A CASE STUDY ON INTEGRATED URBAN WATER MODELLING USING AQUACYCLE

P. KARKA[1], E. MANOLI[1], D.F. LEKKAS[2] and D. ASSIMACOPOULOS[1]

[1] School of Chemical Engineering, National Technical University of Athens
Heroon Polytechneiou 9, Zografou Campus, GR-15780, Athens, Greece.
[2]Department of Statistics and Actuarial-Financial Mathematics, University of the Aegean,
Vourlioti building, 83200 Karlovassi, Samos, Greece.
e-mail: dlekkas@env.aegean.gr

EXTENDED ABSTRACT

The traditional approach to urban water management is primarily based on a supply-oriented approach, where water follows a one-way path from supply to a single use, to treatment and then discharged to the environment. The wide acknowledgement of the need to shift towards more sustainable practices has led to the recognition that demand is multi-faceted; delivered supply should correspond to the varying characteristics of users, taking into account their actual needs in terms of quantity, quality and level of reliability. Such an approach can entail the application of reuse and reclamation methods, which allow for the multiple use of water to meet higher to lower quality needs.

Integrated urban water cycle modelling can be a powerful tool in estimating the potential for the application of such options, as it considers issues related to water supply, wastewater production and stormwater runoff in a holistic framework. This paper presents preliminary results from the application of an integrated urban water balance model, Aquacycle, in the Greater Athens Area. The Aquacycle model accounts for water pathways by simulating two subsystems of the urban water cycle (the rainfall-run-off network and the water supply-wastewater network), and the interactions between them. The software package can also be used for evaluating alternative stormwater and wastewater reuse schemes.

In this paper, Aquacycle was used for simulating water use, wastewater production and stormwater drainage in the Greater Athens Area. For applying the model, the region was divided into smaller – cluster – scales, according to specific structural characteristics. Then, the model was calibrated and validated against measured data, so that model outputs can account for the overall complexity of the Athens urban environment. Finally, three alternative scenarios, comprising the application of on-site recycling and reuse technologies were simulated and evaluated on the basis of three sustainability indicators (i.e. reduction of imported freshwater, wastewater and stormwater discharge).

Keywords: Urban water management, integrated modelling, Aquacycle software, Greater Athens area.

1 INTRODUCTION

A central assumption in the design of water systems and planning of water services throughout the world has been the perception that water is an infinite resource, and operate on once-through, linear terms: water falls as rain, is captured, stored and/or extracted, then treated to meet very high quality standards, regardless of the actual end-use requirements, distributed to customers, used, collected and treated, and finally discharged to the environment.

It could be argued that sustainability improves when a system or process operates more equitably, more efficiently or in a way that reduces its environmental impact. Sustainably designed and operated water services should acknowledge the finite nature of resources, and operate on terms of cycles of source, usage, collection and treatment, recycling, re-sourcing and reusing as much as possible, and thus minimizing their environmental footprint. Sustainable water services should supply only as much water as is actually required, and match the quality of supplied water with that actually required by end-use(r)s [1].

"Water sensitive" urban system design is based on the integration of water supply, wastewater and stormwater management. This concept is now encapsulated in many efforts to promote a more sustainable urban water management, as outlined in the following quote: "water sensitive urban design is the application of a wide range of within catchment measures to manage the impacts of urban developments on the total water cycle" [2].

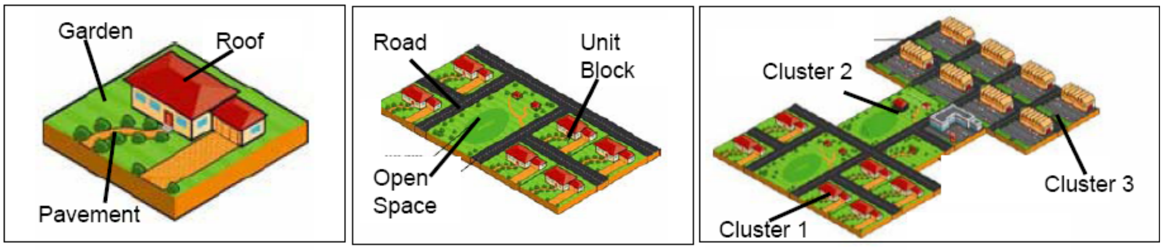
Integrated urban water cycle management is a way of managing water in which all components of the water system are viewed as interlinked in a holistic structure, in order to ensure the optimal use of available resources. This optimal use should be characterised by minimal impacts on water sources, but also on other resources and users, including the environment. A key benefit of a holistic management approach in urban water systems is the range of opportunities available to develop more sustainable systems [3]. Such opportunities can include the application of technology options, such as recycling and reuse methods, stormwater harvesting for aquifer and waterways support, decentralized management, community participation etc.

In the above context, integrated urban water system models can be a powerful tool in exploring the performance of alternative reuse-recycling schemes, and facilitate decision-making by permitting the analysis of diverse, more decentralized solutions. This paper aims at presenting the outcomes of a preliminary application of the Aquacycle integrated urban water management model [4, 5, 6] in the Greater Athens Area. The model was calibrated against measured data and then used to estimate the impact that alternative recycling and reuse schemes could potentially have on freshwater withdrawals, wastewater discharge and stormwater drainage. Although the analysis outlined herein does not make specific recommendations, results indicate that the implementation of on-site recycling and reuse options could contribute towards a more sustainable operation of the Athens urban water system.

2 THE AQUACYCLE MODEL

There is a large number of models available for describing the urban water system. Graham (1976) developed a simple generic total water balance, based on empirical equations, with a daily time step and in a catchment scale [7]; Grimmond et al. (1986) developed a generic water balance model, which includes an evapotranspiration module, requiring estimates on surface aerodynamic characteristics [8]. However, in the past, the interactions among the potable water supply, wastewater discharge and the rainfall-stormwater runoff networks were rarely considered within the same modelling framework, which could provide a more holistic view of the urban water system. WaterCress and Aquacycle are quasi-distributed daily time step models [6]. The former divides a study area into water system components (nodes) that are interconnected by drainage or supply links, while the latter divides the study area allotment clusters that comprise allotments, roads and open spaces. WaterCress models the quality characteristics of water streams, whereas Aquacycle focuses more on urban water balance aspects, estimating the volume of water demand and available stormwater and wastewater in different spatial scales.

Aquacycle operates on a daily time step. It has been developed with the objective to simulate the urban water cycle as an integrated system and can be a powerful tool in investigating the use of locally generated stormwater and wastewater as a substitute for imported (fresh)water in order to improve efficiency in water use (Mitchell et al. 2001). The modelling approach accounts for all stages in the passage of water through the urban water cycle, including the operation of water supply, wastewater production and stormwater runoff systems. The "cycle" starts with water entering as precipitation or (fresh)water imported in order to meet indoor and outdoor water use requirements. It then passes through the urban water system and exits in the form of evapotranspiration, stormwater and wastewater. Aquacycle operates on three spatial scales (unit block, cluster, and catchment), in order to enable the modelling of alternative system configurations and the evaluation of alternative recycle and reuse schemes (Figure 1). The **unit block** can refer to a single household, industrial site, or a public or commercial facility. This scale represents the smallest unit for the management of water supply, disposal and recycle-reuse operations, and is spatially divided into roof, garden and pavement areas. A **cluster** represents a group of uniform unit blocks that can form a local neighbourhood or suburb. In addition to unit blocks, it includes roads and public open spaces, and is used to represent the spatial scale at which community water servicing operations are managed. Finally, the **catchment** is made up of a group of clusters.



Unit Block Cluster Catchment

Figure 1: Spatial scales used in Aquacycle

In Aquacycle, water flows through different processes (stores) that are part of the urban water cycle. The urban water cycle is approached considering all water pathways in two main subsystems; the rainfall-runoff (i.e. the urban drainage system), and the water supply and wastewater system. In both subsystems the water balance is estimated taking also into account the interactions between them. The overall conceptual representation is illustrated in Figure 2. The processes of interception, storage, infiltration, inflow, and drainage are modelled using conceptual stores with parameters that can either be calibrated or introduced by the user. Such parameters include the percentage area of water stores, roof area initial losses, effective area and initial losses for roof, pavement and road areas, the base flow index and the base flow recession constant, the percentage of surface run off that inflows into the wastewater system, the infiltration index and the infiltration store recession constant, and the trigger-to-irrigate ratios for gardens and open spaces. The model receives input both from precipitation and imported water, as well as indoor water use requirements and evapotranspiration data. In Aquacycle, surfaces are divided into two categories: pervious and impervious. Impervious surfaces (roofs, road and paved areas) are represented as single stores that overflow when full. Pervious areas are divided into areas which produce runoff during a rainfall event and those that do not. Water evaporation from both pervious and impervious surfaces is calculated according to daily evapotranspiration values. The algorithms calculate the total amount of water discharged as stormwater runoff from roads, roofs, and paved areas and pervious areas. The amount of water imported into an area is the sum of indoor water use, irrigation, and leakage. The total wastewater discharged from the catchment is the sum of indoor water use, infiltration and inflow from the stormwater drainage system.

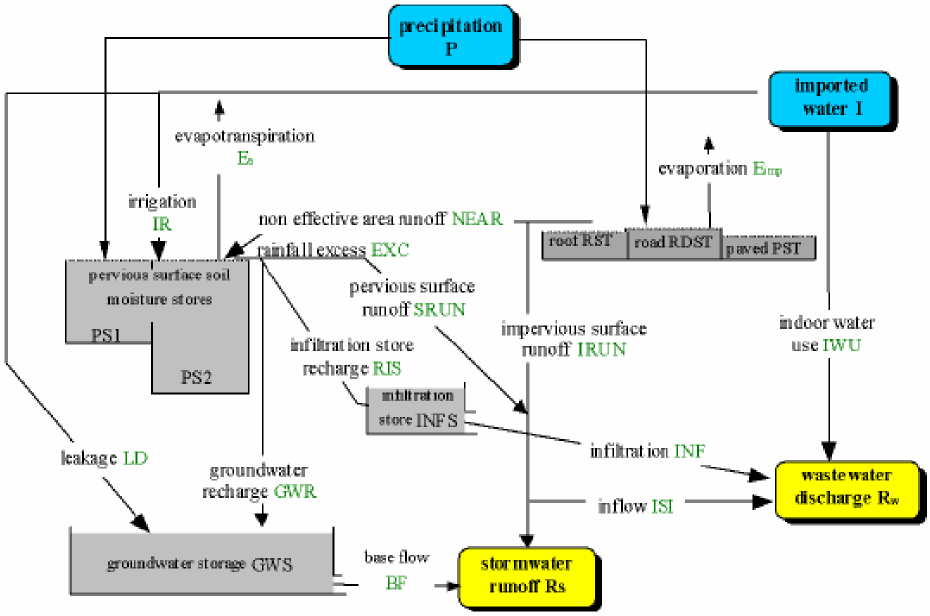


Figure 2: Structure of the urban water cycle and algorithms, as represented by Aquacycle [5]

The Aquacycle input data requirements are related to physical characteristics of the modelled catchment. A distinction is made between measured and calibrated parameters. Measured parameters are related to physical catchment characteristics and their values are determined through measurement, observation or local experience, whereas calibrated parameters are used in the estimation of water use, wastewater production and stormwater drainage.

The Aquacycle package also models a range of technologies which have the potential to provide alternative individual and community scale water service systems. At the unit block scale, options for stormwater and wastewater exploitation include the installation of rainwater tanks, on-site wastewater treatment units and subsurface irrigation with grey water. At the cluster scale, methods include stormwater storage, wastewater treatment and storage and aquifer recharge and recovery. Finally, centralized options applicable at the catchment scale can also be examined, including wastewater reuse and stormwater storage in order to meet the needs of a particular or several clusters.

3 CASE STUDY: A PRELIMINARY APPLICATION OF AQUACYCLE IN THE GREATER ATHENS AREA

The Greater Athens Area covers an area of approximately 400 km^2 and has a permanent population of 3.894.573 persons (2001 Census). The region has a moderate climate with average maximum daily temperatures ranging from 13°C in January to 33°C in July, while the average annual rainfall ranges between 200 and 300 mm/yr. The entire area is serviced by the Athens Water Supply and Sewerage Company (EYDAP SA), through an extensive distribution network of 1.796.500 metered connections. The Athens water supply system includes four reservoirs (Mornos, Evinos and Marathon reservoirs and the Yliki Lake), 350 km of main aqueducts, 15 pumping stations and more than 100 boreholes. Water treatment is performed in four water treatment plants (in Galatsi, Aharnai, Polydendri, Aspropyrgos), which produce up to 1.400.000 m^3/d.

With the exception of a small section in the city centre, where the combined storm and sewerage system has not been replaced, the largest part of the sewerage system of the region is separate, and connected to the Wastewater Treatment Plant of Psyttalia.

3.1 Data processing and modelling of urban water use

The application of Aquacycle in the Greater Athens Area involved the definition of three groups of parameters/data: (a) the indoor water usage profile, used in the estimation of domestic water use, (b) meteorological data, comprising daily precipitation and daily evapotranspiration and (c) the physical catchment characteristics.

The definition of indoor water usage profile at the unit block scale was based on the Canberra water use profile [9]. Due to lack of information, the profile was approximated by adjusting the indoor water usage values that have been developed for Canberra to the average per capita water consumption estimated for Greece (220 lt/cap/day – [10]). The adjustment was based on a 20% reduction of the data provided, also taking into account the average household occupancy of 2.7 persons/hh in Greece [11]. The derived values are presented in Table 1.

Table 1: Estimated indoor water usage profile for Athens

Household Occupancy	Kitchen	Bathroom	Toilet	Laundry
1	24.8	79.2	72	40.8
2	40	128.8	118.4	75.2
3	51.2	174.4	155.2	130.4
4	59.2	206.4	189.6	163.2
5	63.2	227.2	211.2	187.2
6	76	257.6	238.4	214.4
7	88.8	287.2	265.6	240.8

Meteorogical data on daily precipitation were obtained from the Hellenic National Meteorological Service. Data processing involved the calculation of mean values from the 2005 measurements of two meteorological stations (N. Philadelphia and Elliniko). Evapotranspiration was calculated using the Penman-Monteith method, using mean monthly values for minimum and maximum temperature, relative humidity, wind speed and solar radiation, due to the lack of more detailed information.

The definition of measured parameters describing the three spatial scales (unit block, cluster and catchment) of the Aquacycle package entailed the collection of relevant information from various data sources, including digitized maps and satellite images.

In order to arrive at a simplified catchment representation and account for data limitations, it was assumed that the majority of buildings pertain to residential blocks and that the relative share of commercial or public buildings is negligible. Furthermore, and as the majority of buildings in the study area are apartment blocks, the smallest spatial scale selected for the catchment representation (i.e. the unit block) was the flat, and the total number of unit blocks was approximated by the total number of metered connections.

On the basis of satellite images, the catchment area was divided in 5 clusters (see Figure 5), according to the number of buildings per block and/or residential building characteristics, such as garden area, building height etc. Measured parameters included total residential block area, average number of buildings per block, the total roof area and the total garden area. Total road length and area at the cluster level were derived from digitized maps, assuming an average lane width of 1.5 m. Similarly, the total pavement length was approximated as twice the total road length. The pavement area was then derived assuming an average pavement width of 1.5 m. The population of each cluster was obtained from the aggregation of the 2001 census data, and, in combination to the average household occupancy, it was used for deriving the number of unit blocks per cluster. The characteristics of the modelled clusters are outlined in Table 2.

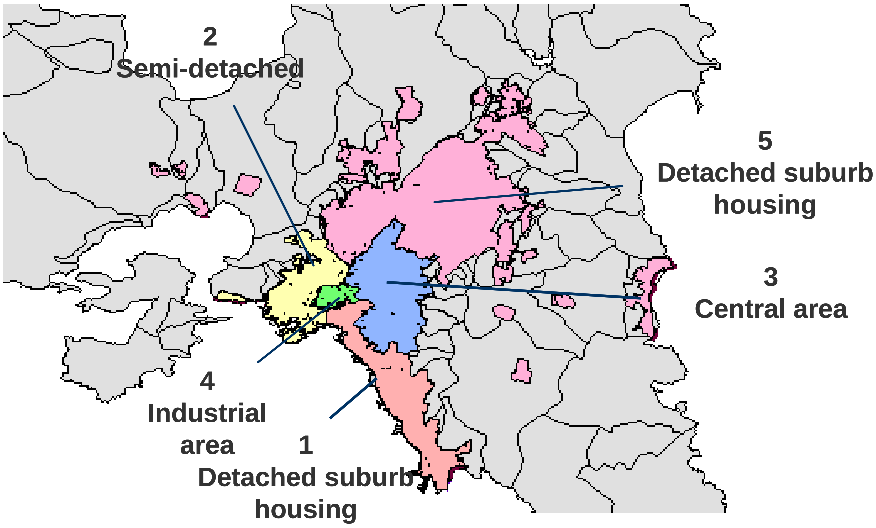


Figure 3: The clusters defined for the Greater Athens Area

Clusters 1 and 5 are characterized as "detached suburb housing"; however, they are represented as different clusters due to differences in the size and characteristics of the respective residential blocks. A typical Cluster 1 residential block is bigger and has a larger garden area than a Cluster 5 block. Cluster 3 corresponds to the Athens city centre, whereas Cluster 4 represents an industrial area characterized by low density housing and large open spaces.

Table 2: Cluster characteristics

Cluster ID	**Population**	**Total Area (km^2)**	**Garden & Open Space (km^2)**	**Pavement area (km^2)**	**Roof area (km^2)**	**Road area (km^2)**
1: Detached suburb housing	430,000	51	30.6	5.1	5.1	10.2
2: Semi-detached	700,000	38	7.6	3.8	22.8	3.8
3: Central area	1,200,000	56	11.2	5.6	28	11.2
4: Industrial area	31,000	5	3.5	0.35	0.15	1
5: Detached suburb housing	1,300,000	207	124.2	10.35	62.1	10.35

3.2 Model calibration and verification

The calibration and verification of Aquacycle was based on data on water supply and wastewater production recorded by EYDAP S.A. in 2005. The calibration process involved the definition, through trial and error, of parameters which have a critical influence to the three major model outputs (water use, stormwater and wastewater production). These included the pervious storage capacity, effective roof area, effective paved area, road area initial loss, effective road area, % of surface run off as inflow, infiltration index, and the garden and open space trigger-to-irrigate ratios. In order to arrive at a set of representative values, which minimize the model error, the following assumptions were necessary:

- All impervious areas are 100% effective in runoff production.
- The "trigger-to-irrigate" ratio for garden and open space areas is very high indicating maximum soil moisture in the irrigated area.

- The percentage of surface runoff that enters the wastewater network is considered equal to 10% for the centre of Athens (combined sewerage system), and 2% in other areas (separate sewerage network).
- The infiltration index depends on the current network condition and construction materials, and an empirical value of 0.2 was chosen.

Figures 4 and 5 portray the model simulation results against recorded data on water supply and wastewater production. Overall, it can be concluded that the model performance is satisfactory; however, the use of monthly average evapotranspiration values instead of daily ones affects irrigation water requirements, and consequently the estimated bulk daily water supply volume. Furthermore, the model cannot adequately account for the drop in water supply and wastewater production volumes, which are experienced during the first half of August. Such variations are attributed to population fluctuation, which the Aquacycle software package does not take into account.

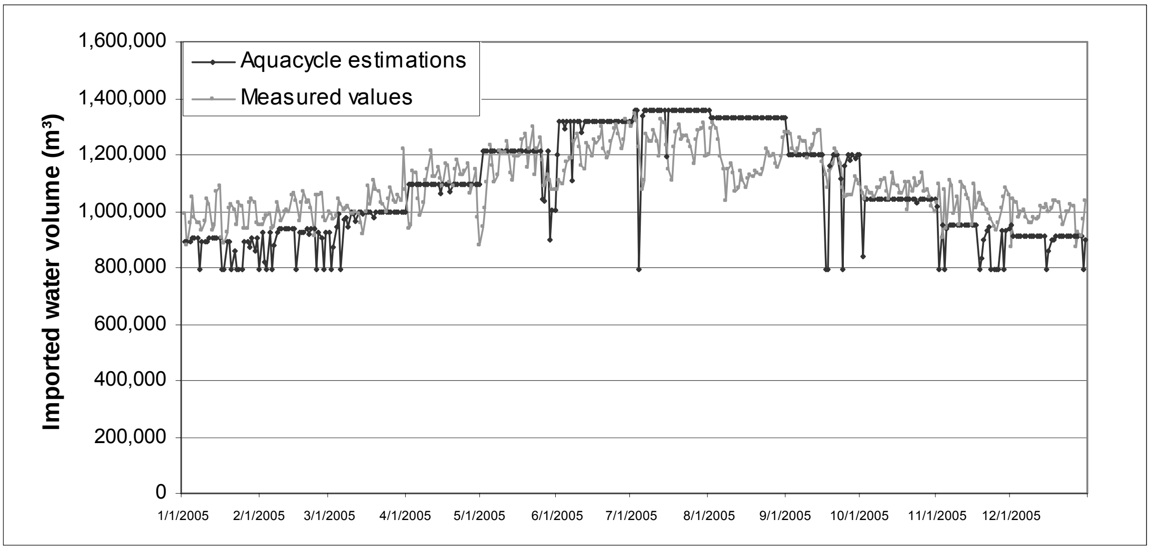


Figure 4: Measured and estimated imported water volumes

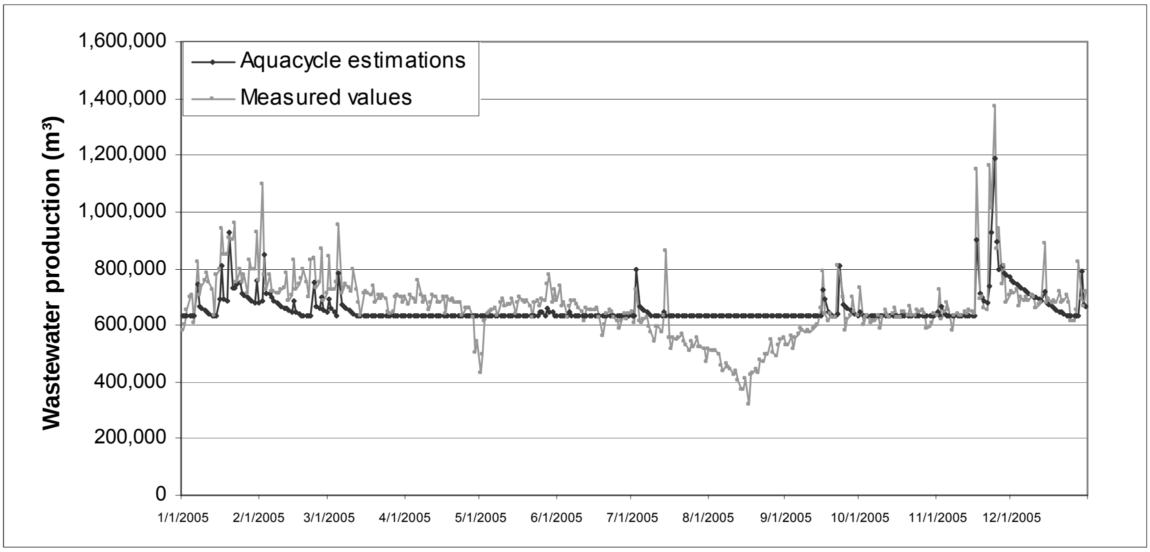


Figure 5: Measured and estimated wastewater production

4 MODELLING AND EVALUATION OF ALTERNATIVE OPTIONS

Following calibration, Aquacycle was used for modelling and assessing the performance of urban water reuse options through scenario analysis. In urban water management, scenario analysis is the process of using analyzed and modelled data, and aims at describing an urban environment in terms of its water, wastewater and stormwater systems [12]. The overall purpose is to identify possible improvements in the urban system, by developing and simulating alternative scenarios and comparing appropriate indicators.

Within the Aquacycle software package, modelled technology options are applied either on-site (unit block scale) or at the cluster and catchment scales, and aim at water saving, reduction in wastewater production and stormwater use. On a preliminary level, only on-site methods were examined and evaluated against a baseline case, according to values obtained for three sustainability indicators: (a) reduction in imported water, which is related to the minimization of freshwater withdrawals and the corresponding cost, (b) reduction in wastewater production, related with the minimization of wastewater treatment costs and environmental impacts from untreated wastewater discharge, and (c) reduction in stormwater runoff, which is related to the minimization of pollution at the receiving water bodies, the minimization of wastewater treatment costs in the case of combined sewerage systems, and possibly contributes to reduced flood risks. Furthermore, each method was applied successively to all modelled clusters, in order to identify how the relative size and characteristics of each cluster affects the impact of the method.

The options analysed with Aquacycle, each formulated as a unique water management scenario were:

- **On-site rainwater use**, involving the introduction of a 2 m^3 capacity rainwater tank at the unit block scale. The tank collects roof runoff for indoor (kitchen, laundry, bathroom, toilet flushing) and outdoor water uses (garden irrigation). Tank overflows are directed to the stormwater drainage network, and water supply deficits are met through freshwater imports.
- **On site wastewater reuse**, where household wastewater is treated in an on-site wastewater treatment unit. A 5 m^3 storage tank is used for storing treated wastewater, which is further used for toilet flushing and irrigation purposes at the unit-block scale.
- **Sub-surface grey water irrigation**, where grey water flows from kitchen, bathroom, laundry and toilet uses, are used to meet garden irrigation requirements. Grey water is directly distributed to the garden through a sub-surface drainage field, according to the daily irrigation requirements.

Additionally, and in order to facilitate comparison, a baseline scenario was also formulated, representing the current status in water use, wastewater production and stormwater runoff in the Greater Athens Area, where water needs are met only through freshwater imports and no water recycling or reuse methods are applied.

Figures 6, 7 and 8 present the results obtained from the successive application of the three technology options. The effectiveness of the application of the technologies increases according to the size of the each cluster. The introduction of each alternative measure to Cluster 5 results in the greatest reduction of imported water, equal to 26% for on-site wastewater treatment and reuse, 14% for subsurface grey water irrigation, and 4% for the installation of rainwater tanks. Furthermore, the successive application of the on-site wastewater treatment and reuse is more effective in the reduction of imported water and wastewater discharge than the on-site grey water irrigation method. In the former case, treated wastewater is directed to both indoor and outdoor uses, whereas in the second method grey water is used only for meeting irrigation needs.

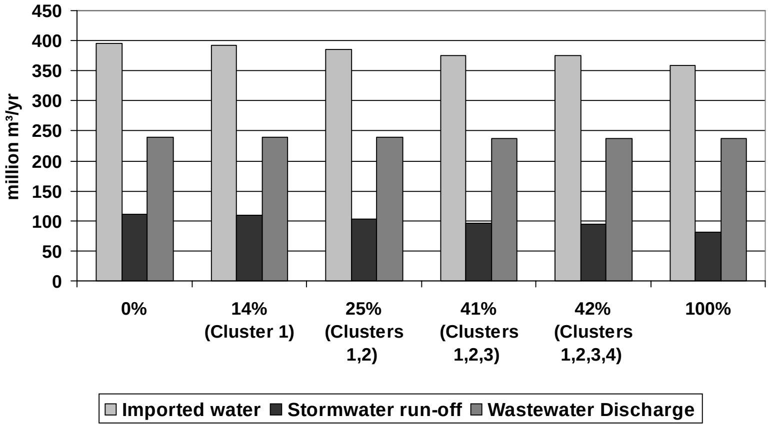


Figure 6: Performance of the rainwater use option

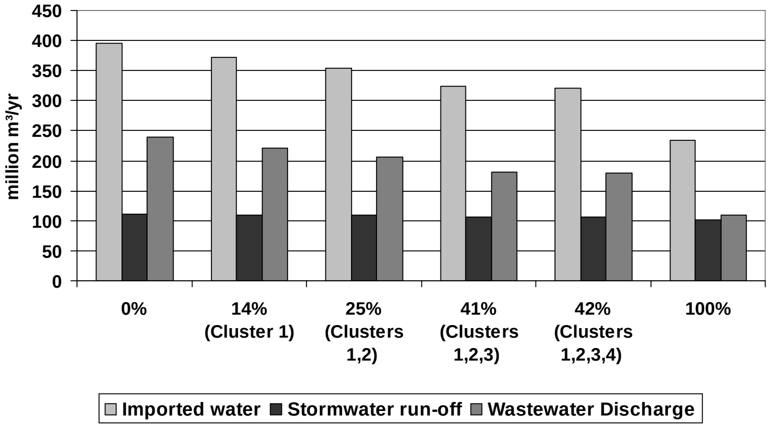


Figure 7: Performance of the on-site wastewater treatment option

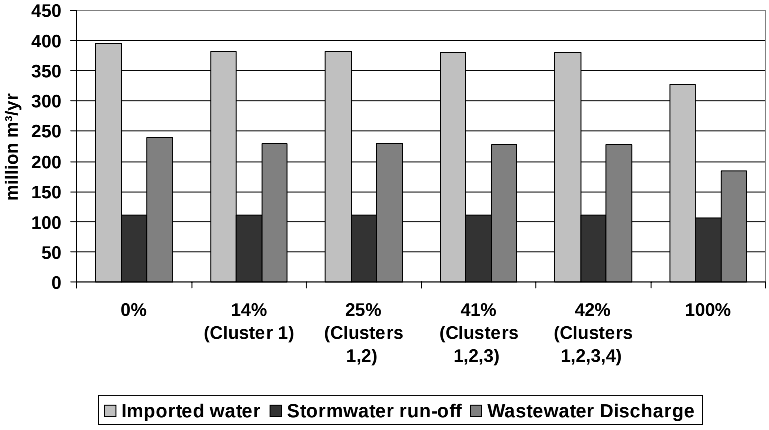


Figure 8: Performance of the sub-surface grey water irrigation option

Table 3 summarizes the overall results obtained from each scenario with regard to the three selected indicators. Overall, the application of on-site wastewater treatment units resulted in a 41% decrease of imported water demand and is therefore the most effective method for achieving significant reduction in freshwater withdrawals. Furthermore, the option has a significant impact on wastewater production, recording a decrease of 54%. The application of subsurface irrigation with grey-water also has a significant effect on freshwater supply and wastewater discharge, whereas the extensive application of rainwater tanks can result in a small decrease in imported water supply and a rather important reduction in stormwater run-off volumes.

Table 3: Performance of alternative schemes (100% application)

	Imported water (million m^3/yr)	**Stormwater runoff (million m^3/yr)**	**Wastewater discharge (million m^3/yr)**
No interventions	395	112	239
Rainwater use	359 (-9%)	82 (-27%)	238 (-1%)
On-site wastewater treatment	235 (-41%)	101 (-10%)	110 (-54%)
Subsurface irrigation with grey water	326 (-17%)	107 (-4%)	184 (-23%)

Therefore, it can be concluded that wastewater reuse methods, even when applied at the unit block scale, can have a significant impact on catchment inflows and outflows; however this approach would require more infrastructure than “rainwater use”, due to the large wastewater production volumes.

5 CONCLUDING REMARKS

The preliminary simulation results obtained from the case study outlined in this paper indicate that the application of on-site technologies, aimed at demand management, can contribute to a reduction in freshwater withdrawal, and reduce the quantity of stormwater and wastewater discharged from an urban area. However, and as the applicability potential of each on-site method also depends on several parameters, including user awareness and economic incentives, a more detailed and accurate representation of the Athens catchment and a feasibility assessment should be undertaken in order to adequately explore the full application potential.

The Aquacycle model, on which the case study outlined in this paper was based, is a generic model that can be applied to any urban area, by integrating water supply, wastewater production and stormwater drainage into a single modelling framework. The model can accurately simulate water supply and the wastewater production even if monthly average evapotranspiration values are used. Furthermore, the options for alternative schemes of recycling and reuse that are available within Aquacycle can be used for the development of scenarios. However, the software cannot account for short-term changes in water use and wastewater discharge due to monthly population changes or temporal and spatial change in water use profiles, and has limited capacity in analyzing long-term scenarios on population growth, urban expansion and climate change.

REFERENCES

1. Greenfield Manual (2002), New approaches to water services, July 2002.
2. WBM Oceanic Australia (1999), Stormwater Recycling Background Study, Queensland Water Recycling Strategy, Department of Natural Resources.
3. Speers A., Mitchell G., (2000), Integrated Urban Water Cycle, National Conference on Water Sensitive Urban Design – Sustainable Drainage Systems for Urban Areas, August 30th & 31st 2000 (Melbourne) Commonwealth Scientific and Industrial Research Organisation (CSIRO)
4. Mitchell, V.G., Mein, R.G., McMahon, T.A. (1999). Assessing the reuse potential of stormwater and wastewater in urban areas. Industry Report 99/14, CRC for Catchment Hydrology, Melbourne.
5. Mitchell, V. G., Mein, R. G., & McMahon, T. A. (2001) Modelling the Urban Water Cycle, *Journal of Environmental Modelling & Software*, **16** (7) pp. 615-629.

6. Mitchell G., Diaper C., Gray S.R., Rahilly M. (2003), UVQ: Modelling the Movement of Water and Contaminants through the Total Urban Water Cycle, 28th International Hydrology and Water Resourses Symposium, 10-14 November 2003, Wollongong, Australia.
7. Graham G.S., Urban Water Resources Modelling, M.Eng.Sc. Thesis, Monash University.
8. Grimmond C.S.B. Oke, T.R., and Steyn D.G. (1986), Urban Water Balance 1, Model for Daily Totals. *Water Resources Research*, 22(10) pp. 1397-1403.
9. Mitchell, V.G. (2000). Aquacycle User Manual, CSIRO Manufacturing and Infrastructure Technology for Catchment Hydrology. Monash University, Australia.
10. World Resources Institute 2001, http://www.wri.org/.
11. European Environment Agency, Indicator Fact Sheet Signals 2001 – Chapter Households, Household number and size
12. Eiswirth M. Wolf L., Holtzl H. (2002), Balancing the contaminant input into urban water resources, IAH Conf. Mar dal Plata, 2002