Assessing the combined benefits of water recycling technologies by modelling the total urban water cycle

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This study investigates the potential benefits of new technologies, modern appliance, and innovative techniques that help to improve the performance of the urban water cycle. Urbanisation is a major source of additional pressures (both qualitative and quantitative) on the environment. For example abstractions to cover the increased demands for water supply or alterations of the topographic and geomorphologic properties of the land cover result in considerable changes to the dynamics of the hydrosystem (change of average and maximum values of flows). Sustainable, water-aware technologies, like SUstainable Drainage Systems (SUDS) and rainwater harvesting schemes, can be implemented to reduce these adverse effects. These technologies introduce interactions between the components of the urban water cycle. Rainwater harvesting for example, apart from the potable water demand reduction, may have significant influence on the generated runoff. Consequently, an integrated modelling of the urban water cycle is necessary for the simulation of the water-aware technologies and the identification of their combined benefits. In this study, two hypothetical developments implement rainwater harvesting schemes and SUDS, and are simulated using the Urban Water Optioneering Tool (UWOT), which is able of using rainfall time series of arbitrary time step. The two hypothetical developments were studied to investigate the contribution of the water-aware technologies to the minimisation of the environmental pressures. Significantly different urban density was assigned to these developments to highlight the influence of urban density on the efficiency and reliability of the water-aware technologies. The results indicate that: (a) water-saving schemes like rainwater harvesting and greywater treatment can reduce significantly the pressures of new developments (e.g. reduction of potable water demand by 27%); (b) the reliability of the water-aware technologies decreases with urban density; (c) if localised rainwater harvesting is implemented then the efficiency of the water appliances influences considerably the generated runoff.

Keywords: greywater treatment, optimisation, rainwater harvesting, runoff model, sensitivity analysis, urban water cycle

1. Introduction

Urbanisation changes drastically the form of the landscape and the properties of land cover. Paved, impervious surfaces result in altered stormwater runoff patterns that include both greater volumes and higher rates of runoff, which directly and negatively impact receiving water bodies through channel modification, increased sediment loadings, and destruction of aquatic habitat (Jacob and Lopez, 2009). Furthermore, urbanisation results in increased water abstractions to cover increased demands for water supply (Xenos et al., 2002). The magnitude of these impacts depends on the size and density of the urban area. Water-aware technologies, i.e. technologies that help to improve the performance of the urban water cycle, can be implemented to reduce these impacts (WRA, 2003).

Rainwater harvesting is certainly not a “new” technology. It has been used for millennia for collecting and storing rainwater from rooftops, land surfaces or rock catchments using simple techniques such as natural and/or artificial ponds and reservoirs (Crouch et al., 1996). Although harvested rainwater might be polluted by bacteria and hazardous chemicals (May and Prado, 2006), techniques like slow sand filtration, solar technology and membrane technology are able to provide treated rainwater at quality levels suitable even for drinking (Wegelin et al. 1994). According to Sommer et al. (1997) the solar water disinfection-pasteurisation as continuous flow system (SODIS reactor) can produce around 100 L of disinfected water per square metre of solar collector and day. This indicates a strong potential for rainwater harvesting as a method to increase (distributed) urban water supply.

There are three major forms of rainwater harvesting (Helmreich and Horn, 2009):

- Domestic. The water is collected from roofs and stored in local tanks. The domestic rainwater harvesting, apart from reducing the potable water demand, has as side benefit the reduction of the runoff volume.
- In situ. The rainfall is collected on the surface where it falls and stored in the soil. The most promising version of this form is SUstainable Drainage Systems (EA, 2003). SUDS have combined benefits like manage runoff flow-rates, groundwater recharge and even provide a habitat for wildlife in urban watercourses.
- External. The runoff originating from rainfall over a surface elsewhere is collected and stored offside.

This study will focus on the first two forms, the domestic and the in situ. According to Rippl method (Prakash et al., 1996) the optimum capacity of a storage unit depends on the maximum deficit/surplus between the inflows and the outflow (demand). Therefore, for domestic rainwater harvesting, the optimum capacity of the local tanks depends on the statistical characteristics of the rainfall and on the demand for rainwater. Likewise, the optimum capacity of in situ schemes (e.g. for SUDS-type of structures) depends on the characteristics of the development (ratio of pervious/impervious area), on the operation of the local tanks (of which the spill is added to the total development runoff) and on the statistical characteristics of the rainfall.

If a domestic rainwater harvesting scheme is combined with a greywater recycling scheme then further reductions of the potable water demand can be achieved (Zhang et al., 2009). In such a case both the treated greywater and the harvested rainwater are stored in the local tanks. The level inside these tanks depends on the demand of the water appliances, the capacity of the greywater treatment unit and the rainfall. The overflow from these tanks could be considered as runoff. As the overflowing volume from the local tanks increases, SUDS with larger capacity would be required to compensate for the additional volume of runoff. It becomes evident that in a development with water-aware technologies, where the water flows (supply, wastewater and runoff) interact, the modelling tools that are used for simulation should adopt a total urban water cycle approach.

The present study has three objectives. The first objective is to identify the achievable reduction of the potable water demand and runoff, taking into account the cost, in two hypothetical developments that implement water-aware technologies. The second is to investigate the influence of urban density on the runoff from a development that implements water-aware technologies. The third and more important objective is to examine the potential of rainwater harvesting schemes for restoring the flow pattern of a disturbed hydrosystem to its pre-urbanisation form.

In this study the Urban Water Optioneering Tool (UWOT) is used. UWOT is a decision support tool that simulates the total urban water cycle and assesses its performance using techno-economical, environmental and social metrics (Makropoulos et al., 2006; Natsis et al., 2006; Memon et al., 2007).

Two hypothetical developments were assessed. The developments had the same size but different urban density. Development H had high urban density (158 m^2/person) whereas development L low (315 m^2/person). For the purposes of this study synthetic “observations” of runoff were produced using a rainfall-runoff model. Runoff in this case concerned: runoff from the undisturbed landscape, runoff from development H and runoff from development L. All “observations” correspond to the same rainfall events, which were obtained from a meteorological station in Athens, Greece (NTUA, 2008).

The paper starts with a short description of UWOT and the rainfall runoff module. This is followed by the description of the developments (H and L), the modelling and the results.

2. Urban water optioneering tool

The urban water cycle model that will be used in this study is called UWOT (Rozos et al., 2010; Makropoulos et al., 2008). UWOT is a decision support tool that simulates the urban water cycle by modelling individual water uses and technologies for managing them and assessing their combined effects at development scale. UWOT 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). The water system components of the development are represented inside UWOT using a three level hierarchical structure (Figure 1):

(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 centralised greywater treatment, centralised wastewater treatment or SUDS). Each household includes (a) water using appliances, (b) in-house water infrastructure (local 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 new neighbourhood to a new village or small town. An urban development 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.

Figure 1: Hierarchical representation of the water system of an urban development in UWOT.

UWOT is linked to a database (hereafter referred to as the “technology library”) that contains information on the major characteristics of both in-house and development scale water system components. Though the database has been populated with information concerning basically the UK market, new records can be added for new brands or for an application of UWOT to another region. The type of information contained in the technology library for each technology is the following:

(1) 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 are used to calculate a series of performance indicators (e.g. required energy, cost). The information on local appliances that is included in the technology library was obtained from market surveys (e.g. technical specifications provided by manufacturers) as well as from research and practitioner manuals (e.g. the frequency of use and the water consumption per use for each appliance).

(2) 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.

(3) Local tanks and central reservoirs. The cost of local water tanks (used for storing treated and untreated recycled water and rainwater) and central reservoirs was assumed proportional to their volume.

(4) 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 assess the sustainability of the urban water cycle through the use of sustainability indicators. These indicators can be classified into four sustainability capitals: environmental, economic, social and technical. Simultaneous optimisation of the indicators (or the subset of the indicators in interest) is achieved either through the use of a normalisation method (e.g. simple weighting, fuzzy inference systems etc) or through the use of a multi-objective approach. UWOT implements for optimisations the genetic algorithm NSGA-II (Deb et al., 2000) through the use of the Excel add-in GANetXL (Bicik et al., 2004).

UWOT distinguishes development areas according to the property owner into public and private areas. Public areas include the public buildings, the streets, the parks and the side walks. Private areas are the households. UWOT also distinguishes development areas according to the type of surface into pervious and impervious. Impervious are considered the building roofs, the paved areas and the streets. Pervious areas are considered the gardens, the parks and every area with low runoff coefficient (lower than 0.3).

The pervious/impervious ratio plays a significant role in the generation of runoff. The rainfall that falls onto pervious areas is considered to either evaporate or infiltrate. The rainfall that falls onto impervious areas plus any overflow from household tanks is considered to generate runoff. To simulate the routing of this volume to development output, UWOT implements a simple level-pool reservoir routing technique (Fread, 1993). This is a simplification of the Muskingum method (US Army Corps of Engineers, 1994). In Muskingum method, the storage linearly depends on both the inflow and outflow from the reference volume. In the level-pool reservoir, the storage inside the reference volume is considered to be proportional only to the outflow. This technique needs two parameters, the rescission coefficient μ [T^{-1}] and the retention threshold K [L^3]. The outflow, corresponds to the runoff from development, is $O_t = \mu\, h_t$ if $h_t<K$ otherwise $O_t = (h_t - K) / \Delta t + \mu\, K$, where h_t is the storage [L^3] and Δt is the simulation time step.

3. Case study

3.1 Developments H and L

The Hypothetical developments H and L have urban density of 158 and 315 m^2/person. These values are close to the upper and lower boundaries of the range of the European cities urban density (Newman and Kenworthy, 1989). The typical households of each development were considered identical apart from the size of gardens (smaller in H). This simplification was adopted to exclude from the study factors that are socially related (like occupancy, frequency of use, installed appliances etc) in order to focus on the effects of the urban density. The total area of each one of the developments was assumed to be 126 hectares (68 hectares occupied by households and 58 hectares of public areas). The characteristics of the two developments are shown in Table 1.

Table 1: Characteristics of developments H and L.

The hypothetical developments employ a water-recycling scheme with Centralised Treatment (CT) and local rainwater harvesting scheme and SUDS (according to Fletcher et al. (2007) in typical urban catchments, a combination of management measures such as flow detention, infiltration and enhancement of evapotranspiration, along with stormwater harvesting, are required if the objective is to achieve ‘natural’ flow regimes).

The water cycle of the developments is shown in Figure 2 (since waste water stream is not in the scope of this study it is omitted to improve the clarity of this figure).

Figure 2: Water cycle of the hypothetical developments (1000 households for development L and 2000 for development H).

Each household includes a tank that stores both harvested rainwater (R_t) and water from the central treatment (Figure 3). The water of this tank is used by washing machines and for toilet flushing (Y_t). The supply from central treatment (Mn_t) is activated whenever the stored water in the tank (V_t) drops below a threshold (Vmin). The central treatment treats water coming from hand-basins, showers and baths (Mr_t). These appliances are supplied with potable water from mains (Mp_t). A typical diurnal water demand fluctuation pattern (EA, 2008) is assumed throughout the whole simulation, repeated as many times as the number of the days of the simulation period. The same pattern is used both for the demand of potable water and for the demand of water from the local tanks.

Figure 3: Water cycle of the households of the hypothetical developments.

The runoff from each household (see Figure 4) equals the sum of the water that spills from the local tank (On_t) plus the runoff (Fi_t) from the impervious area (Ai-Ah). The rainwater falling on the pervious area (Ap) does not runoff but is assumed to either infiltrate or evaporate.

Figure 4: Generation of runoff on the hypothetical household.

3.2 Synthetic observations

Rainfall data (10 minutes time step) were obtained from a meteorological station located in the campus of National Technical University of Athens, Greece (NTUA, 2008). The time series length is 61 days starting from 1st of January 2003 and ending at 2nd of March 2003. Three sets of synthetic “observations” of runoff were produced with the model ZYGOS (NTUA, 2008b) using each time a different set of parameters at this model. The first set of parameters corresponds to the undisturbed landscape whereas the other two to developments H and L without SUDS and recycling technologies (referred hereafter as conventional developments).

Figure 5: Synthetic runoff “observations”.

The set of parameters that corresponds to the undisturbed landscape was obtained with manual calibration to achieve runoff coefficient equal to 0.11 (UDFCD, 2001). This value corresponds to soil group C for a rainfall event with 3 years return period (this is the return period of the 25/1/2003 event, the most intense event of the simulation period). The sets of parameters for developments H and L were obtained with appropriate adjustment to result in an increase of the discharge peak by a factor of 3.5 and 2.3 respectively. These are the expected runoff-increase values (Kibler et al., 1996) for urban areas similar to development H and L of this study (see Table 1).

3.3 Calibration of UWOT rainfall-runoff module

UWOT is simulating the runoff generated in the developments at each time step (caused by rainfall on both public and private impervious areas plus the overflows from the household tanks). The simulation of the routing of the generated runoff to the development outputs is accomplished with the runoff module of UWOT.

The parameters of this module were calibrated to fit the simulated runoff to the “observed” runoff (produced with ZYGOS using parameter sets 2 and 3) at the output of the developments. The simulations presented in Figure 6 and Figure 7 correspond to a rainfall event that started at 25/1/2003 3:40:00 pm and ended at 26/1/2003 6:20:00 am.

Figure 6: Simulated runoff at the output of the conventional development H before (left panel) and after (right panel) the calibration of the runoff module (μ=0.03 min^{-1}, K=7000 m^3) versus the “observed” runoff at the output of development H.

Figure 7: Simulated runoff at the output of the conventional development L before (left panel) and after (right panel) the calibration of the runoff module (μ=0.05 min^{-1}, K=3000 m^3) versus the “observed” runoff at the output of development L.

3.4 Optimisation of the water-aware technologies

The capacity of the households' local tanks, the capacity of the SUDS and the central treatments were optimised to achieve simultaneously: a) rainfall-response similar to the one before the urbanisation; b) minimisation of the potable water demand and c) minimisation of the cost. The objective function was the weighted summation of the potable water demand plus the capital cost plus the correlation between the runoff from the development and the runoff from the undisturbed landscape. The optimisations were performed with the NSGA-II algorithm.

The optimum capacity of local tanks was found to be 7000 L whereas the optimum capacity of SUDS was found to be 9000 m^3 and 4400 m^3 for developments H and L respectively.

4. Results

4.1 Runoff and potable water demand

The runoff peak and the potable water demand of developments H and L with optimised technologies are given in Table 2. Table 2 also includes, for reference purposes, the corresponding values of the conventional developments.

Table 2 indicates that the potable water demand was reduced by almost 27%. Further reduction could be achieved if rainwater and treated greywater was used in more water appliances (like hand basin, dish washer, etc). The runoff peak of H and L developments is 3 and 2.2 times higher than the runoff peak of the natural flow regime. The implementation of the rainwater/stormwater harvesting schemes resulted in a reduction of this peak by 66% in development H and 54% in development L (i.e. natural flow regime was restored).

Table 2: Runoff peak and potable water demand of the conventional and optimised developments.

The runoff hydrographs from developments H and L that correspond to the rainfall event that started at 25/1/2003 3:40:00 pm and ended at 26/1/2003 6:20:00 am are displayed in Figure 8. This figure also includes, for reference purposes, the runoff hydrographs from the conventional developments. The diagrams of this figure indicate that the optimised technologies not only reduced significantly the peak of the runoff but also resulted in responses similar to those from the undisturbed landscape. This was an expected outcome that is consistent with the concept of stream restoration (Walsh et al., 2005), which has been introduced more than two decades ago (e.g. see Rosmiller, 1987).

Figure 8: Runoff from the undisturbed landscape, the conventional and the optimised developments (left panel development H, right panel development L).

4.2 Sensitivity analysis

To investigate the influence of the efficiency of the appliances supplied from the local tanks on the runoff generation, an alternative type of toilet was assessed. The initial choice of conventional siphon toilet (7 L/use) was replaced with a dual valve flush toilet (2.4 L/use). Also the sensitivity of the development runoff on the SUDS and on the local tanks' capacity was investigated using the one-at-a-time method (Saltelli et al., 2000). The results of this analysis are shown in Table 3. From the values of this table can be inferred that the runoff from development L is less sensitive on the characteristics of the water appliances and water-aware technologies. The runoff from development H is highly sensitive on the capacity of the local tanks.

Table 3: Sensitivity analysis

5. Conclusions

This study investigated the impacts of a new development on the environment. The decision support tool UWOT was used to examine the influence of urban density, of water-aware technologies and of water appliances efficiency on these impacts. The results of this study indicated that:

- Water-aware technologies can effectively reduce the impacts of new developments on the environment by decreasing both the potable water demand and the volume of generated runoff.
- A carefully designed rainwater harvesting scheme can be used to restore the flow pattern of a disturbed hydrosystem to its pre-urbanisation form.
- The runoff from developments that implement rainwater harvesting schemes depends on the efficiency of the appliances that use water from local tanks.
- The sensitivity of the runoff peak on the capacity of local tanks and SUDS increases with urban density. This fact hinders further the stormwater management in high density urban areas, which are already characterised by increased runoff coefficients.

The modern water-saving technologies provide a promising solution for the increasing pressures on the environment. However these technologies introduce interactions between the components of the urban water cycle. In such cases, modelling of the total urban water cycle along with a global optimisation algorithm are required to support the design of new developments and to investigate thoroughly the impacts of retro-fit solutions.

For future research we are planning to couple UWOT with a land-use model that will automatically simulate the urban growth and will generate the development characteristics (including the socially related factors). This will provide estimates of the specific demands for each urban region over time.

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Table 1: Characteristics of developments H and L.

	Development H	**Development L**
Household floor-area ratio	0.47	0.24
Occupancy per household	4	4
Number of households	2000	1000
Public pervious areas	16 hectares	32 hectares
Public impervious areas	42 hectares	26 hectares
Imperviousness	58%	33%

Table 2: Runoff peak and potable water demand of the conventional and optimised developments.

	Conventional development (H/L)	Optimised development (H/L)
Runoff peak (m^3/s)	3.26 / 2.38	1.12 / 1.09
Runoff peak decrease (%)	65 / 54	
Potable water demand (lcd)	140/140	103 / 103
Potable water demand change (%)	27 / 27	

Table 3: Sensitivity analysis.

	Percentage increase of runoff peak (H)	Percentage increase of runoff peak (L)
Dual valve flush	58	31
Decrease 10% of local tank capacity	86	33
Decrease 10% of SUDS capacity	57	33

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Figure 2: Water cycle of the hypothetical developments (1000 households for development L and 2000 for development H).

Figure 3: Water cycle of the households of the hypothetical developments.

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Figure 5: Synthetic runoff "observations".

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