Rethinking urban areas: an example of an integrated blue-green approach
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ABSTRACT
The provision of high quality urban water services, the assets of which are often conceptualised as ‘blue infrastructure’, is essential for public health and quality of life in the cities. On the other hand, parks, recreation grounds, gardens, green roofs and in general ‘green infrastructure’, provide a range of (urban) ecosystem services (including quality of life and aesthetics) and could also be thought of as inter alia contributors to the mitigation of floods, droughts, noise, air pollution and urban heat island (UHI) effects, improvement of biodiversity, amenity values and human health. Currently, these ‘blue’ and ‘green’ assets/infrastructure are planned to operate as two separate systems despite the obvious interactions between them (for example, low runoff coefficient of green areas resulting in reduction of stormwater flows, and irrigation of green areas by potable water in increasing pressure on water supply systems). This study explores the prospects of a more integrated ‘blue-green’ approach – tested at the scale of a household. Specifically, UWOT (the Urban Water Optioneering Tool) was extended and used to assess the potential benefits of a scheme that employed locally treated greywater along with harvested rainwater for irrigating a green roof. The results of the simulations indicated that the blue-green approach combined the benefits of both ‘green’ and ‘blue’ technologies/services and at the same time minimised the disadvantages of each when installed separately.

Key words | blue-green approach, green roofs, local treatment, rainwater harvesting, urban heat island effect, urban water modelling

INTRODUCTION
The combined effects of climatic changes and increasing urbanisation call for efficient planning of new and retrofitting of existing urban areas. It has been argued (Maksimovic 2012), that this requires a paradigm change, rethinking ways of planning, designing, constructing, operating and maintaining urban water systems (blue assets) and urban vegetated areas (green assets), not separately, but in combination. Synergies between green and blue infrastructure could increase amenity and urban health, enhance resilience to drought and flood risk, reduce noise and air pollution, while enhancing biodiversity and quality of life. A clear example of such a synergy can be seen in the case of the impact of urbanisation on the city’s mesoclimate (known as the urban heat island effect or UHI). This effect has been being studied for almost two centuries, starting from Howard (1820), and several specific actions have been proposed to mitigate it (EPA 2012), including increasing tree and vegetative cover, installing green roofs, and using cool pavements. However, these solutions require water for irrigation, which means increased abstractions from the environment. This prerequisite is against the need to protect and manage water resources (Directive 2000/60/EC), especially in water scarce environments – mostly related to climates with a distinctively hot season, where UHI is more pronounced (Koppe et al. 2004).

Happily, water-aware distributed technologies such as rainwater harvesting and water recycling (Makropoulos & Butler 2010) can be used to cover some of the typical...
in-house water needs (e.g. toilet flushing, washing machines) while also supporting additional needs for irrigation of green roofs. However, the benefits from these water-aware technologies/practices cannot be easily estimated since they depend on interactions with other appliances/technologies in the household as well as on climatic conditions. For example, the demand reduction from a rainwater harvesting scheme (with a given tank capacity) depends on rainfall depth, on the frequency of rainfall events and on the number and the type of household appliances that can use harvested rainwater instead of potable water (Rozos et al. 2010). Therefore, a combined modelling approach is required to configure household set-ups in such a way as to take advantage of the benefits of the ‘green’ part of the urban system (reduce UHI effects and runoff volume) without putting additional pressure on the ‘blue’ part.

Arguably, the most prominent urban water modelling tool that employs to some extent combined modelling of blue and green assets is UVQ (Urban Volume and Quality) (Mitchell & Diaper 2010). UVQ runs with daily time steps to estimate the amount of water required for irrigating green areas and can estimate the reduction of potable water required for irrigation in case treated wastewater and/or harvested rainwater are used supplementary to potable water. However, UVQ’s application scale (preliminary assessment) (Mitchell & Diaper 2005) suggests that the tool does not have all the required characteristics (e.g. fine time step to simulate runoff, a metric to quantify the mitigation of the UHI effect, etc.) to fully explore the envisaged blue-green approach.

In this study a new version of the Urban Water Optio-neering Tool (UWOT) (Makropoulos et al. 2008) was developed and used with multiple time steps (5 min, 10 min, and daily) to examine the performance of blue-green technologies at a hypothetical household. The results of this simulation were compared against the results of the simulation of a conventional household to highlight the potential benefits and drawbacks of blue-green technologies.

**METHODS**

UWOT is a bottom up (micro-component based) urban water cycle model, which simulates the demand starting at the water appliance level. Urban water models often use a hydraulics-based conceptualisation of the urban water network, simulating actual water flows, including runoff, potable water and wastewater. UWOT uses an alternative approach based on the generation, aggregation and transmission of a demand signal, starting from the household water appliances and moving towards the source. The simulation results in the estimation of (i) potable water demand, (ii) water level changes inside the tank and reservoirs, (iii) leakages, (iv) evaporation, (v) runoff, (vi) urban water cycle energy consumption (including both energy required for water circulation, e.g. pump of rain water inside the tank, and energy consumed by the water appliances, e.g. heat water for showering), and (vii) capital and operational costs. An analytical description of UWOT is provided by Rozos & Makropoulos (2013). For the purposes of this study, three new components were added to UWOT to assess the blue-green synergy. These are: the blue-green component (BG), the DeTention component (DT) and the signal lag component (SL).

**The UWOT blue-green component (BG)**

The function of the BG component is to simulate the interaction of the urban green assets with the urban water cycle. Specifically, a soil moisture balance model (Thornthwaite-Mather model; Alley (1984)) was used to simulate the principal BG function. A forward numerical scheme is used to estimate soil moisture, runoff, infiltration, root abstractions and real evapotranspiration. The time step $\Delta t$ of the numerical scheme equals that of UWOT simulation. The soil moisture content ($V$) in mm at time step $t$ is given by the formula:

$$V_t = \min(V_{t-1} + \Delta t(R - V_{t-1}f - E(1-lzp)), K) \quad (1)$$

where $f$ is the infiltration coefficient (same units with $\Delta t^{-1}$), $R$ is the rainfall intensity over the green area in mm/$\Delta t$, $K$ is the maximum amount of water in mm that can be retained in the substrate soil, $E$ is the real evapotranspiration of the green area in mm/$\Delta t$ and $lzp$ the percentage of plant water needs covered from the saturated zone. From Equation (1) it becomes evident that the simulated soil moisture fluctuates between 0 and $K$. In this study we assume 0 (the datum) to correspond to the soil moisture conditions of
the readily available water threshold (or RAW, see Allen et al. (1998)). Then it becomes evident that the sum of RAW + $K$ corresponds to field capacity of substrate.

The real evapotranspiration is estimated assuming crop coefficient curve of conifers or reference crop, which practically means it equals the potential evapotranspiration (crop coefficient constant and equal to 1 according to Allen et al. (1998)). The potential evapotranspiration is estimated using the Thornthwaite formula (Thornthwaite 1948).

The parameter $lzp$ was introduced to simulate areas where vegetation includes big trees. In these areas a percentage of evapotranspiration is assumed to be covered with water abstracted by roots from the lower saturated zone (see Sacramento model; Fiedler 2000). In cases where the roots are very shallow (e.g. green roofs, urban grassed areas, etc.) this parameter is assumed 0.

Excess rainfall $Q$ in mm/$\Delta t$, which results in the generation of runoff, occurs when the soil moisture level exceeds $K$. This is estimated at each time step by the formula:

$$Q \Delta t = \max(V_{t-1} + \Delta t(R - V_{t-1}f - E(1 - lzp)) - K, 0) \quad (2)$$

According to Allen et al. (1998), plant water requirement is defined as the amount of water required to compensate the evapotranspiration loss. In our case, the irrigation water requirement basically represents the difference between the vegetation needs and effective precipitation. This amount is symbolised by $D$, has units mm/$\Delta t$ and is estimated at each time step by the formula:

$$D \Delta t = -\min(V_{t-1} + \Delta t(R - V_{t-1}f - E(1 - lzp)), 0) \quad (3)$$

From Equation (3), and the definition of $K$, it can be deduced that irrigation is triggered to ensure that the soil moisture content does not fall below RAW.

Evaporating water consumes large amounts of energy ($En$ in kWh/$\Delta t$), which can be calculated using the following formula:

$$En = AE\rho\lambda \quad (4)$$

where $A$ is the green area in $m^2$, $\rho$ is the density of water in kg/L and $\lambda$ is the latent heat of vaporisation (or latent heat flux), which at 20°C is 2.45 MJ per kg of evaporated water (Shuttleworth 1993) or 0.68 kWh/kg. When evaporation takes place in the open air this energy is absorbed from the surrounding air, thus its temperature is lowered and this is called evaporative cooling. Thus evaporation process from urban green spaces can be used in reducing UHI.

**The UWOT DeTention component (DT)**

Green areas help to mitigate the adverse impacts of excess rainwater both because of retention, i.e. the water that is retained on vegetation plus the water that is retained in innumerable depressions on the surface (Pilgrim & Cordery 1993), and detention, i.e. the lag and attenuation of the runoff hydrograph (Stovin et al. 2012). It should be noted that in this conceptualisation, based on Stovin et al. (2012) and HEC (Hydrologic Engineering Center) (USACE 2000), detention is only assumed to alter the shape but not the volume of the hydrograph. Concerning runoff, the BG component described above simulates only the retention process. Detention is simulated by a dedicated component, the DT component. The modelling of this component can be carried out and calibrated based on the results of the studies of a research team in the University of Sheffield, which performed a series of experiments using a monitoring test bed (Kasmin et al. 2010; Vesuviano & Stovin 2012; Yio et al. 2012). In these studies, a conceptual model with a transient reservoir storage element was used to simulate detention.

The depth $h$ of water stored in the transient reservoir in mm is given according to the model 4 of Yio et al. (2012), by the formula:

$$h_t = h_{t-1} + \Delta t(Q_t - Q_o)/A, \quad Q_o = kh_{t-1}^{1.5}A \quad (5)$$

where $Q_t$, the inflow in L/$\Delta t$ to the transient storage element, is the excess rainfall (output of the BG component); $Q_o$, the outflow in L/$\Delta t$ from this element, is the routed runoff; and $k$ is the detention coefficient in mm $^{-0.5}/\Delta t$.

**The UWOT signal lag component (SL)**

A third component (termed signal lag or SL) is used to introduce lag to hydrographs. This component shifts without
transformation the incoming hydrograph by \( n \) time steps. This is required to model the effects of green components on the (increase of) concentration time of a hydrograph.

**The case study**

These three new UWOT components were used to study a single family hypothetical household that implements blue-green technologies. Figure 1 displays the UWOT representation of the conventional household (used for reference purposes). Potable water connections have been marked with dashed lines.

The demand of each water appliance was calculated by multiplying together the average consumption (L/use) per household appliance (taken from EEA (2001) and Grant (2006)), the frequency-of-use (average values taken from Grant (2006)) and the occupancy. The frequency-of-use (uses/person/day) was assumed constant (no diurnal or seasonal fluctuation). For the summation of the individual demands of the water appliances, the blue component marked with an ‘\( \Sigma \)’ was used whereas for the summation of the output of the appliances along with the runoff from roof (100 m\(^2\) covered with asphaltic material with runoff coefficient assumed equal to 1) the component marked with an ‘\( M \)’ was used.

Figure 2 displays the network of a household that implements blue-green technologies. In Figure 2, the connections of which the demand signal has opposite direction to the flow (this includes demands covered from both potable and green water from local tank) have been marked with dashed lines. This household has the same footprint as the conventional (100 m\(^2\)), but only half of the roof is covered with asphaltic material. The rest of the roof is green. The harvested rainfall (both from the conventional and the equally sized green roof, see Figure 2) is collected in a local tank with capacity 2,000 L, which receives also treated greywater from a local greywater treatment unit with capacity 150 L/d. This unit receives water from both shower and washbasin. The water stored inside the tank is
used (in this example) to irrigate the green roof as well as for flushing the toilet and for use in the washing machine. When there is no water inside this tank, these demands are covered using potable water from the mains.

The conventional and the blue-green households were simulated with UWOT using three alternative stress scenarios:

- The first simulation had a time step of 5 min and a length of 60 min. A uniform rainfall event with total depth of 1.5 mm was assumed for the first 15 min of the simulation (i.e. 0.1 mm/min). This simulation was performed to validate UWOT against the measurements obtained from the experimental set in Sheffield University (Yio et al. 2012).
- The second simulation had time step of 10 min. The historical time series used in this simulation (starting 1 January 1990 and ending 31 December 1999) were obtained from FreeMeteo (2008) for a weather station in Greece (Athens-Hellinikon). This simulation was performed to assess any potential benefits regarding the cooling effect of blue-green technologies.
- The third simulation was based on historical daily time series (temperature and rainfall) starting from 1 January 1990 and ending 31 December 1999 and obtained from NTUA’s weather station (NTUA 2008). This simulation was performed to assess any potential benefits regarding runoff volume reduction from blue-green technologies.

The occupancy of the two households was assumed to be 3.5 (a value close to the average occupancy in Greece according to Hellenic Statistical Authority (2012)). The green roof (50 m²) was simulated with a BG component (‘Green roof’ in Figure 2) with moisture capacity equal to 30 mm. In the simulations with fine time steps, the excess

Figure 2 | Representation in UWOT of the household that implements blue-green technologies (in this case a blue-green roof and rainwater harvesting tank).
rainfall from this component was routed with a DT component (Detention) with detention coefficient equal to 0.034 mm \(^{-0.5}/\text{min}\) (see 5th and 6th rows of Table 1 in Yi et al. (2012)). In the simulation with 5 min time step, an SL component (Lag) was used to introduce a lag of one time step in the hydrograph (average delay of green roofs with 150 mm MCS substrate according to Table 1 of Yi et al. (2012)).

RESULTS AND DISCUSSION

Figure 3 shows the runoff from the conventional roof (no substrate) and the green roof (150 mm substrate) of the first simulation (5 min time step). The simulated response displayed in Figure 3 is similar to model 4 of Yi et al. (2012) (see their Figure 4(c)), which gives confidence in UWOT simulations.
Figure 4 displays the responses of the conventional household and the household with BG components of the second simulation (10 min time step). This figure displays the output of black components marked with ‘M’ in Figures 1 and 2 for the most intense event (started at 25 January 2003 3:40:00 pm and ended 26 January 2003 6:20:00 am) of the simulation period. According to this figure, the green roof and the local tank offered a significant reduction of the runoff volume (2,516.81 instead of 4,856.39 L) because of the retention effect (no runoff occurs until the tank overflows). After the soil moisture reached field capacity and the tank filled, the green roof offered a minor reduction of the peak discharge (0.66 instead 0.77 L/s) because of the detention effect.

Figure 5 displays the potable water demand of the conventional and the households with blue-green technologies, as they were estimated from the third simulation (daily time step). The demand of the conventional household was constant (result of the constant frequency-of-use assumption) and equal to 131.5 L/p/d whereas the demand of the blue-green household fluctuates (greater during summer due to the water required for irrigating the green roof) with an average value equal to 114.0 L/p/d.

The required energy for the in-house water appliances (estimated as the product of the energy consumption per use multiplied by the frequency of use per occupant per day multiplied by the occupancy multiplied by the simulation length in days) of the conventional household is 10.03 kWh/d. The required energy of the blue-green household is 11.14 kWh/d (slightly higher because of the energy required for local treatment) and fluctuates between 10.91 and 11.68 kWh/d because of the increased water demand for irrigation of the green roof (pumped from the tank) during summer.

Figure 6 displays the energy equivalent of the evaporative cooling, which according to Figure 6 exceeds the 300 kWh/d during summer. This figure seems surprisingly large (almost 30 times the average consumption of household water-appliances) but can be verified by some simple calculations. A typical potential evapotranspiration value for July in Mediterranean climates is 250 mm (Koutsoyannis & Xanthopoulos 1999). This translates to roughly 8 mm/d or 8 kg/m²/d. This amount multiplied by the latent heat of water vaporisation (0.68 kWh/kg) results in an equivalent cooling effect of 5.44 kWh/m²/d. For a green roof of 50 m² this amounts to 272 kWh/d. It should be noted that an accurate estimation of the amount of energy saved for household cooling/heating would require thermodynamic modelling of the microclimate (Alexandri & Jones 2006). Although we do not provide in this study such an estimation, it is evident that a portion of the evaporative cooling will be beneficial to the household energy.
budget while the rest of the evaporative cooling will help to reduce the UHI effect.

CONCLUSIONS

This study explores the potential for the adoption of a ‘blue-green’ approach to urban water management. To identify possible benefits and synergies of such an approach, a conventional and a blue-green household were simulated with a new version of UWOT with multiple time steps. The results of the simulations indicated that the blue-green synergy combined the benefits of the ‘blue’ and ‘green’ technologies while minimising their (individual) disadvantages. Specifically, the green roof, irrigated using greywater, offered a significant cooling effect to the household of which the energy equivalent during summer reached up to 50 times the average energy consumption of household water-appliances. Furthermore, although the water demand appeared to have increased during summer due to the green roof’s irrigation, the average annual water demand was decreased by almost 13% due to the contribution of the recycling schemes. Finally, the green roof helped to reduce the annual runoff volume by 40% and peak discharge by 15%.

The findings reported here are, of course, applicable to the climatic conditions (Mediterranean) and the specifications of the blue-green technologies (e.g. 150 mm substrate depth) of the case study. It is expected that the multiple benefits of the blue-green technologies (evaporative cooling, runoff volume, etc.) will vary according to the specific climatic conditions and configurations of each application. However, these results are a good initial indication that the elicitation of synergies between green and blue infrastructure could indeed be promising for enhancing resilience to drought (reduced water demand) as well as flood risk (reduced runoff volumes/flows), while reducing energy requirements, both in terms of building insulation, and mitigating UHI effects (cooling due to evapotranspiration), improving aesthetics, biodiversity and quality of life in the cities.

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REFERENCES


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