EXPLORING THE LINK BETWEEN URBAN DEVELOPMENT AND WATER DEMAND: THE IMPACT OF WATER-AWARE TECHNOLOGIES AND OPTIONS

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Abstract

In conventional urban planning, water demand is covered exclusively by potable water supply and used wastewater is directly conducted to the sewers. One of the disadvantages of this practice is that the expansion of an urban area puts additional pressure on existing water infrastructure (both water supply and wastewater networks), which may result in capacity exceedance. In such cases, the required upgrades of existing infrastructure are slow and potentially very costly. On the other hand, modern decentralized water-aware technologies (including for example grey water recycling and rainwater harvesting) enable water reuse at the scale of a household or a neighbourhood. Such options reduce the pressure on the infrastructure and alleviate the need for upgrading centralized infrastructure, hence reducing the cost of urban growth. In an attempt to quantify the potential benefits of these technologies we coupled an urban water management model with a land-use model based on Cellular Automata (CA). The land-use model produces scenarios of urban growth/transformation, which are then assessed through the use of an urban water management model. The assessment is based on indicators including potable water demand, peak runoff discharge and volume of produced waste water. The final result is a representation of the evolution of these indicators as a function of urban growth contrasting conventional and innovative practices.

Keywords
Cellular automata, geography, urban growth, urban water management, water demand, water optioneering

1. INTRODUCTION

In the classic model of the urban water cycle (input-use-disposal), the capacity of the sewerage needs to equal the capacity of the drinking water supply network, which in turn needs to equal water demand. Consequently, the ongoing expansion of urban areas, with its associated increase in demand, results in additional pressure on these networks. This pressure, proportional to the urban growth and to the water demand per household, results in an increasing cost for maintaining and expansion of existing urban water infrastructure. In this study we are investigating the influence of these two factors, water demand per household and urban growth, on the urban water cycle.

To manage this water demand, a growing portfolio of technologies for decentralized urban water management enable water reuse at the scale of a household or a neighbourhood rather than wasting this resource by direct disposal to the sewage network [1]. The benefits from these technologies include the decrease of potable water demand and wastewater (WW) volume. Further reduction of potable water demand can be achieved with rainwater harvesting, which has also the advantage of decreasing flood risk in urban areas [2]. Therefore new decentralized technologies may not only be environmentally beneficial (reduction of the required water resources and volume of disposed WW), but also economically (including energy) advantageous. In this study the Urban Water Optioneering Tool (UWOT) [3], [4] was used to simulate both conventional and innovative elements of the urban water cycle and investigate the impact of decentralized water technologies.

Urban growth takes place either at the boundaries of large urban areas and/or at small isolated population centres. Various approaches have been used to model this development with cellular automata being one of the most popular [5]. Urban growth resembles the behaviour of a cellular automaton in many aspects. An automaton is an entity that has its own spatial and non-spatial characteristics but also has the mechanism for processing information based on its own characteristics. Cellular Automata (CA) are a special type of automata that are arranged in regularly tessellated space, for example, a regular grid. Information can be processed and transmitted between cells (or automata), which propagates through neighbouring automata [5].

UWOT and a CA model were coupled to investigate the combined effects of water demand per household and urban growth on the urban water cycle. The case study area was the broader area of Mesogeia in east Attica, Greece, which is characterized by intense building-construction activity, supported and fuelled by the high-speed motorway that connects the centre of Athens with its new international airport.

2. STUDY AREA

In order to apply the CA model on the case study area a set of geographical layers was prepared and a series of geographical manipulations were performed. More specifically: (i) the Corine land-cover raster data for the year 2000 was obtained from European Environment Agency [6] and was re-projected to the Greek coordinate system GGRS 1987; (ii) the Digital Terrain Model (DTM) of the area was obtained [7] and the initial resolution of the DTM (25×25 m^2) was lowered to the resolution of the land-cover raster map (100×100 m^2); (iii) the transportation network of the area was also obtained [8] and was converted to a raster map containing the primary and secondary roads, the railway stations and the motorway links; (iv) a map with the boundaries of the municipalities was also obtained [9]; (v) the urban properties (real estate) of the studied area were classified into four *urban categories* according to their characteristics (Figure 1) and a map with the regions where each category dominates was manually digitized (Figure 3 right panel) based on the knowledge of the area and on satellite images.

Figure 1. Representative orthophoto images [10] of the categories (from left to right) 1, 2, 3 and 4 respectively

The aggregated characteristics of the properties contained in a CA cell for each one of the four categories are shown in Table 1. The numbers in the table, refer to average numbers of the category in question, inside a CA cell of an area of 100×100 m^2. Specifically, “Occupancy” refers to the average number of persons accommodated into one household. “Buildings” refers to the average number of buildings inside a CA cell. “Public impervious areas” refers to average area occupied by roads in the cell. The “Private pervious areas” refers to the average area of the gardens in the cell and “Private impervious areas” refers to the average area of the roofs of the buildings inside a CA cell.

Table 1. Characteristics of the four categories of urban properties

	Cat. 1	Cat. 2	Cat. 3	Cat. 4
Occupancy	21	4	14.5	3.5
Buildings	13	21	19	17
Public impervious areas (m^2)	1815	1768	2298	750
Private pervious areas (m^2)	2577	5178	2246	5151
Private impervious areas (m^2)	5643	3052	5442	4101

3. APPLICATION OF CELLULAR AUTOMATA

Fuzzy constrained cellular automata [5] were used to model the urban development of the studied area, following a successful application of this method by Mantelas [11]. This approach is deployed by forming a number of independent, parallel fuzzy inference systems (FIS), each one focusing on one specific, distinct set of urban growth factors. Multiple-input-single-output and single-input-single-output FIS were employed with linguistic terms derived from human reasoning [12]. The use of a set of independent FIS leads to a highly configurable mapping pattern, in which rules and variables can be added, subtracted or modified without altering the rest of the model flowchart.

Mamdani-type fuzzy systems [13] were chosen because of their extensive applicability, their simplicity of formulation and their generality of use. The category of inputs used in the multiple-input-single-output system was the road network accessibility (including primary and secondary roads, as well as motorway links), whereas the input variables used in the single-input-single-output systems were the Corine land-use/land-cover indices, the elevation and the mass transportation availability, expressed as a distance from railway stations (a different FIS was created for each input). The input variables were mapped to a set of fuzzy values with the fuzzification process. The fuzzy values were defuzzified with the use of the centre-of-gravity technique in order to provide the corresponding crisp values of the output variables, which for all fuzzy systems represent a Suitability Factor (SF) that quantifies the suitability for urbanization driven by the specific input variable(s). The SF values derived from each FIS were combined together with a linear formula to obtain the overall SF, with values ranging from 0 (completely unsuitable for settlement) to 1 (completely suitable). This process, applied for each cell of the studied area, resulted into a raster map of SF values. The inputs of the CA model are the initial urban/non-urban states of the cells (in our case provided by the Corine 2000) and the SF raster map. Two rules of urban expansion and one rule of spontaneous growth were employed [11]. These rules combine the SF with the number of urban cells in the Moore neighbourhood (radius 1, 2 and 3 for the two expansion and the spontaneous growth rules respectively). This combination gives the probability for the state of a cell to change from non-urban to urban. After the first step's estimation of cells that turn into urban, the rules are applied again using the updated states for the next time step (Figure 2).

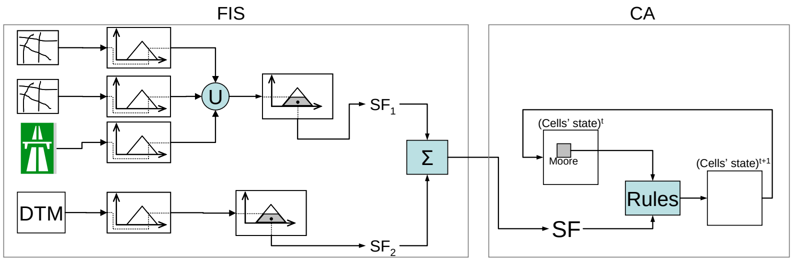

Figure 2. Flow chart of the fuzzy constrained cellular automata used in this study

The result of the application of the CA model from 2000 to 2020 (using a yearly time step) is shown in Figure 3.

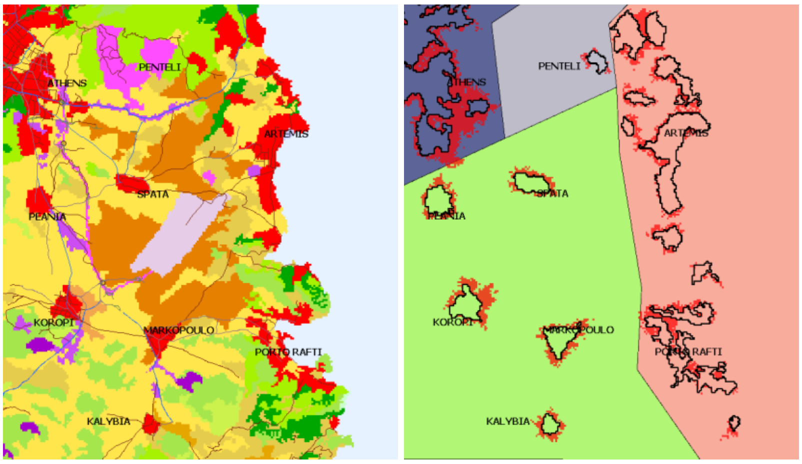

Figure 3. Left panel: Geography of the studied area including land-uses (Corine 2000), road network and railway stations. Right panel: Expansion of the urban area between 2000 (thick black lines) and 2020 (red areas); with different colours the areas of the four categories (blue=cat. 1, pink=cat. 2, green=cat. 3 and grey=cat. 4)

In Table 2 the number of new urban cells as predicted by the CA model for the year 2020. Similar tables were derived for the years 2005, 2010 and 2015.

Table 2. Results of the CA model for the year 2020.

	ATHENS	PEANIA	KOROPI	KALYBIA	PENTELI	SPATA	ARTEMIS
Cat. 1	1154	0	0	0	0	0	0
Cat. 2	0	0	0	0	1	1	757
Cat. 3	17	154	260	105	0	135	0
Cat. 4	0	0	0	0	44	0	0

4. APPLICATION OF UWOT

The UWOT version used in this study is compiled into a Matlab executable and it is integrated into a platform along with a database, which stores a library with the specifications of the water technologies and the topology of the network.

For each category of urban properties, two sets of configurations, the “conventional” and the “innovative”, were assessed. The innovative configuration is shown in Figure 4. This figure displays the demand signals (not the flows) emitted and received from/by water appliances. For example the blue line connecting a Kitchen Sink (KS in Figure 4) with the water supply network (PL in Figure 4) denotes the use of potable water to cover the needs of this appliance. The conventional configuration is similar to the one depicted in Figure 4 but without the Tank, the Local Treatment (LT in Figure 4) and, of course, with the demand of all appliances covered with potable water.

Using manual optimization the capacities of local tanks were defined as 40 m^3, 10 m^3, 40 m^3 and 10 m^3 for the urban categories (from 1 to 4 respectively) discussed above. The capacity of the local treatment unit was 300 L/d and 150 L/d for categories 1 and 3 and no local treatment was used in the remaining two categories.

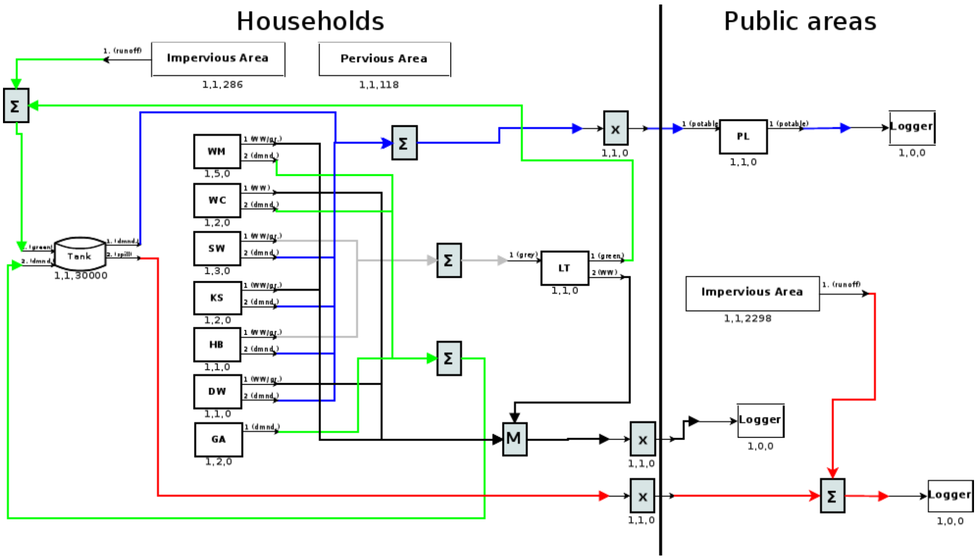

Figure 4. Configuration of the innovative water network

UWOT was used to simulate the water cycle in each of the four categories of Table 1 with a daily time step (historical daily rainfall timeseries were obtained from [14]). The results of the simulation, displayed in Table 3, correspond to the period from 1/1/1980 to 31/12/1999. The values displayed in this table include average potable water demand and WW and maximum runoff volume for the simulation period.

Table 3. Results of simulations of the four categories with UWOT

		Cat. 1	Cat. 2	Cat. 3	Cat. 4
Potable Demand (L/d)	Innovative	26253	8639	27759	5459
	Conventional	34807	10977	35177	7743
WW Out (L/d)	Innovative	29360	10234	30714	7249
	Conventional	33260	10234	33564	7249
Max Runoff Volume (m^3)	Innovative	650	537	441	681
	Conventional	1037	675	1076	681

5. COMBINATION OF UWOT WITH CA

The combination of the results of UWOT with the CA model is based on the Cartesian product of the spatial distribution of the four categories with the spatial distribution of the new urban areas (as modelled by the CA). The result of this product, when grouping new urban areas by municipalities, can be seen in Table 2. The final urban water flows of the new urban areas (grouped by municipality) are then obtained by multiplying the rows of Table 3 (results of UWOT) with the columns of Table 2. The result of this multiplication for the year 2020 is displayed in Table 4 (some of the municipalities appearing in Figure 3 are omitted in this table because of width limitations).

The multiplication of the "Max Runoff Volume" row of Table 3 with the columns of Table 2 gives the maximum runoff volume from new urban areas per municipality. To estimate the maximum discharge, the SCS triangular hydrograph method along with the Kirpich formula [15] were used. The duration of the rainfall episode that gives the maximum runoff (141.3 mm recorded at 26/3/1998) was assumed 10 hours. This was the recorded duration of the 26/3/1998 episode at a meteorological station close to the study area [16] that measures rainfall with a time step of 10 minutes (not used in this study because its record length is short). A uniform slope S=3% (a value derived from inspection of the slope in the case study area) is considered for the whole study area. The maximum length of flow L inside new urban areas was calculated using the assumption that the deployment of the new urban cells in the municipalities of the study area follows the form of a simple geometric shape (rectangle). In this case n new urban cells are organized into a $\sqrt{n}\times\sqrt{n}$ rectangle having diagonal length $L=\sqrt{2}\times\sqrt{n}\times 100$ (with 100 being the raster resolution). Because of these rough assumptions, the maximum discharge values provided in Table 4 are indicative and can server only as a comparison between "innovative" and "conventional" configurations.

Table 4. Urban water flows of new urban areas built from 2000 to 2020

		ATHENS (Cat. 1)	ARTEMIS (Cat. 2)	KOROPI (Cat. 3)	PENTELI (Cat. 4)
Potable Demand (m^3/d)	Innovative	30768	6540	7217	249
	Conventional	40765	8310	9146	352
WW Out (m^3/d)	Innovative	34404	7747	7986	329
	Conventional	38953	7747	8727	329
Max runoff (m^3/s)	Innovative	28.8	15.7	4.6	1.2
	Conventional	46.2	19.7	11.1	1.2

Figure 5 displays the evolution of urban water flows for the town of Koropi (category 3) for the years 2005, 2010, 2015 and 2020. The slope of these curves reflects the urban growth rate, which is high in the period 2005-2010, low in the period 2010-2015 and again high in the period 2015-2020.

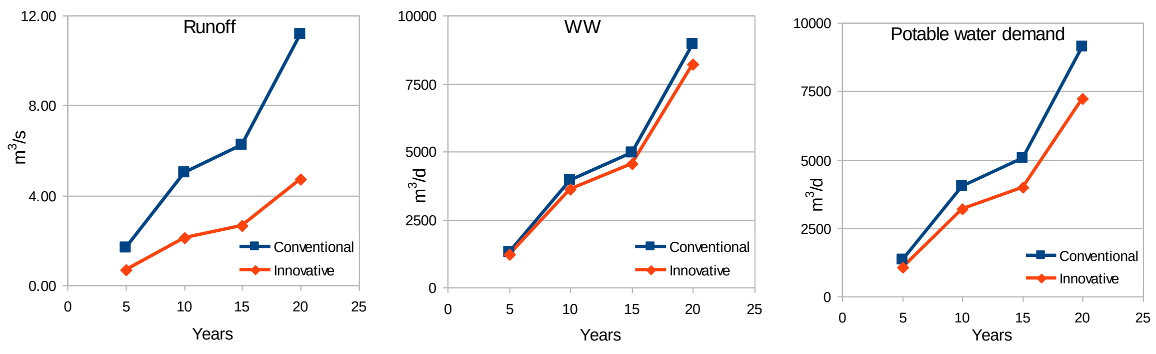

Figure 5. Evolution of urban flows with urban expansion of Koropi

6. CONCLUSIONS

In this paper the urban water cycle model UWOT was coupled with a land-use model developed for this study in an attempt to quantify the potential benefits of water-aware technologies for urban growth. The conclusions derived from this study are:

- Spatial analysis of demands over time: The combination of an urban water cycle model with a land-use model facilitates the planning of urban expansion because it provides estimates of the specific demands for each urban region (in this case, the municipality boundaries but in principle other areas of interest, for example, areas corresponding to the nodes of a drainage network) over time. This helps the decision makers to both define the implementation that achieves the best compromise between different metrics and to define the optimum location and time schedule of the required actions/interventions.

- Benefits in low density urban areas: In low density urban areas (categories 2 and 4 in this study) the rainwater harvesting scheme provides considerable reduction of the potable water demand but marginal reduction of the runoff peak. This is because of the low water withdrawal rate from the tank (due to low occupancy), which results in a reduction of the tank availability to store rainwater. Nevertheless, this is not a major disadvantage since these areas usually do not generate significant volumes of runoff due to the low overall runoff coefficient. On the other hand these areas can exhibit increased water demands that can be covered with rainwater (e.g. watering of gardens), which renders attractive the rainwater harvesting scheme.

- Benefits in high density urban areas: In high density urban areas (categories 1 and 3 in this study) the runoff peak and the potable water demand can be reduced considerably by a combined scheme that includes rainwater harvesting and local water treatment. The high occupancy (multi-store buildings) results in high rates of water withdrawal from the tank that stores rainwater, keeping the volume inside it low and consequently the storage availability high. This is positive since it helps reduce stormwater pressure on the urban network at the areas that usually have high runoff coefficients. However, in order to compensate the high withdrawal rate and ensure availability of non-potable water, water treatment should be used as a supplementary source. This has the additional benefit of WW volume reduction.

- Geography and urban modelling: The increasing availability of open geographic information (satellite and orthophoto images, street maps, land-use maps etc) combined with the interoperability of modern mathematical tools (e.g. Matlab, Octave etc) and modern geographic information systems (e.g. ArcGIS, QGIS etc) provide easy implementation of advanced spatial analysis and modelling methods and tools that can be customised for any area of interest, analysing site specific properties and providing customised solutions and interventions for combining urban development studies and innovative, distributed, whole water cycle management.

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