

# Turning black into green: ecosystem services from treated wastewater

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## Abstract

In order to reduce the impact of the urban effluents on the environment, modern societies have imposed restrictions regarding the quality of the disposals. For this reason, in the majority of the western world cities, the wastewater is treated before disposal. However, on the other side of the urban water cycle, water abstractions keep putting an increasing pressure on the water resources. As a countermeasure, treated wastewater is used occasionally as an alternative resource by employing large scale infrastructure to treat and supply water for either irrigation or industrial uses. Despite the existence of numerous successful applications, this practice is not very common mainly because of the increased capital and operational costs, usually exceeding the cost of fresh water. The response of the market to this drawback was to introduce in-situ small scale treatment units to cover local water needs. In this study, we assess the benefits of a compact wastewater treatment unit that is used to provide water for irrigating a green area. Apart from the aesthetic improvement, benefits are expected because of the evaporative cooling (latent heat), which reduce the air temperature. A pilot scheme was set up in KEREFYT, the research centre of Athens water supply company. This scheme was simulated with UWOT model to estimate the heat fluxes and the results were fed into Energy2D (a model that simulates heat transfer) to estimate the expected temperature drop.

## Keywords

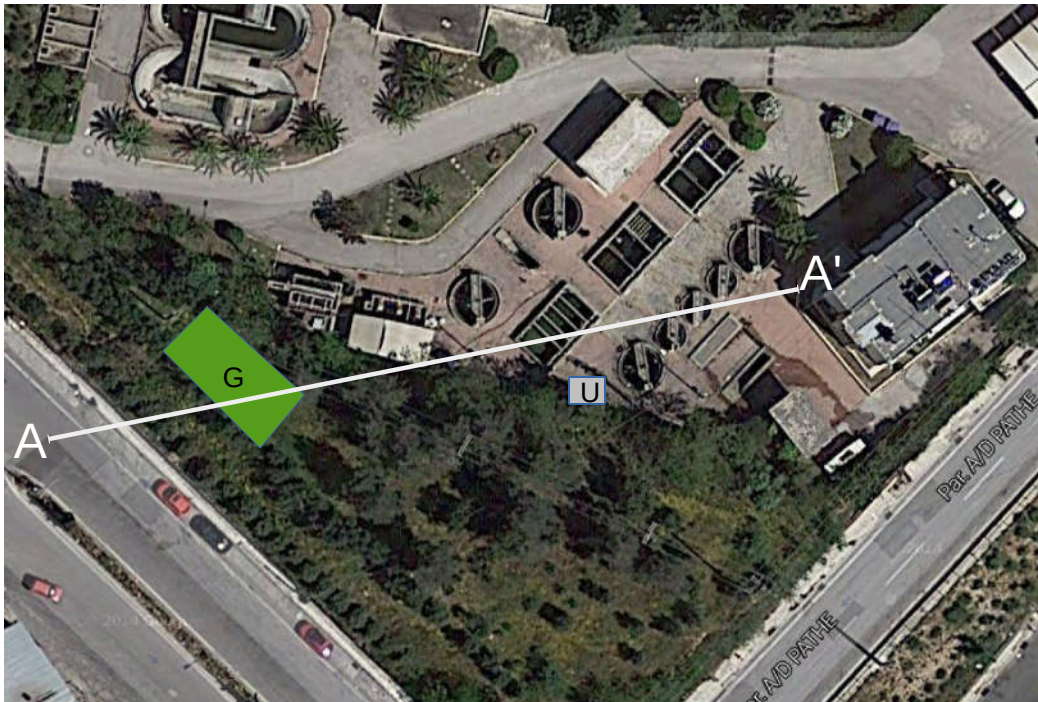
Ecosystem services; local treatment; urban heat island

## INTRODUCTION

In this study we are assessing the benefits of using treated water for irrigating a green area of 50 m<sup>2</sup> in KEREFYT, the research centre of Athens water supply company. The water for irrigation comes from a pilot compact treatment unit with capacity of 1 m<sup>3</sup>/d. The compact treatment unit consist of two adjacent boxes: one 2.16×2.00×2.87 m<sup>3</sup> box contains the membrane bioreactor whereas the other 2.16×3.00×2.87 m<sup>3</sup> box contains the reverse osmosis and the controllers of the unit. The unit is processing wastewater obtained from the Metamorfosis treatment plant and returns the produced sludge back to the plant.

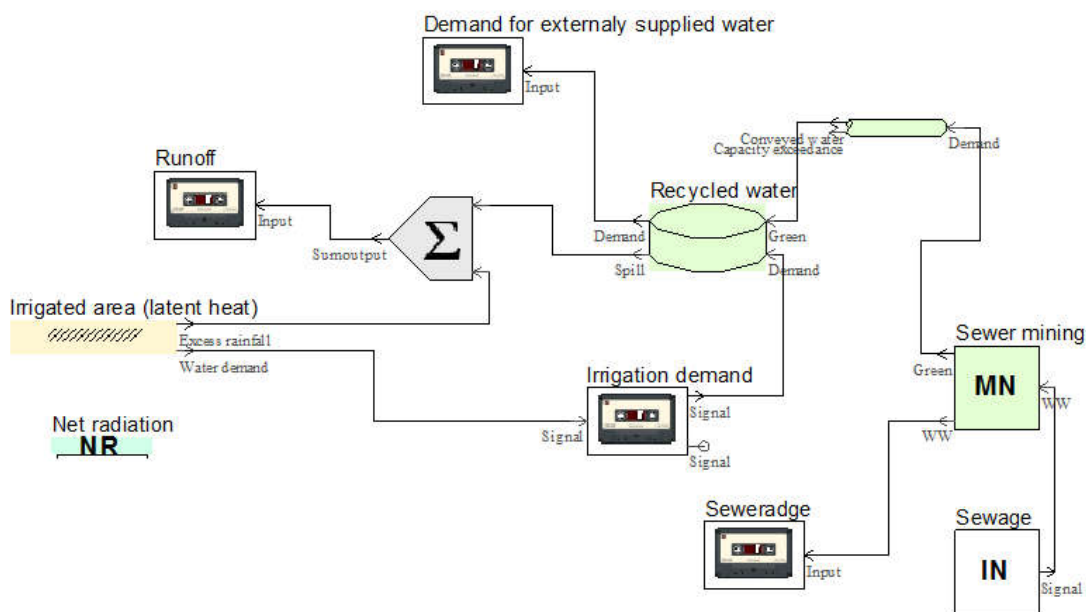
The objective of this study is to provide a methodology for quantifying the ecosystem services provided by the green area in terms of reducing the Urban Heat Island (UHI) effect (Howard, 1818). To accomplish this, the urban water cycle model UWOT (Rozos et al., 2013) is combined with the heat transfer model Energy2D (Xie, 2012). UWOT is used to estimate the water demand of the green area, the latent heat, the net radiation and the direct solar beam, whereas Energy2D is used to estimate the temperatures at the case study area.

The studied area is shown in Figure 1. This figure displays the irrigated green area and the compact treatment unit locations. The methodology that is going to be presented will estimate the water that the treatment unit should provide and the temperature difference (along the line AA') between the green area and the concrete paved areas during a significantly hot summer day.



**Figure 1.** The irrigated green area (marked with G) and the compact treatment unit (marked with U) in KEREFYT. AA' line gives the axis over which Energy2D is run.

Figure 2 displays the water network of the studied area as it is represented in UWOT. UWOT is employing a demand-oriented representation of the network (Rozos and Makropoulos, 2013; Bouziotas et al., 2015), in which demand signals instead of flows are simulated. UWOT distinguishes between two types of demand signals, the push and the pull signals. Push signals are related with a need to dispose an amount of water (e.g. stormwater). Pull signals have to do with the need to bring water to cover a demand. In the UWOT schematic representation of a network, pull signals have opposite direction to the resulting water flow (e.g. in Figure 2 a water demand signal is emitted from the irrigated area and received, after passing through a signal logger, by the local tank, which results in a flow from tank to the irrigated area).

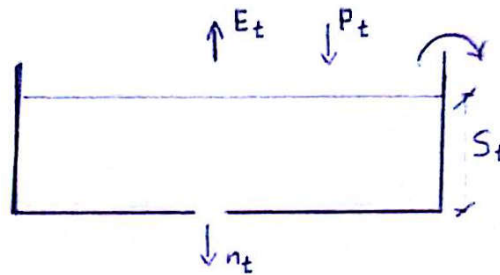


**Figure 2.** Representation of the case study water network in UWOT.

In Figure 2, the wastewater is pumped into the treatment unit (marked with MN) and the treated water is stored in a local tank. The local tank provides the water required for irrigation, it spills, if the tank capacity is exceeded, and it obtains water from the mains in case it gets empty. The simulated water flows (the demand signals more precisely) are recorded with the use of appropriate UWOT components (called loggers and bear a compact cassette icon). The unconnected component NR (is not influencing the water cycle) is used to estimate the net radiation.

### UWOT SIMULATION

The UWOT component that simulates the irrigated area has a dual role. It simulates the water demand and the latent heat. For the former, a soil moisture balance model is employed (Rozos et al., 2013). A schematic representation of this model is displayed in Figure 3. The rainfall falling on the simulated area increases the soil moisture. If the soil capacity is exceeded, any additional water generates runoff (see emitted signal 'Excess rainfall' of component labelled 'Irrigated area (latent heat)' in Figure 2). The soil moisture decreases because of the evapotranspiration and infiltration. If soil moisture is completely depleted, a demand for additional water to cover the remaining evapotranspiration is generated (see emitted signal 'Water demand' of component labelled 'Irrigated area (latent heat)' in Figure 2).



**Figure 3.** Soil moisture model used in UWOT to estimate latent heat and water demand.

The latent heat in kWh/d is calculated using the following formula:

$$LE_t = A \times ev_t \times 0.683 \text{ kWh/L} \quad (1)$$

where  $ev_t$  (mm/d) is the evapotranspiration calculated by Hargreaves (1985) method and  $A$  ( $m^2$ ) is the surface area. Since the area is irrigated when soil moisture is depleted, it is assumed that the evapotranspiration equals the potential evapotranspiration. The crop coefficient is assumed constant and equal to 1.

UWOT employs a dedicated component to simulate the net radiation (labelled 'Net radiation' in Figure 2). The net radiation in kWh/d is calculated with the following formula:

$$Rn_t = 0.000278 \text{ (kWh/kJ)} \times ( (1 - \alpha) S_t - Ln_t ) \times A \quad (2)$$

where  $\alpha$  is the albedo (taken equal to 0.23, a good overall average value for grassland according to Shuttleworth, 1993),  $S_t$  ( $\text{kJ}/\text{m}^2/\text{d}$ ) is the direct solar beam (the amount of solar energy reaching earth surface) estimated by Bristow-Campbell formula (Bristow and Campbell, 1984) and  $Ln_t$  ( $\text{kJ}/\text{m}^2/\text{d}$ ) is the net long-wave radiation (see 4.2.7 of Shuttleworth, 1993). The estimation of the latter requires the relative sunshine, which is estimated from the formula (see 4.2.12 of Shuttleworth, 1993):

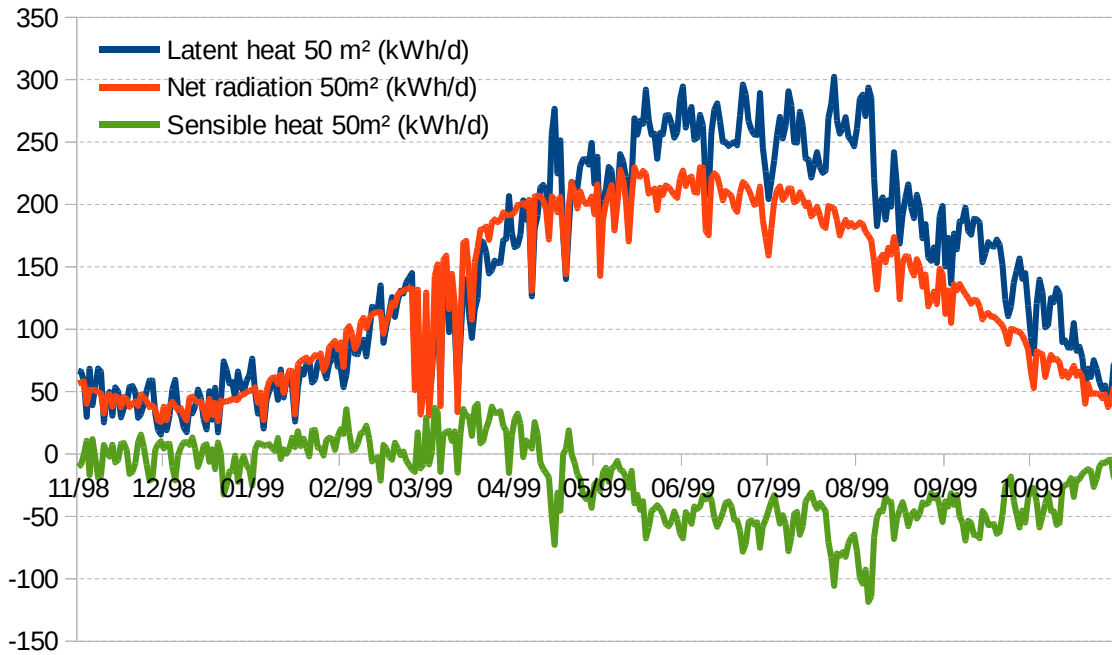
$$nN = (S_t / So_t - 0.25) / 0.50 \quad (3)$$

The extra-terrestrial radiation  $So_t$  is calculated using astronomical formulas (see 4.4.4 of Shuttleworth, 1993).

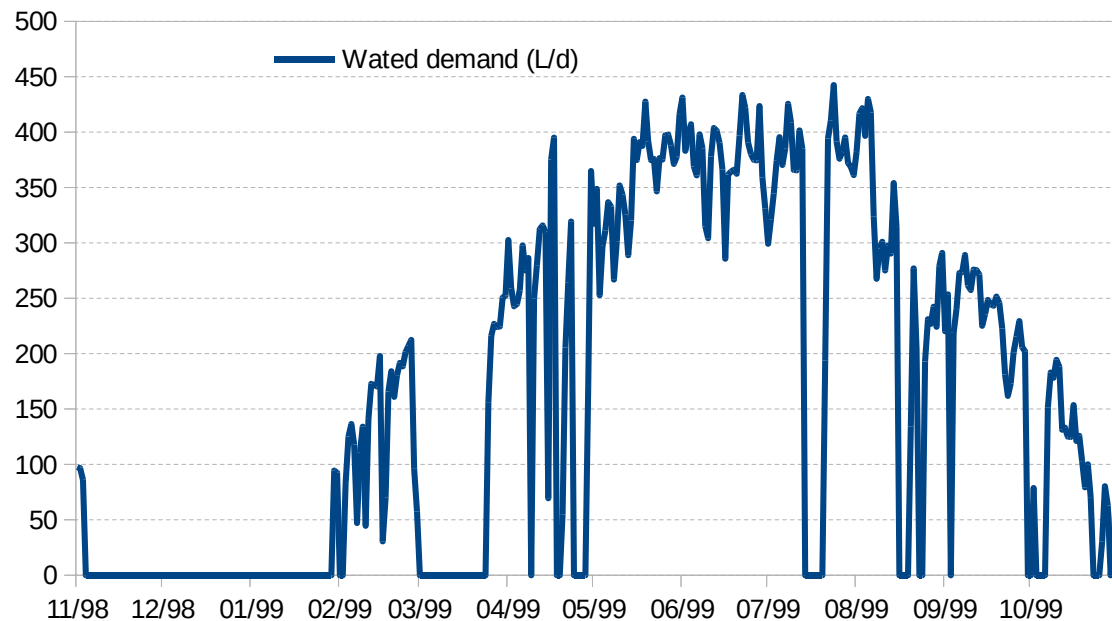
Then, the sensible heat in kWh/d can be calculated by the formula:

$$H_t = Rn_t - LE_t \tag{4}$$

Figure 4 displays the various heat fluxes of the simulated area. From this figure becomes evident that both latent heat and net radiation increase during the dry season. However, the latent heat is greater than net radiation during dry season, which results in negative sensible heat (cooling effect).



**Figure 4.** Heat fluxes estimated by UWOT for the 50 m<sup>2</sup> green area.



**Figure 5.** Water required for irrigation as estimated by UWOT.

Figure 5 displays the water required for irrigation (as it is recorded in the component labelled ‘Irrigation demand’ in Figure 2). No water is required during the wet period and whenever irrigation needs are covered by rainfall (e.g. during the rainy March of 1999, which also demonstrates a low net radiation due to the cloudy conditions).

The only meteorological data required by this approach is the maximum and minimum daily temperatures. UWOT was run for the period 18-Nov-1998 to 18-Nov-1999. The obtained (from openmeteo.org) temperature timeseries ( $T_{\min}$  and  $T_{\max}$ ) were recorded in the NTUA weather station.

## ENERGY2D SIMULATION

Figure 4 displays the heat fluxes. To estimate the impact of these heat fluxes on the air temperature, the heat equation (a parabolic partial differential equation) needs to be solved. Because only rough estimations are required in this study, the convective effect (heat transfer because of airflow) was neglected to speed up the numerical scheme (otherwise very fine time steps should be employed to ensure stability). The heat conduction is modelled using the following partial differential equation (Versteeg and Malalasekera, 1995):

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot [k \nabla T] + q \quad (5)$$

where  $k$  is the thermal conductivity tensor (W/ K m),  $T$  is the temperature (K),  $c$  is the specific heat capacity (J/ kg K),  $\rho$  is the density (kg/m<sup>3</sup>), and  $q$  is the internal heat generation (W/m<sup>3</sup>).

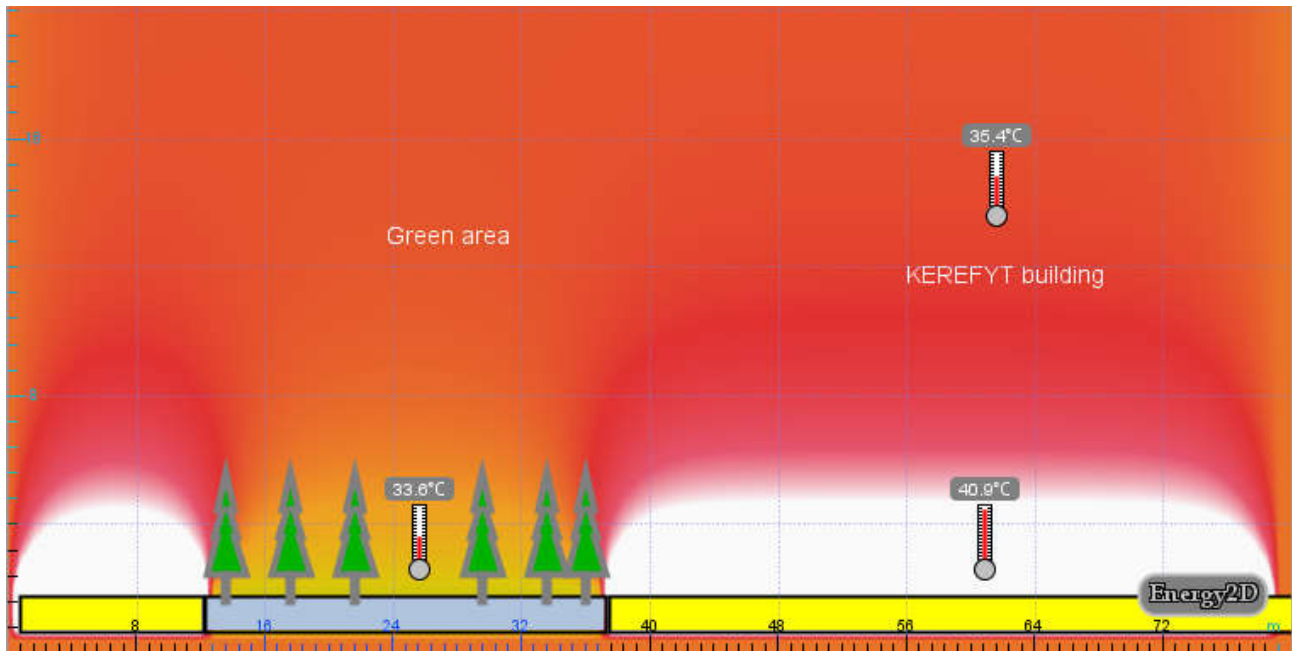
Normally, the heat equation has two parts: the diffusion part characterized by the thermal conductivity and the advection part characterized by the velocity field. The last one is zero (since convective effect is neglected) and does not appear in the equation above. The internal heat generation term  $q$  can be thought of as an external load, which is estimated by UWOT (the sensible heat). Energy2D is a two dimensional model that uses the finite-difference time-domain (FDTD) method to solve this equation. This is an implicit scheme, which is unconditionally stable.

The simulation was carried out for the meteorological conditions regarding the very hot day of 9<sup>th</sup> July of 1999. The simulation was run until steady state conditions were reached. The simulation domain is 80 meters width by 40 meter height, which is discretized by a 100×100 grid. The two dimensional modelling was performed along the AA’ line (Figure 1). For the simulation, the following assumptions were made:

- The initial air temperature was taken equal to 35.3 °C. This is the average daily temperature on 9<sup>th</sup> of July. The initial air temperature does not influence the steady state solution, influences only the convergence speed.
- The initial concrete paved areas temperature was taken equal to 59.8 °C. This is calculated employing the formula 1:1.3.9 given by Neitsch et al. (2009) for the temperatures recorded on 9<sup>th</sup> of July. This formula requires the max and min daily temperatures and the direct solar beam. The latter can be estimated by employing the UWOT PA component (not shown in Figure 2).
- The boundary conditions were considered to be constant temperature equal to 35.3 °C.
- The internal heat generation in the green area was set equal to -65.1 W/m<sup>3</sup> whereas in the parking lot and paved areas equal to 217.8 W/m<sup>3</sup>. Both values can be obtained from Equation (4), which gives the sensible heat. In green areas, and according to Figure 4, the latent heat during summer days is very high, hence the negative sensible heat. On the other hand in paved areas, where no vegetation and consequently no evapotranspiration, the latent

heat is 0 and hence the sensible heat equals the net radiation. It should be noted that Figure 4 gives the heat values over the 50 m<sup>2</sup> green area in kWh/d. To turn into units of W/m<sup>3</sup> (as it is required by Energy2D), the heat values on 9<sup>th</sup> of July were multiplied by 1000 W/kWh, then divided by 50 m<sup>2</sup> and finally divided by 24 h. Assuming that the AA' slice has a thickness of 1 m, one obtains the values of -65.1 W/m<sup>3</sup> sensible heat and 217.8 W/m<sup>3</sup> net radiation.

The results of the simulation are shown in Figure 6. This figure displays the temperature over the green area (33.6 °C) the temperature over the paved areas (40.9 °C) and the air temperature at a higher level (35.4 °C). Therefore the temperature difference between green and paved areas is 7.3 °C.



**Figure 6.** Simulation of the heat fluxes and resulting temperatures.

It should be noted that in reality, the climatic processes (even at this small scale) are complex and dynamic. The principal heat source, the sun, exhibits a diurnal fluctuation that is not taken into account in this model (the heat fluxes used in the model are constant and equal to the average daily values). For these reasons, the exact temperatures recorded on a day (and during a day) cannot be reproduced with this simple heat transfer model. Only the difference between the temperature over green and non-green areas can serve as an indicator of the urban heat island effect reduction. Indeed, the difference estimated by this model is very close to the values reported in Figure 7 of Alexandri and Jones (2008), who employed a sophisticated heat and mass transfer model.

Finally, it should be noted that a more comprehensive approach would require repeating the heat model simulation for various days each one having distinct meteorological conditions. This would allow obtaining an average year-round picture concerning the benefit of green areas.

## CONCLUSIONS

The introduction of on-site scalable compact wastewater treatment units for supplying water for irrigating green areas provides a new perspective on re-engineering the urban environment. This approach allows ecosystem services to be offered without additional pressure on the water resources. However, the compact treatment units have considerable capital and operational cost, which discourage the wide adoption of such schemes. In this study we are attempting a first step towards a thorough evaluation of the benefits regarding the ecosystem services obtained from

irrigating green areas with treated water. More specifically, we are attempting to provide a methodology that could help to quantify the ecosystem services in terms of urban heat island effect reduction.

The methodology used is generic and minimally demanding regarding the data requirements. Only rainfall, minimum and maximum daily temperatures are required. These data can nowadays be easily obtained online (e.g. from freemeteo.com) for any place in the world.

The methodology was tested in KEREFYIT, the research centre of Athens water supply company. A pilot compact treatment unit, which employs MBR-RO technologies to treat wastewater, provides water irrigating a green area of 50 m<sup>2</sup> close to the treatment unit. Estimates of the required water for irrigation and the urban heat island reduction were derived by appropriate modelling. An urban water cycle model (UWOT) was coupled with heat transfer model (Energy2D). UWOT was used to estimate the required water for irrigation and the heat fluxes (net radiation, latent heat and sensible heat) whereas Energy2D was used to estimate the air temperatures over the studied area.

The results of the simulations indicated that the sensible heat over the paved areas for a hot summer day is very high whereas the sensible heat is negative over the green area. This effect, usually noticed over green areas during dry meteorological conditions (Sellers, 1965), resulted in a temperature difference between green and paved areas equal to approximately 7 °C (this value is in accordance with studies that have employed more sophisticated approaches). It is important to highlight that this benefit was accomplished exclusively with treated wastewater. This means that this technique could be employed widely without additional pressure on the water resources.

Future research should include on-site meteorological observations to verify the findings of this study. Ideally, the temperature should be monitored at three locations, at the irrigated green area, at a non-irrigated green area and at a paved area. This will provide not only a verification of the method, but also a clearer view regarding the benefit of introducing irrigated vegetation against natural vegetation. A full set of meteorological variables (rainfall, humidity, wind speed) should be monitored at the site to allow deriving conclusions regarding the influence of all these variables on the urban heat island effect.

Finally, a study regarding the whole spectrum of the benefits from ecosystem services should also include the profits from real estate values increase because of the amenities, the ecological benefits because of the biodiversity improvement, the enhanced resilience to drought and flood risk, the noise and air pollution reduction, and the general improvement of the quality of life.

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