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Modelling green roof hydrologic performances under various conditions: geography, climate change scenarios, simulation time step

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Highlights

- Green roofs perform very differently in various cities in the world: local design is necessary.
- Future time series show a significant influence of climate change on green roof performance.
- Simulation time steps from 1 to 15 min show minor differences on total outflow results.

Introduction

Event and long-term hydrological performance indicators of green roofs (retention, evapotranspiration, peak flow attenuation, outflow, etc.) depend on numerous factors. For a given green roof with a particular design (e.g. substrate depth, underlying storage capacity, controlled outflow, etc.), its performance varies dramatically according to its geographical location and to the prevailing meteorological conditions. For a given location, the performance varies for current climate (annual variability) and will evolve in the future due to climate change. Based on long-term simulations (10 to 20 years), the Olympluie project aims to evaluate and compare the performance of an advanced green roof with different designs for eight cities around the world, and, for some of these locations, to estimate how the performance will change by using future time series based on the IPCC RCP 8.5 scenario. In this abstract, some of the results obtained for Lyon, Melbourne, Montreal, and Seoul are presented. As time series data are not available with the same time resolution in all cities, the influence of the simulation time step is also investigated.

Material and methods

Green roofs

The advanced green roof simulated in this work (see Figure 1) includes i) a substrate depth ranging from 60 to 240 mm, ii) a separation plate with cells filled with clay pellets, and iii) an additional underlying storage layer below the separation plate with a storage capacity ranging from 52 to 150 mm (or L/m²). The green roof is vegetated with sedums and equipped with outflow controllers. It is manufactured by the French company Le Prieuré and will be installed on the roofs of the Athletes' Village buildings managed by the SOLIDEO company for the Paris 2024 Olympic Games (hence the project name "Olympluie", i.e. Olympic rain).

Historical and future time series

Rainfall intensity, and potential evapotranspiration (PET) or air temperature data were collected for eight cities (see Table 1) around the world, with time steps from 1 minute to 1 hour (resp. 1 day). When PET data were not available, PET was estimated from the measured or calculated average daily temperature by means of the Oudin formula (Oudin *et al.*, 2005). Rainfall intensity (I , mm/h) and PET (PET , mm/h) time series have been processed (detection of data gaps, outliers, etc.) and prepared for simulations, with time steps ranging from 1 to 60 minutes (see **Erreur ! Source du renvoi introuvable.**). For five cities, IPCC RCP 8.5 climate projections data at daily resolution for future precipitation and temperature are available and easily accessible. Combined with historical time series, these data have been used to create 10 future time series for the decade 2090-2099 by means of dynamical and statistical downscaling coupled to bias correction with the MRC (multiplicative random cascade) approach (see details of the method in Pons *et al.*, 2022).

Table 1. Cities and time series used for simulations. Due to limited space, only results for time series marked with * are shown in this abstract.

| City, Country | Historical I and PET time series | Future I and PET time series | Simulation time step of I and PET time series |
|-------------------------|----------------------------------|------------------------------|---|
| Lyon, France | 2000-2019* | 2090-2099* | 6 min |
| Melbourne, Australia | 2000-2019* | 2090-2099 | 6 min |
| Seoul, South Korea | 2000-2019* | 2090-2099 | 1, 6 and 15 min |
| Montreal, Canada | 2005-2021* | 2090-2099 | 1, 6 and 15 min |
| Los Angeles, USA | 2000-2019 | in progress- | 1 hour |
| Dourados, Brazil | 2009-2021 | in progress- | 15 min and 1 hour |
| Cape Town, South Africa | 2000-2019 | in progress- | 1 hour |
| Trondheim, Norway | 2000-2019 | 2090-2099 | 1 and 6 min |

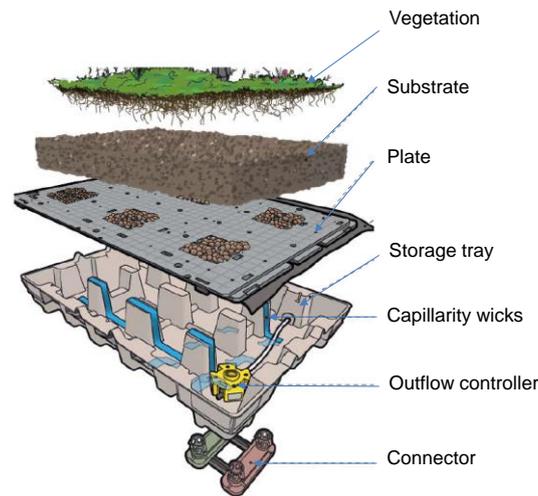


Figure 1. Scheme of the OASIS advanced green roof.

Green roof model and specifications

The Gepeto model developed by INSA Lyon in partnership with Le Prieuré is used for the simulations. It was previously tested and calibrated with experimental data (Bournique *et al.*, 2019; Principato *et al.*, 2015). The green roof standard key specifications are the following ones: substrate depth = 80 mm with a storage capacity = 52 mm, separation plate cells storage capacity = 4 mm, underlying storage capacity = 52 mm, controlled outflow = 10 L/s/ha, threshold depth in the underlying storage to initiate the outflow control = 9.83 mm (only storage below this value), and two outflow controllers per roof.

Simulation scenarios

Simulations are carried out with both historical and future time series listed in **Erreur ! Source du renvoi introuvable.** In the first phase of work presented in this abstract, two design specifications varied: i) the thickness of the substrate, with seven values = 60, 80 (default value), 100, 120, 160, 200, and 240 mm, and ii) the underlying storage capacity, with five values = 52 (default value), 75, 100, 125, and 150 mm. Simulations are run with time steps ranging from 1 minute to 1 hour. For each city and each meteorological time series, 35 simulations are run. In total, more than 1500 simulations are carried out.

Results and discussion

Some examples of simulation results are given hereafter for Lyon, Melbourne, Montreal, and Seoul.

Evapotranspiration efficiency

Evapotranspiration efficiency (EE) is defined as the percentage of water that is evapotranspired by the green roof compared to the amount of rain for a given duration. A 60% EE means that 60% of the rain falling on the green roof during the simulation period are evapotranspired. Reciprocally, 40% of the rainfall volume are i) discharged by the green roof either as controlled outflow or as overflow in case the green roof maximum total storage capacity (substrate + cells + underlying storage) is reached, and ii) stored in the substrate, in the cells, and in the underlying storage at the end of the simulation period.

In Lyon, the global simulated EE for the period 2000-2019 for a standard green roof (substrate depth = 80 mm, underlying storage = 52 mm) is 66.7%. The global EE is only 60.0% with the same roof for the future climate period 2090-2099. The box plot of the annual EE for both periods is shown in Figure 2. For the period 2000-2019, the annual EE varies from 58.3% to 87.6%. For the period 2090-2099, it varies from 51.8% to 70.8%.

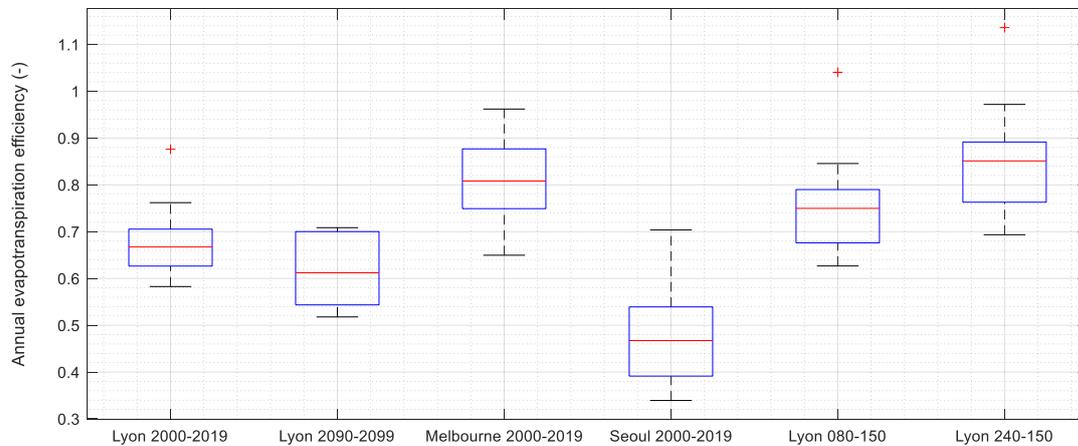


Figure 2. Box plot (with standard 1.5 IQR limits) of annual evapotranspiration efficiencies in Lyon 2000-2019, Lyon 2090-2099, Melbourne 2000-2019, Seoul 2000-2019 for a standard roof (substrate depth = 80 mm, underlying storage = 52 mm), and Lyon 2000-2019 for two other green roof designs (substrate depth = 80 mm, underlying storage = 150 mm and substrate depth = 240 mm, underlying storage = 150 mm).

Simulations for Melbourne and Seoul over the period 2000-2019 give global EE equal to 79.9% and 46.2% respectively. **Erreur ! Source du renvoi introuvable.** shows the comparison of annual EE for the same roof as in Lyon simulated in Melbourne and Seoul. In Melbourne, the annual EE ranges from 65.0% to 96.2%, which is better than in Lyon due to differences in climatic conditions (not detailed here). In Seoul, the annual EE ranges from 33.9% to 70.4%: this lower performance, compared to Lyon and Melbourne, is due to the very strong rainfall events which are observed during the monsoon period from mid-June to mid-September. In such a case, the green roof design must be adapted, with thicker substrate, or increased underlying storage, or lower maximum controlled outflow (less than 10 L/s/ha), or any combination of these parameters (results not shown here) to reach a given level of performance.

The influence of green roof design is illustrated in Figure 2 with box plots of annual EE for two roofs in Lyon, for the period 2000-2019, with the following specifications: i) substrate depth = 80 mm, underlying storage = 150 mm, and ii) substrate depth = 240 mm, underlying storage = 150 mm). The EE improves compared to the standard roof, with global EE of 73.8% and 83.6% respectively. For the year 2017 in Lyon, the annual EE is higher than 1 (outliers in the boxplots): this year has the lowest rainfall depth (490 mm), after a rainier year in 2016 (718 mm): at the end of 2016, 191.5 mm of water are stored in the 240-150 green roof (84.7 mm in the substrate and 106.8 mm in the underlying storage): they will be evapotranspired in 2017, which explains an EE higher than 1.

Results for other performance indicators (seasonal variability, event interception efficiencies according to classes of rainfall depth, peak attenuation) will be presented during the conference for all cities and simulated scenarios.

Influence of simulation time step

In Montreal, the raw rainfall data were the raingauge tipping times over the period 2005-2021. Rainfall intensities have then been calculated for 1 min, 6 min and 15 min time steps, and simulations of the standard green roof (80 mm substrate and 52 mm underlying storage) have been run accordingly. The comparison is based on the green roof total outflow (i.e. controlled outflow + overflow) as this quantity is more quickly reactive to rain intensity, and therefore influenced by the simulation time step, than the slowest evapotranspiration process. Results are shown for various indicators in Table 2. Globally, the distributions of

the non-zero total outflow values appear very similar for the three different time steps (figure not shown here). The first most significant difference is observed for the maximum total outflow value, which decreases from 30.6 to 3.2 mm/h when the time step increases from 1 to 15 minutes, whereas the 99.9% percentiles are very similar. The second most significant difference is observed for extremely low total outflow values (i.e. negligible total outflow less than 10^{-6} mm/h), corresponding to approximately 3.5% of the values. However, their influence on the cumulated outflow depth is negligible. Mann-Whitney tests at 5% significance level indicate that distributions of total outflow values higher than 10^{-6} mm/h are not significantly different between 1 min and 6 min time steps, while they slightly differ between 1 min and 15 min, and between 6 min and 15 min. Similar results are obtained for Seoul with the same green roof when comparing total outflow distributions obtained with 6 min and 15 min time steps. Consequently, it is recommended to use simulation time steps from 1 to 6 minutes.

Table 2. Comparison of total outflow results for Montreal - 080-052 roof - 2005-2021 simulations run with 1 min, 6 min and 15 min time steps.

| Indicator related to total outflow | Time step 1 min | Time step 6 min | Time step 15 min |
|---|-----------------|-----------------|------------------|
| Percentage of time with non-zero outflow (%) | 33.43 | 33.42 | 33.42 |
| Total outflow cumulated depth from 2005 to 2021 (mm) | 6452 | 6437 | 6403 |
| Difference (%) of above indicator compared to 1 min | 0 | -0.23 | -0.75 |
| Mean value of non-zero outflow (mm/h) | 0.1295 | 0.1293 | 0.1286 |
| Median value of non-zero outflow (mm/h) | 0.1038 | 0.1037 | 0.1037 |
| 90% percentile value of non-zero outflow (mm/h) | 0.2888 | 0.2883 | 0.2864 |
| 99% percentile value of non-zero outflow (mm/h) | 0.4474 | 0.4468 | 0.4454 |
| 99.9% percentile value of non-zero outflow (mm/h) | 0.5134 | 0.5131 | 0.5140 |
| Max value of non-zero outflow (mm/h) | 30.6 | 7.4 | 3.2 |
| Percentage of total outflow values < 10^{-6} mm/h (%) | 3.55 | 3.54 | 3.45 |
| Cumulated depth of total outflow values < 10^{-6} mm/h (mm) | 2.4e-6 | 1.8e-5 | 5.8e-5 |

Conclusions

The Olympluie project simulated various green roof design scenarios for 8 cities in the world, with different climatic contexts, including future climate derived from IPCC data sets:

- Various performance indicators are evaluated for a detailed comparison of scenarios, allowing to adapt the green roof design to each geographical and climatic context, in particular climate change.
- Future climate time series tend to show lower performances compared to historical time series.
- Compared to 15 min, time steps of 1 min or 6 min are recommended to ensure outflow peak values are not underestimated.

The full paper will present and discuss all simulation results for all cities and will show how to adapt the green roof design to various climatic contexts for given performance specifications.

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