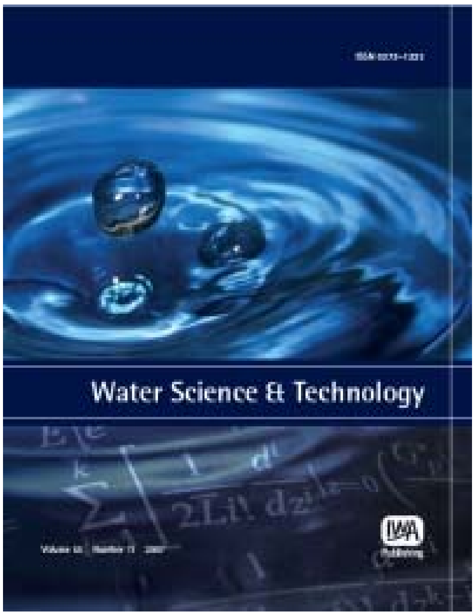

Assessing the urban water balance: the Urban Water Flow Model and its application in Cyprus

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ABSTRACT

Modelling the urban water balance enables the understanding of the interactions of water within an urban area and allows for better management of water resources. However, few models today provide a comprehensive overview of all water sources and uses. The objective of the current paper was to develop a user-friendly tool that quantifies and visualizes all water flows, losses and inefficiencies in urban environments. The Urban Water Flow Model was implemented in a spreadsheet and includes a water-savings application that computes the contributions of user-selected saving options to the overall water balance. The model was applied to the coastal town of Limassol, Cyprus, for the hydrologic years 2003/04–2008/09. Data were collected from the different authorities and hydrologic equations and estimations were added to complete the balance. Average precipitation was 363 mm/yr, amounting to 25.4×10^6 m^3/yr, more than double the annual potable water supply to the town. Surface runoff constituted 29.6% of all outflows, while evapotranspiration from impervious areas was 21.6%. Possible potable water savings for 2008/09 were estimated at 5.3×10^3 m^3, which is 50% of the total potable water provided to the area. This saving would also result in a 6% reduction of surface runoff.

Key words | semi-arid areas, urban water balance model, water demand management, water savings

INTRODUCTION

Urban communities are facing a critical challenge to manage and protect their water resources under the pressure of climate change and population growth. The current approach to water management in urban areas involves supplying potable water and removing wastewater and stormwater (Mitchell *et al.* 2001). There are many who agree that this conventional approach has to change in order to adapt to urbanization trends and current and future climatic changes (e.g. Ashley *et al.* 2005; Wong & Brown 2009). With competition for freshwater resources increasing, wastewater and stormwater should be viewed as alternative sources of water and not just nuisances.

The increase of impermeable areas in cities has led to an increase in the quantity of stormwater runoff with consequences such as floods. Sustainable Urban Drainage Systems (SUDS) are proving to be of major importance with regards to stormwater management (Marsalek & Chocat 2002; Bastien *et al.* 2010). In semi-arid areas, especially in regions where sporadic rainfall tends to be intensive, SUDS would not only facilitate the effective drainage of stormwater, but may also offer the potential of using the captured water for fit-for-purpose productive use. Chanan *et al.* (2010) and McArdle *et al.* (2011) present examples of rainwater harvesting integration in urban areas and emphasize that rainfall harvesting and its treatment should be included in the planning of new developments.

Although the increase of impermeable areas decreases groundwater recharge in cities, there are additional sources of recharge within urban areas, such as leaks from water network systems and septic tanks, storm drains, recharge and retention basins and over-irrigation of gardens (Lerner 2002). These new sources tend to reduce the quality of groundwater in cities, resulting in decreased urban abstraction, which in many cases contributes to flooding (Davison *et al.* 2002; Lerner 2002; Wakida & Lerner 2005). Borehole positioning is critical as water for different uses can be abstracted from different areas of a city (Davison *et al.* 2002).

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Wastewater production is another issue for urban communities, as it increases with population growth and, the more cities expand, the further wastewater will have to be carried to a treatment plant. Treated wastewater may be used for agricultural purposes, for reuse applications at household or neighbourhood level or for aquifer recharge. The selection of centralized or smaller decentralized water supply and wastewater treatment schemes in urban areas requires optimization and both options should be considered (Barton & Argue 2009; Chanan *et al.* 2010; Makropoulos & Butler 2010).

The efficiency and effectiveness of water use in urban environments could be improved through water conservation techniques, advanced technologies, planning requirements and government incentives (Chung *et al.* 2008; Butler *et al.* 2010). In Zaragoza, Spain, in 1997 a new water efficiency culture was promoted through the installation of individual water meters, water saving equipment in homes and water saving awareness campaigns. This resulted in water consumption of 96 L/d per person, the lowest value in Spain (Dworak *et al.* 2007).

The requirement to view stormwater, wastewater and potable water holistically rather than individually has led to the development of various models over the last few decades. These models simulate the urban water and contaminant balances, investigating the impacts of alternative water management options from the household scale up (Mitchell *et al.* 2001; Hardy *et al.* 2005; Mitchell & Diaper 2006; Chung *et al.* 2008; Makropoulos *et al.* 2008; Barton & Argue 2009). These models undertake detailed simulation of the complete urban water cycle, and inevitably require significant data and information for setup as well as specialist knowledge to operate.

The island of Cyprus, located in the far eastern corner of the Mediterranean basin, often suffers from droughts, leaving inhabitants with limited supplies of water. Decades of groundwater pumping for irrigation have resulted in the depletion of groundwater reserves and salt-water intrusion. A large number of dams has been constructed since the 1960s to catch as much surface water as possible, but a step change in the precipitation time series at the beginning of the 1970s, with a 15–25% decrease in mean annual precipitation (Rossel 2001), has led to less water runoff into the dams than expected. Desalination was introduced in Cyprus in 1997 to make up for the deficit in the island's water balance. The latest drought was in 2008, which proved to be one of the most severe on the island as water had to be imported from Greece.

Water saving awareness is promoted on the island by the Water Development Department (WDD), including lectures to more than 40,000 school children in 2010. Spending on water-saving campaigns reached €2.1 million in 2009. Subsidies for four household water saving measures over the past 14 years have been estimated to result in savings of 1.7×10^6 m^3/yr, which is 2.3% of the island's domestic demand (I.A.CO Ltd 2011). Around 80% of these savings are from a borehole subsidy, which aims to replace the use of potable water with that of groundwater, but as such does not reduce the overall consumption of water. During 1997–2010 a total of 7,666 borehole subsidies have been granted, costing €3.2 million to the Cyprus government. Cyprus' programme of measures for the implementation of the European Union's Water Framework Directive recommends, among other things, the expansion of recycled water use as well as the introduction of rainfall harvesting for reuse and groundwater recharge, the reduction of leakage from supply networks, the continuation of water saving subsidies and water saving campaigns, the establishment of a swimming pool levy, regulations for the installation of efficient water use systems in new buildings and increased water prices.

The objective of this research was to develop a simple, user-friendly tool that provides a basic overview of the water flows and losses in an urban area and computes possible water savings. The model can be used by water professionals such as local authorities and researchers to identify and prioritize opportunities for optimizing water management in urban environments, prior to conducting more detailed modelling studies. At the same time, non-experts can easily compute water savings without needing in-depth knowledge. The model was applied to the town of Limassol, Cyprus for the hydrologic years 2003/04–2008/09.

METHODOLOGY

Limassol town is the second largest city of the Republic of Cyprus, located on the south coast of the island, and is considered an important tourist, trade and service centre. The town has a semi-arid climate, with an extended summer and average annual rainfall of 360 mm for 2003/04–2008/09. The case-study area coincides with the area served by the Water Board of Limassol (WBL), a potable water utility, which includes the municipalities and communities of Limassol, Pano Polemidia, Kato Polemidia, Mesa Geitonia and Agios Athanasios. The area covers approximately 70 km^2, housing a population of 156,254 at the end of

2009. No dams or ponds exist within the area and the two streams that cross the town are dammed upstream. An assessment of Limassol's water balance was carried out on water flows in and out of the case-study area, but not on surface runoff or groundwater inflow from higher areas.

A systematic approach to computing the water balance was taken, with the different water users and wastewater producers comprising the systems within the case-study area (Figure 1). The balance is computed and visualized using Microsoft Excel. The model consists of nine spreadsheets, with colour codes to allow for easy identification and understanding of the water flows. The two main components of the spreadsheet are the water balance summary and water-savings application sheet, in which water balances and savings are computed and visualized in pie and bar charts on a yearly basis. Other sheets comprise collected data and equations for computing missing elements and annual summaries. The model is referred to as the Urban Water Flow Model (UWFM).

Systems within the case-study area

The systems within the case-study area include households, hotels, industries and businesses/commercial buildings (including government, non-government, shops, schools, churches and army camps), impervious areas (roads, footpaths and parking lots) and pervious areas (empty plots and fields). The areal coverage of these systems was estimated with the help of Google Map Maker. For estimation purposes the case-study area was divided into low, medium and high population density areas. As the port of Limassol is within the case-study area, potable water supplied to ships was also considered. The aquifer is linked to the study area through groundwater abstraction from boreholes, leakage from the piped networks and soil leaching. Apart from potable water and wastewater networks, the area also includes a recycled water network that provides water to public and hotel gardens and green areas.

Residents within the case-study area were interviewed to find out their habits with regards to garden irrigation, swimming pool management, private borehole use and general household water use. The number of domestic swimming pools was determined from satellite images using Google Map Maker and assumed to be constant throughout the period 2003–2009. Swimming pool installers were contacted to obtain information on pool dimensions and management. The average sized domestic swimming pool measures 4 m by 8 m in area and 1.10–1.80 m in depth. The number and sizes

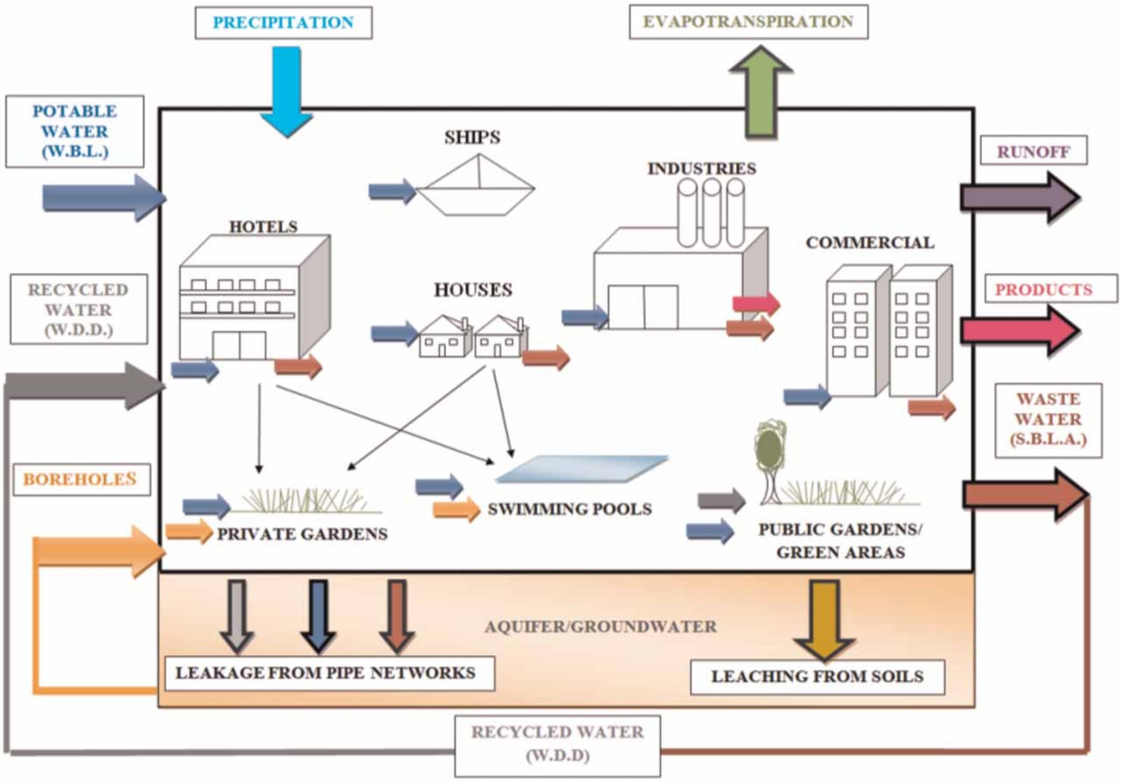

Figure 1 | Illustration of the systems and flows computed by the Urban Water Flow Model.

of the pools at local hotels were assessed through site visits, as well as the source of water used to fill the pools and the refilling sequences.

Water flows entering the case-study area

The precipitation volume was calculated by multiplying daily rainfall data from the Cyprus Meteorological Service local weather station by each area of the system. The WBL provided 4-monthly data on potable water supplied to different water users in the area, while the WDD office in Limassol provided 2-monthly data on recycled water.

The WDD also provided a record of the number of licensed private boreholes, used for watering gardens and/or filling swimming pools. Interviews indicated an average size of 50 m^2 for gardens with boreholes. All garden owners generally kept their gardens well watered, but many used efficient drip and micro-sprinkler irrigation systems. Therefore, it was assumed that garden irrigation was equal to reference evapotranspiration, which represents the evapotranspiration of a uniform surface area of actively growing grass (see next section). Swimming pool owners said that they preferred using potable water to fill their pools.

Water flows exiting the case-study area

Precipitation in the area of Limassol town runs off into a separate stormwater drainage system that discharges the rainwater to sea. Daily runoff was estimated using the Curve Number equation (USDA 1986), selecting a runoff curve number of 98 for impervious areas, 69 for non-irrigated pervious areas and 61 for irrigated pervious areas, considering that the soils in the case-study area could be classified as United States Department of Agriculture (USDA) Hydrologic Soil Group B.

Evapotranspiration from impervious areas was computed as the remainder of the precipitation minus runoff. Similarly, evapotranspiration from households, commercial buildings and industries was computed as the remainder of their potable water consumption, after subtraction of their wastewater and products in the case of industries. To calculate evaporation from private and hotel swimming pools the Penman open water evaporation (Eo) equation, as defined by Craig (2006), was used.

For pervious areas, reference evapotranspiration was computed with the FAO Penman-Monteith equation (Allen *et al.* 1998). Actual evapotranspiration and leaching from irrigated pervious areas (house and hotel gardens and public green areas) and non-irrigated pervious areas were computed using a daily soil water model:

$$\mathrm{SM}_i = \mathrm{SM}_{i-1} + P_i + \mathrm{IR}_i - Q_i - \mathrm{ET}_i - L_i \tag{1}$$

$$\mathrm{IR}_i = 0.5\,\mathrm{TAW} \text{ for } \mathrm{SM}_{i-1} \leq 0.5\,\mathrm{TAW} \tag{2}$$

$$\mathrm{ET}_i = \max(\mathrm{ET}_{o,i}, \mathrm{SM}_i) \tag{3}$$

$$L_i = \max((\mathrm{SM}_i - \mathrm{TAW}), 0) \tag{4}$$

where SM_i is the soil moisture of day i (mm), SM_{i-1} is the soil moisture of day i–1 (mm), P_i is precipitation (mm), IR_i is irrigation (mm), Q_i is surface runoff (mm), ET_i is evapotranspiration (mm), $\mathrm{ET}_{o,i}$ is the reference crop evapotranspiration, L_i is groundwater leaching (mm) and TAW is the soil's total available water capacity (mm). The TAW was assumed to be 80 mm, based on the information provided by a soil map. Equation (2) ensures that, if the soil moisture was less than half the soil water holding capacity, soils would be filled up with irrigation.

Water is exported in the form of beer, wine and milk produced by factories in the case-study area, but no production data could be obtained. According to Fillaudeau *et al.* (2006), the production of 1 L beer requires 5–6 L of potable water, while Hospido *et al.* (2003) mentioned that 4.4 L of potable water are required per 1 L of milk produced. It was, therefore, assumed that the water embedded in products is 20% of the potable water supplied to the factories by the WBL.

The Sewage Board of Limassol-Amathus (SBLA) estimates that wastewater production from households amounts to about 85% of their potable water consumption. This value was also applied for business/commercial buildings and industries (after the subtraction of water embedded in products). After examining data and estimations by the SBLA on the origin of the wastewater entering the treatment plant, it was estimated that 1% of the influent into the plant is from hotels, which are currently connected to the sewerage network. Approximately 75% of the case-study area was connected to the sewerage network for the 2003–2009 period, while the other 25% of the area had septic tanks and soak-aways in place.

Water leaching to groundwater consists of precipitation and irrigation from pervious areas, leakage from distribution networks, leaching from septic tanks and soak-aways and pool water emptied from swimming pools into empty plots. Considering the infiltration characteristics of the aquifer and the small garden sizes, it was assumed that 99% of wastewater disposed of in septic tanks and soak-aways will leach to the groundwater, while 1% will end up as evapotranspiration. A rate of 5% was assumed for the leakage from the sewerage and recycled water networks of the case-study area, which is somewhat lower than the 10% suggested by Chung *et al.* (2008), due to the fact that the majority of the network is outside the case study area and is relatively new. Data for the losses from the potable water network were provided by the WBL.

Swimming pool installers commented that most pools have systems in place that do not require emptying the water completely from the pool, or at least not every year. It was assumed that on average 10% of the domestic swimming pools are emptied once a year. Pool water is emptied either on the streets or in nearby empty fields and plots. It was estimated that around 20% of this water flows into roadside drains and out to the sea, 20% leaches into the groundwater and 60% would evaporate.

Water saving scenarios

As part of the UWFM, a savings application, which computes and visualizes the effect of possible potable water savings, was incorporated. To guide the users, potential upper and lower boundaries for each saving option are displayed. It was considered possible to reduce household water consumption to a minimum of 100 L/d per person, as Zaragoza's inhabitants were recorded to consume 96 L/d per person. It was also considered that up to 40% of water consumed in households is not required to meet drinking water standards and could be replaced with either grey water or rainwater. These savings could also be applied to businesses/commercial buildings. Gössling *et al.* (2012) present a wide range of values for tourist consumption, which indicates that a reduction of 50% for Cyprus' hotel water use, estimated at 415 L/d per tourist (Klohn 2002), is possible. The maximum groundwater use for household irrigation was set at 60% and for swimming pools at 50%, while maximum recycled water use for public areas' irrigation was set at 90%. It was also considered feasible to reduce potable water network losses to 6%.

RESULTS AND DISCUSSION

Precipitation was the largest contributor to flows into the town, with 2003/04 being the wettest year, while the driest was 2007/08 (Table 1 and Figure 2(a)). The average potable water usage for the period was $12.47 \times 10^6\,\text{m}^3$, which was less than half the average precipitation. Approximately 80% of the potable water consumption is by the domestic sector, while the rest is by industry (including a very small percentage by public gardens). The decrease in potable water use between 2007 and 2009 was due to the decline of water reserves, resulting in water cuts by the authorities. The average volumes of groundwater and recycled water used in the town, which are mainly for irrigation, were less than 1% of the total inflows into town (Figure 2(a)).

Table 1 | Water flows entering the town of Limassol during 2003/04 and 2008/09

Year	Precipitation (10^3 m^3)	Potable water (10^3 m^3)	Ground water (10^3 m^3)	Recycled water (10^3 m^3)
2003/04	34,601	10,522	33	37
2004/05	27,447	13,472	34	37
2005/06	19,264	13,879	38	37
2006/07	28,679	13,420	40	37
2007/08	15,288	12,959	44	31
2008/09	27,279	10,587	41	55
Average	25.426	12,473	38	39

Evapotranspiration was the largest outflow from the town, with an average value for the period 2003–2009 of $14.36 \times 10^6\,\text{m}^3$ (Table 2), making up 37.7% of the outflows from the town (Figure 2(b)). This figure includes evapotranspiration from impervious areas at 21.6% of the total outflows, pervious areas at 16% and evaporation from swimming pools at 0.1%. The next highest outflow was stormwater runoff (29.6%), followed by wastewater sent to the treatment plant (16.7%). Data from the WDD showed that in 2004 39% of the treated wastewater was discharged to sea. This number decreased to 15% in 2007 as treated effluent use in irrigation (mostly outside the case-study area) increased. Flows to the aquifer were a total of 16.2% of the outflows, comprised mostly of leakage from the sewerage and potable water networks. Leakage from the potable water distribution network was 16.5% of the potable water supplied to the area. The difference between the total average inflows ($37.98 \times 10^6\,\text{m}^3$) and total average outflows ($38.04 \times 10^6\,\text{m}^3$) is due to the change in soil moisture storage.

Although it is difficult to recover water lost to evapotranspiration in substantial quantities, stormwater runoff could be collected, treated and used as an alternative flow rather than left to flow directly to the sea. Issues do arise with the quality of stormwater as it would contain dirt, oil and

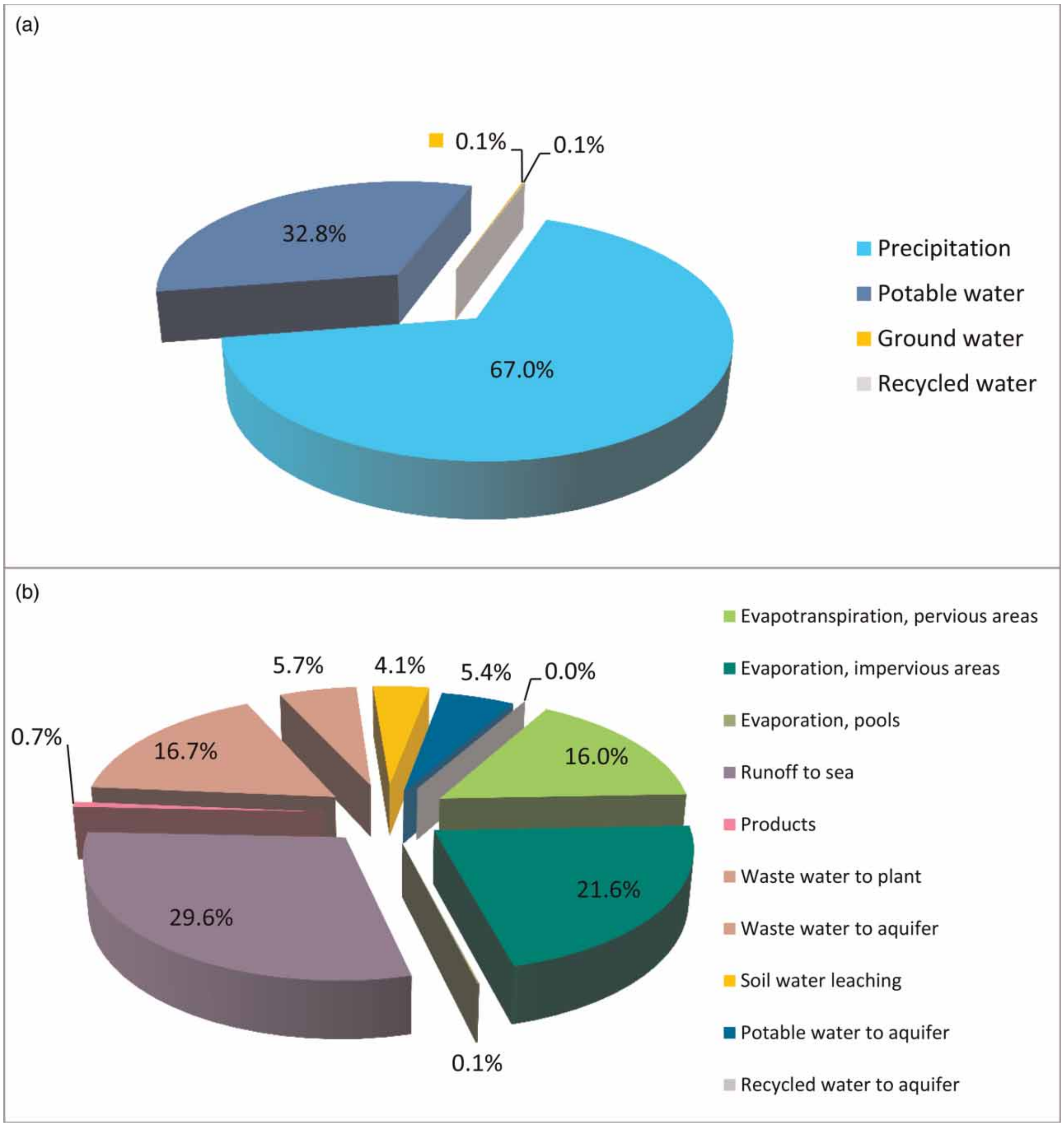

Figure 2 | Average inflows and outflows to Limassol town for the hydrologic years 2003/04–2008/09.

grit, but appropriate treatment and effective storing (Liu *et al.* 2010) would allow for this water to be used for aquifer recharge or irrigation of public areas that are currently irrigated with potable water. In the larger district of Limassol four stormwater retention ponds (of which three are still in the design or construction phase) are to serve as a flood prevention measure, providing a total capacity of $550 \times 10^3\,m^3$. Considering that most water runs off during the wet winter season, these ponds will not be sufficient to capture all of the computed average annual runoff of $11.25 \times 10^6\,m^3$.

Evaporation losses from domestic swimming pools during the summer months (June, July, and August) were calculated to be 223 L/d per pool, while the total evaporation loss from the 684 pools was calculated at $35.20 \times 10^3\,m^3/yr$. Though these quantities may seem negligible compared with the overall consumption of water, the computed average annual water evaporated per pool (141 L/d) is nearly as much as the estimated average potable water use per person (162 L/d). This means that a pool could be considered to be a virtual family member.

Table 2 | Water flows exiting the town of Limassol during 2003/04 and 2008/09

Year	ET[a] (10^3 m^3)	Runoff to sea (10^3 m^3)	Exports (10^3 m^3)	Wastew to plant[b] (10^3 m^3)	Wastew to aq.[c] (10^3 m^3)	Soilw to aq.[d] (10^3 m^3)	Potable to aq.[e] (10^3 m^3)	Recycled to aq.[f] (10^3 m^3)
2003/04	14,246	16,640	271	5,151	1,663	5,163	2,119	2
2004/05	14,889	11,835	265	6,879	2,343	2,605	2,240	2
2005/06	13,511	7,631	280	6,897	2,346	11	2,607	2
2006/07	16,778	12,876	289	6,802	2,324	886	2,283	2
2007/08	10,984	6,115	275	6,571	2,256	8	2,181	2
2008/09	15,766	12,422	240	5,920	2,046	752	880	3
Av.	14,362	11,253	270	6,370	2,163	1,571	2,052	2

[a] Evapotranspiration.
[b] Wastewater sent to treatment plant.
[c] Wastewater losses to aquifer.
[d] Soil water leaching to aquifer.
[e] Leakage from the potable water supply network to aquifer.
[f] Leakage from the recycled water supply network to aquifer.

Aquifer recharge for the 70 km^2 case-study area was calculated to be 5.8×10^6 m^3. This figure is slightly lower than the 3.4×10^6 m^3 direct recharge and return flows reported for the 25 km^2, unconfined Garillis aquifer (WDD 2010), which underlies part of the case-study area. Considering the coastal location of the town and the alluvial characteristics of the aquifer, it was assumed that the groundwater level was static, and if inflow exceeded extraction rates groundwater would flow out to the sea, while for the reverse case (extraction exceeding inflows) seawater would flow into the aquifer. A certain amount of water within the area is also pumped by the WDD and treated through costly reverse osmosis before use. Data from the WBL showed that for 2003–2009 water from dams provided 52–92% of the supply to the case-study area and boreholes 8–36%, while for the years 2008 and 2009, respectively, 26 and 15% of the supply was water shipped in by tankers. Losses of potable water from the network to the aquifer were a small percentage of outgoing flows compared with runoff; it nevertheless is high quality water that costs money to treat and transport and is wasted.

Table 3 presents the 2008/2009 potable water consumption before and after the maximum possible savings were applied, as detailed above. Grey water recycling and rainwater harvesting replaced non-potable water needs by 20% each. Issues, however, may arise with the use of grey water as it could result in reduced and more concentrated wastewater flows to the treatment plant. Network losses for the specific year were already low due to prolonged water cuts during that year. The total savings that could have been achieved in 2008/09 were approximately 50% of the total potable water consumption. Through rainfall utilization, stormwater runoff was also reduced by 6%. Household savings contributed 90% to the total potable water savings.

Table 3 | Potable water use for 2008/2009 before and after savings application, and relative contributions to total potable water savings

System	Before savings application m^3	After savings application m^3	Percentage of total savings %
Households	8,243,203	3,412,686	90.8
Household gardens	35,467	30,213	0.1
Household pools	29,940	14,970	0.3
Hotels	58,584	29,292	0.6
Hotel gardens	861	861	–
Hotel pools	3,555	3,555	–
Businesses/Com	680,400	281,686	7.5
Industries	504,000	504,000	–
Public gardens	12,600	6,495	0.1
Ships	138,709	138,709	–
Network losses	880,180	847,000	0.6
Total	10,587,498	5,269,466	100

The UWFM was presented to water officials in private consultations. They particularly appreciated the capability of the model to provide an integrated view of the water balance and flows in the study area, as they tend to focus on a specific source of water. They commented that an economic aspect could be added to the model that would allow officials and stakeholders to weigh up costs of the different sources.

CONCLUSIONS

The UWFM was developed to allow the quantification and visualization of water flows and losses in urban environments. The model was applied to the coastal town of Limassol on the semi-arid island of Cyprus and allowed for an overview of the overall management of the town, identification of inefficiencies and possible water savings. For the period 2003/04–2008/09 the major losses from the system were stormwater runoff, which was 44% of the precipitation. Rainfall utilization for the area should be further investigated as the amount of stormwater runoff of the area is considerably large and is left unexploited. Another important loss was leakage of potable water from the distribution network, which was 5.4% of the outflows. Investment in reduction of potable water network losses needs to be considered as this is water that has been collected, treated and transported and then lost. Computations of water savings by a special component of the model show that application of water saving measures, rain water harvesting and grey water use could have resulted in potable water savings of up to 50% and a 6% reduction in stormwater runoff for the year 2008/09.

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