact with other components of the urban water cycle. Consequently, integrated modelling of the urban water cycle is necessary to simulate water-aware technologies and identify their synergistic benefits. This study included two hypothetical developments, one with high urban density and one with low which implemented rainwater harvesting schemes and SUDS.

The results of this application supported the claim that water-aware technologies can effectively reduce the impacts of new urban areas on the environment by decreasing both potable water demand and generated runoff. Furthermore, it was shown how a carefully designed rainwater harvesting scheme at the development scale can be used to restore the flow pattern of a disturbed hydrosystem to its pre-urbanisation characteristics and form.

UWOT was also used for the preliminary study of retro-fit solutions for potable water demand reduction in a small, water scarce island in Greece (Agkistri) with a view to explore a more sustainable “green” development. The households of Agkistri were separated into (a) residential, (b) rooms to let and (c) hotels. A benchmark (business as usual) scenario was modelled with UWOT and its results were used as reference values. UWOT assessed the benefits of replacing conventional water appliances with low consumption ones (scenario 1) as well as the benefits of implementing greywater recycling (scenario 2). The results of this application indicated that the annual reduction of the potable water demand achieved was between 21% (for scenario 1) and 60% (for scenario 2).

3. Beyond the State-of-Art

The application of UWOT to these diverse cases and problems, led to additional ideas of what the tool could be used for - which in turn led to requirements for upgrade. Currently a new version of UWOT is under development. In this version the UWOT engine is being redeveloped using C (instead of Simulink). The main advantage of the new version will be its ability to model an arbitrary number of household types, accept changes in the occupancy and the number of households as timeseries (potentially as input from other models, such as landuse change models). Furthermore, the new UWOT will use a Relational Database Management System (RDBMS) to store technology library data, network topology, timeseries (rainfall, occupancy, number of houses, demand trend/fluctuation) and results of simulation. The new version of UWOT will be available as:

1. A stand alone application. A tool for drawing the network, an optimization algorithm, the display and analysis of the results, and the capability to browse the database will be provided through a user friendly graphical interface that will link to the new UWOT engine.
2. A Matlab function. Matlab will run the UWOT engine, read the results of the simulation from the database and employ Matlab tools (e.g. optimization algorithms) to investigate alternative scenarios and analyze the results.
3. An OpenMI compliant model. UWOT will be encapsulated into a dll compatible with the OpenMI standard (www.openmi.org) to allow seamless integration of the tool with other hydrological, hydraulic, socio-economic or meteorological models at runtime.

It is suggested that the new UWOT will be useful as a tool to, inter alia, the following research areas:

- Urban water system metabolism. UWOT will be used in combination with system dynamic models to analyze the urban water system's metabolism and performance. In this context UWOT will provide a mass-balance simulation, including energy, water and related costs for the domestic subsystem which in turn will link to the total urban water cycle and explore the impact of alternative demand reducing practices to the efficiency of the system.
- Addressing water scarcity. UWOT will be linked with a water resources management model to provide a more accurate estimation of the impacts on the environment of stresses caused by an urban area (incl. water abstractions and return flows such as wastewater and runoff). This link will help to deliver more credible water management strategies for the available resources in areas characterized by water scarcity.
- Sustainable (green) urban growth. UWOT will be integrated with a land-use model based on cellular automata to study the interactions between urbanization and the urban water infrastructure, with an emphasis on the effect of the form and type of the urban development on possible alternative water management practices. The alternative solutions will be analyzed in relation to the urban development and the energy demand, whose role in decision making process will be investigated.

4. Conclusions

The Urban Water Optioneering tool (UWOT), both in its current and next version is a powerful tool to investigate the impact of a different paradigm of more distributed, local, water and energy aware management of the complete urban water cycle. This places the tool (and the research that it enables and supports) in the heart of a series of issues currently debated at the European and Global scales, including, but not restricted to the improved efficiency of urban water services and systems, the reduction of the impact of urban areas to water scarcity and the (holy grail of) sustainable (green) urban growth.

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