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# Turning black into green: ecosystem services from treated wastewater

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**ABSTRACT**

To reduce the impact of urban effluents on the environment, strict regulatory requirements have been set up for the disposal of wastewater, in most parts of the western world, requiring treatment before disposal. At the same time, the urban environment requires water inflows to satisfy a range of urban water demands, and the corresponding water abstractions put pressure on (often scarce) water resources. A suggested synergistic solution is to use the effluents from treatment plants as an alternative resource for irrigation or for industrial uses. Despite the existence of numerous successful applications, this practice is not very common mainly because of increased capital and operational costs, usually exceeding the cost of freshwater. A possible response of the market to this drawback could be to introduce in situ small-scale treatment units to cover local water needs. In this study, we assess the benefits of such a compact wastewater treatment unit that is used to provide water for irrigating an urban green area. Apart from the aesthetic improvement, the evaporative cooling (latent heat), which reduces the air temperature, is expected to have a positive impact on thermal comfort. A pilot scheme was deployed in KEREFYT, the research centre of the Athens Water Supply and Sewerage Company (EYDAP). This scheme was simulated with the urban water cycle model to estimate heat fluxes and the results were fed into Energy2D (a model that simulates heat transfer) to estimate the expected temperature drop. The results are promising and suggest that these technologies could play an important role in a more sustainable, circular water economy.

*Keywords:* Ecosystem services; Local treatment; Urban heat island

## 1. Introduction

Human societies are based on natural ecosystems not only for securing essential supplies such as food, water, materials, and energy, but also for amusement and recreation. This wide range of benefits is collectively described with the term "ecosystem services" [1]. Associated with this term, the "ecosystem approach" defines a framework where the ecosystem services become an important criterion in decision-making processes. This criterion reflects the perpetual need for quality of life improvement, which in turn contributes to the increased water-stress plaguing many parts of the world. A possible solution could be, as has been demonstrated by many successful applications [2], the use of treated water for ecosystem services. But this solution comes with two major concerns that prevent its wide adoption: safety and the economic viability. As regards the former, recent studies indicate that treated water fully complies (provided design of the unit is appropriate) with the regulations regarding the quality of water used for irrigation [3], leaving no room for any scientifically based concern (public opinion is another issue that must be addressed separately). As far as economic viability

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is concerned, a recent research suggests that when ecosystem services are taken into account and are valued properly, water reuse is a sustainable practise that can also be financially profitable [4].

In this study, we are trying to promote the ecosystem approach by suggesting a methodology that quantifies the ecosystem services provided by a green area in terms of reducing the urban heat island (UHI) effect [5]. The suggested methodology is based on two different models. An urban water cycle model (the model UWOT) [6] is used to simulate the water demand of a green area and the energy fluxes (latent heat, the net radiation, and the direct solar beam). Subsequently, the heat transfer model Energy2D [7] is used to estimate the temperatures at the studied area and the reduction of the UHI effect over the green area.

This methodology was applied in KEREFYT, the research centre of the Athens Water Supply Company. The case study area employs a water recycling scheme, where the treated water is used for irrigating a green area of 50 m$^2$. The water for irrigation comes from a pilot compact treatment unit with capacity of 1 m$^3$/d. The compact treatment unit consists of two adjacent boxes: one 2.16 × 2.00 × 2.87 m$^3$ box contains a membrane bioreactor, whereas the other 2.16 × 3.00 × 2.87 m$^3$ box contains a reverse osmosis sub-unit and the controllers of the unit. The unit processes wastewater obtained from the Metamorfosis treatment plant and returns the produced sludge back to the plant. It should be noted that in a real-world application, wastewater would be pumped out from a wastewater pipe and the produced sludge would be returned to the same pipe, thus making the unit easily deployable at almost any location of an urban area (subject to existence of a sewerage system).

## 2. Materials and methods

### *2.1. Step 1: simulate water demand and energy fluxes*

UWOT has a dedicated component to simulate both the water demand of an irrigated area and the latent heat. For the former, a soil moisture balance model is employed [8]. A schematic representation of this model is displayed in Fig. 1. The rainfall $P_t$ falling during time step $t$ on the simulated area increases the soil moisture $m_t$. If the soil capacity $m_{\max}$ is exceeded, any additional water generates runoff $Q_t$

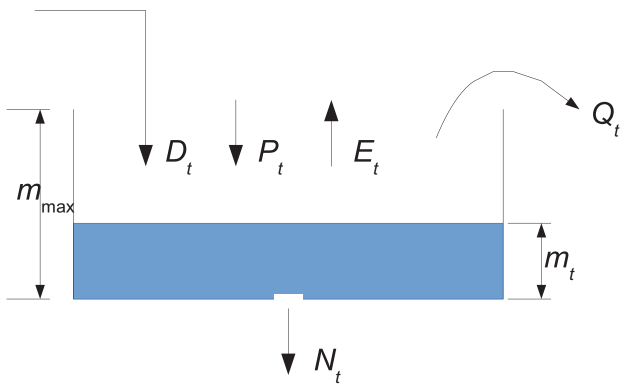


Fig. 1. Soil moisture model used in UWOT to estimate latent heat and water demand.

(this is the emitted signal 'Excess rainfall' of the component labelled 'Irrigated area (latent heat)' in Fig. 4). The soil moisture decreases because of the evapotranspiration $E_t$ and infiltration $N_t$. If soil moisture is completely drained, a demand for additional water $D_t$ is generated (this is the emitted signal 'Water demand' of the component labelled 'Irrigated area (latent heat)' in Fig. 4).

$$m_{t+1/2} = m_{t-1} + (P_t - E_t - N_t)\,\mathrm{d}t \tag{1a}$$

$$N_t = C_\mathrm{d}\, m_{t-1} \tag{1b}$$

$$Q_t = \max(0, m_{t+1/2} - m_{\max})/\mathrm{d}t \tag{1c}$$

$$D_t = |\min(0, m_{t+1/2})|/\mathrm{d}t \tag{1d}$$

$$m_t = m_{t+1/2} - (Q_t - D_t)\mathrm{d}t \tag{1e}$$

where $C_\mathrm{d}$ is the orifice discharge coefficient. It should be noted that in above equations $D_t$ is the specific water demand (the amount of water per m$^2$ required to ensure the evapotranspiration meets the potential evapotranspiration) during time step $t$.

The crop reference evapotranspiration is calculated using Hargreaves method [9] (this is an empirical method, hence not dimensionally consistent).

$$E_t = 0.0023 \times (\mathrm{So}_t/\lambda) \times (\mathrm{Ta}_t + 17.8) \times (\mathrm{Tmax}_t - \mathrm{Tmin}_t)^{0.5} \tag{2}$$

where $\mathrm{So}_t$ is the extra-terrestrial radiation (kJ/m$^2$/d) calculated using astronomical formulas (e.g., Eq. (4.4.4) of [10]), which require only the geographical latitude of the studied area as data; $\lambda$ is the specific latent heat of water (2,460 kJ/kg when water temperature is 17.5°C); $\mathrm{Ta}_t$ is the average temperature of the time step (taken approximately equal to ($\mathrm{Tmax}_t$ + $\mathrm{Tmin}_t$)/2); $\mathrm{Tmax}_t$ and $\mathrm{Tmin}_t$ are the maximum and minimum temperatures of the time step $t$.

The latent heat (outgoing energy as evaporation) in kWh/d is calculated using the following formula (see, definition of $\lambda$ in section 4.2.1 of [10]):

$$\mathrm{LE}_t = A \times E_t \times 0.683\ \mathrm{kWh/L} \tag{3}$$

where $A$ (m$^2$) is the surface of the green area and 0.683 kWh/L is the specific latent heat of water. The crop coefficient is assumed constant and equal to 1.

UWOT employs a dedicated component to simulate the net radiation (labelled 'Net radiation' in Fig. 4). The net radiation in kWh/d is calculated with the following formula (see definition in section 4.2.2 of [10]):

$$\mathrm{Rn}_t = 0.000278\ (\mathrm{kWh/kJ}) \times ((1 - \alpha)\, S_t - \mathrm{Ln}_t) \times A \tag{4}$$

where $\alpha$ is the albedo (taken equal to 0.23, a good overall average value for grassland according to Shuttleworth [10]),

$S_t$ (kJ/m²/d) is the direct solar beam (the amount of solar energy reaching earth surface) estimated by Bristow–Campbell formula [11] (requires only time series of minimum and maximum daily temperatures and the extra-terrestrial radiation) and $\mathrm{Ln}_t$ (kJ/m²/d) is the net long-wave radiation (see, Eq. (4.2.7) of [10]). The calculation of the latter employs the factor $f$, which introduces the adjustment for cloud cover. This factor can be estimated from Eq. (4.2.10) of [10]:

$$f = \mathrm{ac}\ S_t/(0.75\ \mathrm{So}_t) + \mathrm{bc} \quad (5)$$

where $\mathrm{So}_t$ is calculated using the astronomical formulas, $S_t$, as explained previously, is estimated by the Bristow–Campbell formula, ac and bc are the long-wave radiation coefficients for clear skies (suggested values for arid and humid areas are given in section 4.2.2 of [10]).

Then, the sensible heat in kWh/d over the whole green area can be calculated by the formula (see definition in section 4.2.2 of [10]):

$$H_t = \mathrm{Rn}_t - \mathrm{LE}_t \quad (6)$$

From the above equations becomes evident that the only meteorological data required by this approach is the maximum and minimum daily temperatures (Eqs. (2)–(6)) and the rainfall (Eqs. (1a)(1e)).

### *2.2. Step 2: simulate temperatures*

Eq. (6) estimates the heat source (if $H_t$ is positive) or sink (if $H_t$ is negative) of the studied area. To estimate the impact of this source/sink 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 would be required to ensure stability). The heat conduction is modelled using the following partial differential equation [12]:

$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot \left[ k \nabla T \right] + q \quad (7)$$

where $k$ is the thermal conductivity (W/K/m), $T$ is the temperature (K), $c$ is the specific heat capacity (J/kg/K), ρ is the density (kg/m³), and $q$ is the heat source/sink (W/m³).

Normally, the heat equation has two parts: the diffusion part characterized by the thermal conductivity and the convection part characterized by the velocity field. The last one is zero (since convective effect is neglected) and does not appear in the equation above. Energy2D is a two-dimensional model that uses the finite-difference time-domain method to solve this equation. This is an implicit scheme, which is unconditionally stable.

The microclimatic impact of the studied area is approximated assuming constant temperature at the boundaries of the grid equal to the average value of the hottest month (based on temperature time series measured at an urban area of similar conditions with the one studied). Then, virtual components (VCs) are employed in the model setup to introduce the heat stresses (source or sink), i.e., the $q$ of Eq. (7). Assuming that the thickness of the 2D grid employed by Energy2D is $b$ (Fig. 2) and choosing the height of the VC to be equal to the dz of the discretization cells, the following equation can be used to obtain $q$ (W/m³) from $H_t$ (kWh/d, Eq. (6)):

$$q = H_t/(A \times \mathrm{dz} \times 24\ \mathrm{h/d}) \times 1{,}000\ \mathrm{W/kW} \quad (8)$$

It should be noted that the grid thickness ($b$ in Fig. 2) does not influence the relationship between $H_t$ and $q$. This is happening because the sensible heat absorbed by a VC cell is proportional to $b$ (the larger the $b$ value the larger the surface facing the sun) but on the same time, the volume of a VC cell is inversely proportional to $b$. Hence, the power of the absorbed sensible heat per volume does not depend on $b$.

## 3. Case study

### *3.1. Step 1: simulate water demand and energy fluxes*

The studied area is shown in Fig. 3. This figure displays the irrigated green area and the compact treatment unit locations. The methodology presented previously was used to estimate the water required to irrigate the green area and the temperature difference (along the line $AA'$) between the green area and the concrete paved areas during a significantly hot summer day.

Fig. 4 displays the water network of the studied area as it is represented in UWOT. UWOT is employing a demand-oriented representation of the network [6,13], 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

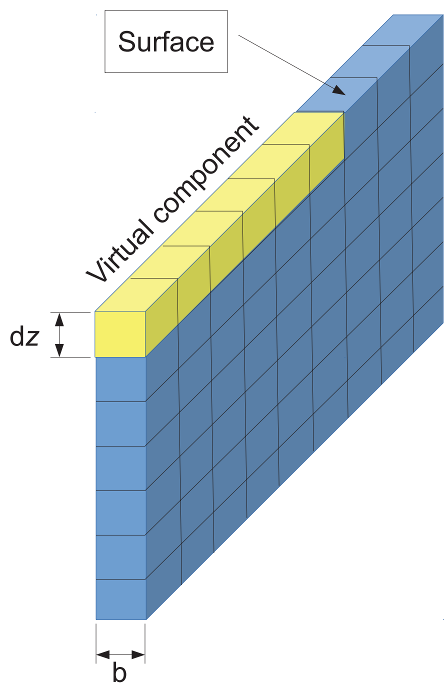


Fig. 2. Part of the Energy2D grid (up to the land surface) with the virtual component highlighted.


Fig. 3. The irrigated green area (marked with the green rectangle G) and the compact treatment unit (marked with the grey rectangle U). *AA*′ line (80 m long) gives the axis along which the Energy2D simulation is performed.

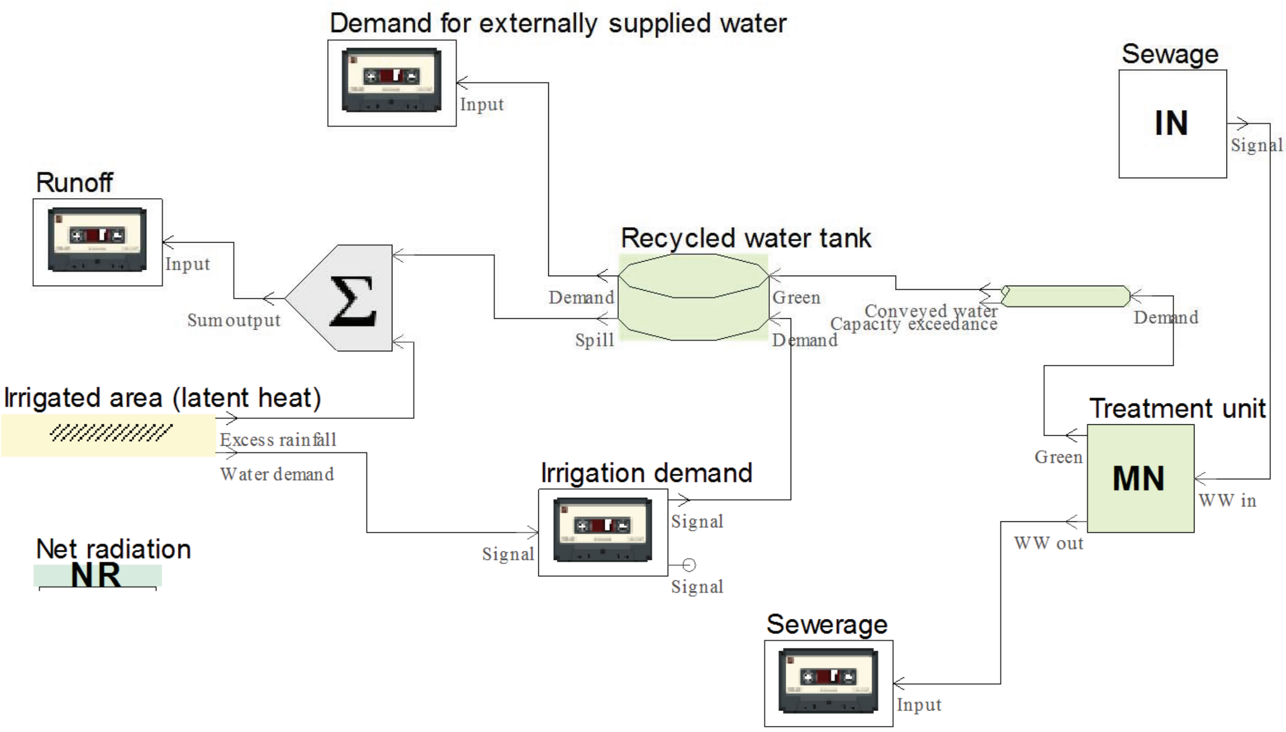


Fig. 4. Representation of the case study water network in UWOT.

dispose an amount of water (e.g., storm water). 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 Fig. 4, a water demand signal is emitted from the irrigated area and received, after passing through a signal logger, by the local tank, which in reality results in a flow from the tank to the irrigated area).

In Fig. 4, 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 bearing a compact cassette icon). The unconnected component 'NR' (not influencing the water cycle) is used to estimate the net radiation (Eq. (4)).

UWOT was run for the period from 1 January 1999 to 31 December 1999 with daily time step. The temperatures (Tmin and Tmax) were obtained from openmeteo.org whereas rainfall time series were recorded at the NTUA weather station. Fig. 5 displays the 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 the net radiation during dry season, which results in negative sensible heat (cooling effect).

Fig. 6 displays the water required for irrigation (as it is recorded in the component labelled 'Irrigation demand' in Fig. 4). No water is required during the wet period or whenever irrigation needs are covered by precipitation (e.g., after the rainfall events of August and September). It is worth noticing that, according to rainfall measurements the second half of March was rainy and consequently cloudy, expected to result in low net radiation values, which was successfully reproduced by the model (Fig. 5).

### 3.2. Step 2: simulate temperatures

The Energy2D simulation was carried out for the meteorological conditions regarding the very hot day of 9 July 1999. The simulation was run until steady-state conditions were reached (Energy2D does not offer steady-state solver). The simulation domain was 80 m width by 40 m height and was discretized by a 100 × 100 grid. The two-dimensional modelling was performed along the *AA'* line depicted in Fig. 3. 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 9th of July. The initial air temperature does not influence the steady-state solution, influences only the convergence speed.
- The boundary conditions were considered to be constant temperature equal to 35.3°C.
- The values of the heat fluxes of the 9th of July (Fig. 5) were used in Eqs. (6) and (8). According to these equations, the heat sink in the green area equals to –162.75 W/m$^3$ whereas the heat source in the parking lot and paved areas equals to 544.5 W/m$^3$. It should be noted that in green areas, and according to Fig. 5, 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.
- The temperature of the soil is set constant equal to 23°C (see, Fig. 1:1-2 of [14]).
- The thermal properties of the components involved are shown in Table 1.

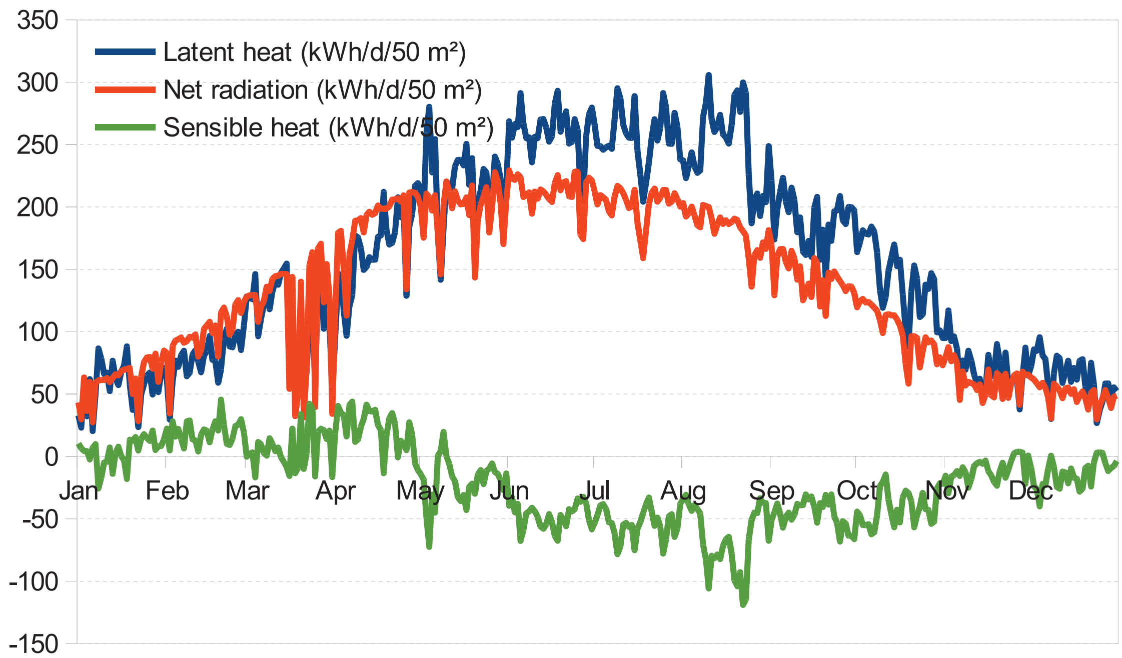


Fig. 5. Heat fluxes over the 50 m$^2$ green area of the case study estimated by the UWOT simulation from 1 January 1999 to 31 December 1999.

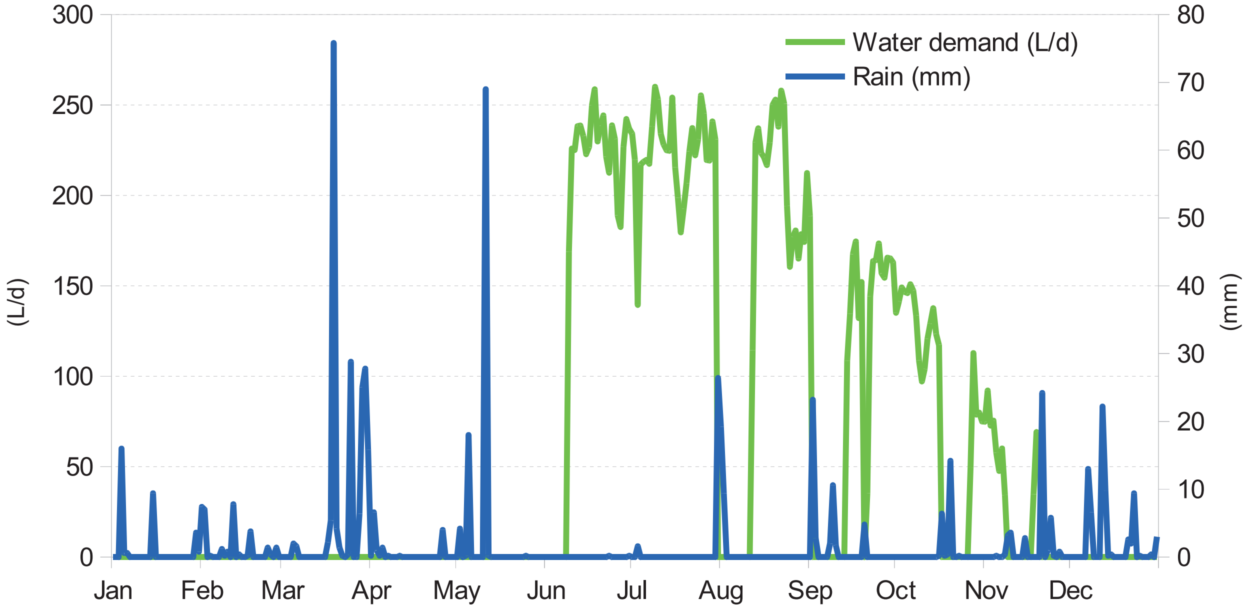


Fig. 6. Water required during 1999 (as estimated by UWOT) for irrigating the 50 m² green area of the case study and rainfall depth during the same period.

Table 1
Thermal properties of the components involved in heat simulation

| | Specific heat (J/kg/°C) | Conductivity (W/m/°C) | Density (kg/m³) |
|---|---|---|---|
| VC heat source | 850 | 1.1 | 2,000 |
| VC heat sink | 1,100 | 0.9 | 1,750 |
| Soil | 1,100 | 0.9 | 1,750 |
| Air | 1,000 | 0.024 | 1.2 |

To study the heat conduction, four components were used. Two VCs were used to introduce the heat source (the two yellow stripes in Fig. 7) in the parking lot and paved area, one VC was used to introduce the heat sink in the green area (the grey stripe in Fig. 7) and one component simulates the soil (the blue area on the bottom of Fig. 7).

The results of the simulation are shown in Fig. 7. This figure displays the temperature over the green area (33.7°C), the temperature over the paved areas (39.9°C), and the air temperature at a higher level (35.3°C). Therefore, the temperature difference between green and paved areas is 6.2°C. This drop, attributed to the negative sensible heat, is usually noticed over green areas during dry meteorological conditions [15].

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. However, the difference between the temperature over green and non-green areas can serve as an indicator of the UHI effect reduction. Indeed, the difference estimated by this model is very close to the values reported in Fig. 7 of Alexandri and Jones [16], 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.

## 4. 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 discourages the wide adoption of such schemes. In this study, we are attempting a first step towards a thorough evaluation of the benefits of the ecosystem services obtained from irrigating green areas with treated water, the so-called ecosystem approach. More specifically, we attempt to provide a methodology that could help to quantify the ecosystem services in terms of UHI effect reduction. The methodology used is generic and minimally demanding regarding the data requirements. Furthermore, the models employed are either freeware or open source.

The methodology steps (including data collection) are as follows:

- Obtain rainfall, minimum and maximum daily temperatures. These data can nowadays be easily obtained online (e.g., from freemeteo.com) for any place in the world.
- Run the UWOT (the only required data are the surface of the green area and its geographical latitude) to estimate water demand and energy fluxes.

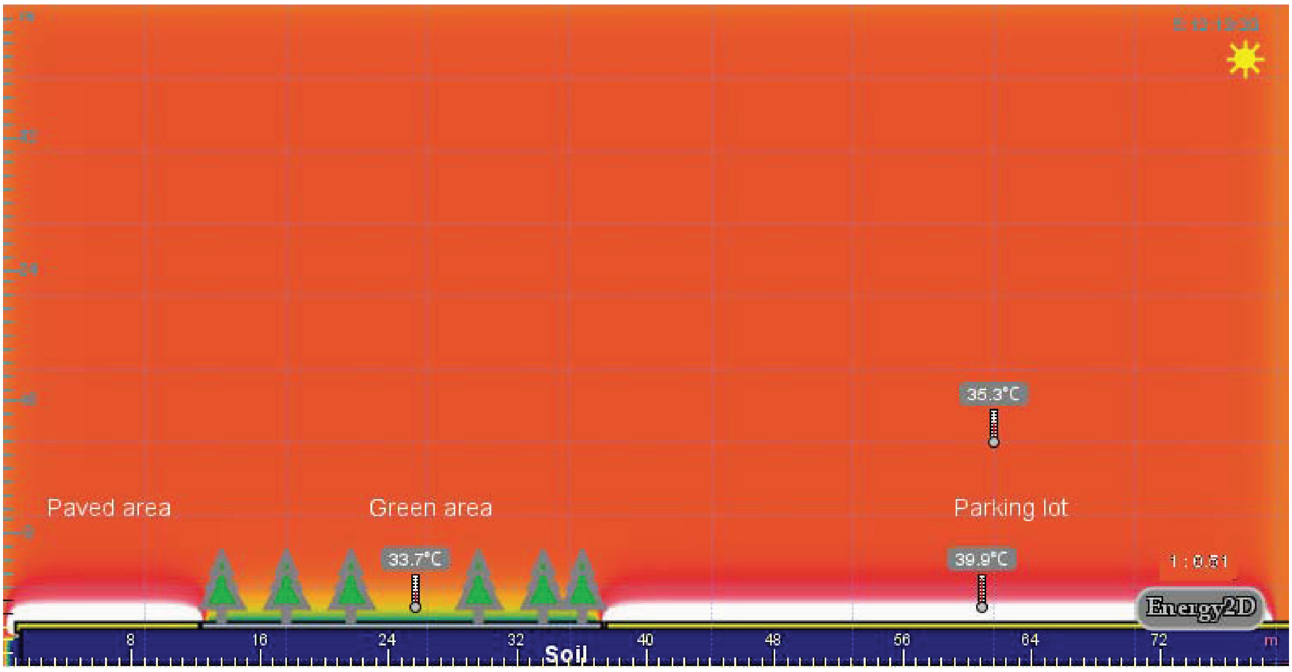


Fig. 7. Simulation of the heat fluxes and resulting temperatures.

- Apply the simulated energy fluxes of the hottest day to a simple heat transfer (Energy2D) model to estimate the temperature drop over the green area.

The methodology was tested in KEREFYT, the research centre of EYDAP, the Athens Water Supply and Sewerage Company. A pilot compact treatment unit, which employs membrane bioreactor and reverse osmosis technologies to treat wastewater, provides water for irrigating a green area of 50 m$^2$ close to the treatment unit. Estimates of the water required for irrigation and the UHI reduction were derived by appropriate modelling. UWOT was coupled with a heat transfer model (Energy2D). UWOT was used to estimate the water required 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 was very high whereas the sensible heat was negative over the green area. This resulted in a temperature difference between green and paved areas equal to approximately 6.2°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.

In this case study, the unit processes wastewater obtained from the sewerage network just before the Metamorfosis treatment plant and returns the produced sludge back to the plant. It should be noted that in a real-world application, wastewater would be pumped out from a wastewater pipe and the produced sludge would be returned to the same pipe, thus making the unit easily deployable at almost any location of an urban area (subject to the existence of a sewerage system).

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 impact of irrigated vegetation and natural vegetation on the urban microclimate. A full set of meteorological variables (rainfall, humidity, and wind speed) should be monitored at the site to allow deriving conclusions regarding the influence of all these variables on the UHI effect.

Finally, a study regarding the whole spectrum of 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 in the quality of life.

## Symbols

| | | |
|---|---|---|
| $t$ | — | Time step (dimensionless) |
| d$t$ | — | Time step length, d |
| $P_t$ | — | Rainfall falling on the simulated area during time step $t$, mm/d |
| $m_t$ | — | Soil moisture during time step $t$, mm |
| $m_{max}$ | — | Soil moisture storage capacity, mm |
| $Q_t$ | — | Runoff per m$^2$ during time step $t$, mm/d |
| $E_t$ | — | Reference evapotranspiration during time step $t$, mm/d |
| $N_t$ | — | Infiltration per m$^2$ during time step $t$, mm/d |
| $D_t$ | — | Demand for water for irrigation per m$^2$ during time step $t$, mm/d |

$C_d$ — Orifice discharge coefficient, 1/d
$So_t$ — Extra-terrestrial radiation, $kJ/m^2/d$
$\lambda$ — Specific latent heat of water, kJ/kg
$Ta_t$ — Average temperature of the time step $t$, °C
$Tmax_t$ — Maximum temperature of the time step $t$, °C
$Tmin_t$ — Minimum temperature of the time step $t$, °C
$LE_t$ — Latent heat during time step $t$, kWh/d
$A$ — Surface of the green area, $m^2$
$Rn_t$ — Net radiation during time step $t$, kWh/d
$\alpha$ — Albedo of the study area (dimensionless)
$S_t$ — Direct solar beam during time step $t$, $kJ/m^2/d$
$Ln_t$ — Net long-wave radiation during time step $t$, $kJ/m^2/d$
ac — Long-wave radiation coefficient for clear skies (dimensionless)
bc — Long-wave radiation coefficient for clear skies (dimensionless)
$H_t$ — Sensible heat during time step $t$, kWh/d
$k$ — Thermal conductivity, W/K/m
$T$ — Temperature, K
$c$ — Specific heat capacity, J/kg/K
$\rho$ — Density, $kg/m^3$
$q$ — Heat source/sink, $W/m^3$
$b$ — Thickness of the Energy2D grid, m
dz — Height of the virtual component employed to introduce heat source/sink, m


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