Evaluating the Effectiveness of "0 emission" Green Roof Solutions under Future Climate Scenarios for Paris

Évaluation de l'efficacité de toitures végétalisées « 0 rejet » sous scénarios climatiques pour la ville de Paris

Subrahmanian Sreethu[1], Versini Pierre-Antoine[1], Schertzer Daniel[1], Sindt Lionel[2], Adrovic Alicia[2], Perrin Rémi[2]

[1] HM&Co, Ecole Nationale des Ponts et Chaussées, IPP - pierre-antoine.versini@enpc.fr
[2] Soprema

RÉSUMÉ

L'intégration de systèmes durables de gestion des eaux pluviales, tels que les toitures végétalisées, permet d'atteindre une logique de « 0 rejet » en favorisant l'infiltration à la source et en régulant totalement le ruissellement excédentaire, contribuant ainsi au maintien de l'équilibre hydrologique et à une meilleure résilience face aux inondations. Compte tenu de la probabilité accrue d'événements de précipitations extrêmes à l'avenir, il est essentiel d'évaluer l'efficacité de ces toitures végétalisées dans le cadre de scénarios climatiques futurs. Ces travaux visent à proposer les bases d'un outil de dimensionnement à même de proposer des solutions dites « 0 rejet » en toiture, adaptées aux contraintes réglementaires locales d'une collectivité. Son application à Paris est présentée ici. Un modèle de réservoir non linéaire, intégrant un modèle de distribution de la taille des pores (PSD) multifractal, a été utilisé pour la modélisation hydrologique et la simulation de l'écoulement de l'eau à travers la toiture végétalisée. La performance de cette dernière a été évaluée à partir de données climatiques (passées et futures) désagrégées à une fine résolution temporelle grâce à un modèle de simulation en double cascade dans le cadre multifractal universel (UM). Les résultats de l'étude indiquent que l'efficacité des toitures végétalisées diminue en raison de l'augmentation de l'intensité des épisodes de précipitations à venir. Et pour lutter contre les futurs épisodes de précipitations extrêmes, la configuration et les conditions de fonctionnement des toitures végétalisées doivent être conçues en conséquence.

ABSTRACT

The integration of sustainable stormwater management systems, such as green roofs, makes it possible to achieve a "zero-discharge" approach by promoting on-site infiltration and fully regulating excess runoff, thereby helping maintain hydrological balance and improving flood resilience. With an increase in the likelihood of extreme precipitation events in future, it is essential to evaluate the effectiveness of green roofs for future climate scenarios. This work aims to provide the foundations for a sizing tool capable of proposing "zero-discharge" rooftop solutions adapted to the local regulatory constraints of a municipality. Its application to Paris is presented here. A non-linear reservoir model embedded with a multifractal-based pore size distribution (PSD) model was used for hydrological modelling and simulation of the water flow through the green roof. The performance of the green roof was evaluated using climate data (past and future) downscaled to fine temporal resolution through a double cascade simulation model in the universal multifractal (UM) framework. The results from the study indicate that the effectiveness of green roofs reduces due to the increase in the intensities of precipitation events in the future. Hence, to combat future precipitation extremes, the configuration and operational conditions of green roofs must be designed and implemented appropriately.

KEYWORDS

Climate Change, Efficiency of Green Roofs, Hydrological Modelling, Universal Multifractal Framework

1 INTRODUCTION

Sustainable stormwater management through Low Impact Development (LID) measures, Nature-Based Solutions (NBS), and Blue-Green Infrastructures (BGI) is increasingly recognized as a key component of the sponge-city approach, offering an alternative to conventional runoff-control techniques. These nature-based practices aim to achieve *zero-discharge* strategies by retaining and managing stormwater at source, enhancing infiltration, and supporting groundwater recharge. Among them, green roofs are widely adopted and particularly effective in dense urban environments where available land is limited (Kim et al. 2024). Green roofs prove advantageous in such cases by facilitating the retention of runoff without requiring the redesign of built-up areas. Hydrological responses from urban landscapes are extremely sensitive to variations in precipitation due to impervious land cover and increased runoff generation. Studies have shown that the intensity of precipitation events tends to increase due to global warming under future climate scenarios (Sun et al. 2024). Therefore, it is necessary to study the effect of future precipitation extremes and temperature on green roofs through hydrological modelling with climate data at a fine temporal resolution (sub-hourly time steps). However, the climate data from the global climate models, such as the Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2016), are only available at coarser resolutions (daily time step).

A preliminary requirement to assess the effectiveness of green roofs in urban areas is temporally downscaled climate data. This study utilises precipitation and temperature data from the CMIP6 model, downscaled to a 6-minute resolution. Downscaling is performed using multiplicative discrete cascade models developed within the framework of universal multifractal (UM) theory (Tessier et al. 1993). The downscaled climate data is used as input for hydrological modelling to study the performance of green roofs. The movement of water within the green roof (a combination of substrate and drainage layer) in the hydrological model is simulated using a non-linear reservoir model. The substrate layer in the green roof is physically modelled using a multifractal-based pore size distribution (PSD) model (Ramanathan et al. 2023). The main objective of this study is to evaluate the effectiveness (performance) of green roofs subjected to the precipitation extremes and temperature conditions anticipated in the future climate scenarios. As the focus of the study was the Paris region in France, reference rainfall events specific to Paris were created from the downscaled data. The inferences from the study could help in designing and planning “zero-discharge” green roof solutions that best fit the future climate. This study was initiated and conducted in collaboration between the HM&Co laboratory of ENPC and the SOPREMA company.

2 METHODOLOGY

2.1 Meteorological Data

The meteorological inputs required to execute the hydrological model are precipitation (reference rainfall specific to the region), temperature, and evapotranspiration data (Figure 1). The reference rainfalls were generated in this study using the UM framework. The rainfall field was assumed to have two scaling regimes: a finer resolution regime (6 minutes to 21 days), and a coarser resolution regime (21 days to 10 years). The UM parameters α and C_1 for the finer resolution were obtained from past observed data, while those for the coarser resolution were derived from climate scenarios (Shared Socioeconomic Pathways: SSP2-4.5 and SSP5-8.5) (Figure 2). In UM theory, α indicates the multifractality index and C_1 indicates the fractal codimension (Schertzer et al. 1997; Tessier et al. 1996). Using the UM parameters from the climate data and the multiplicative double cascade simulation model, reference rainfall scenarios at 6-minute resolution were generated that conform to the zero-emission rules of Paris (Ramanathan et al. 2022). The term “reference rainfall” for Paris refers to events with a return period of 6 months, occurring over a duration of 4 hours, with an accumulated rainfall of 16mm. The reference rainfalls were generated using two climate scenarios: SSP2-4.5 (an intermediate scenario) and SSP5-8.5 (a fossil fuel-based development scenario), for the time period 2031-2050. The reference rainfall events generated in this way will exhibit the patterns of intermittency and heterogeneity that cannot be produced with the probability distribution functions, and hence are ideal for studying rainfall extremes in the future. It was observed from the simulated reference rainfall events that the return period of 16 mm rainfall reduced from 6 months to less than a month in both future scenarios, indicating an increase in the frequency of precipitation extremes in future.

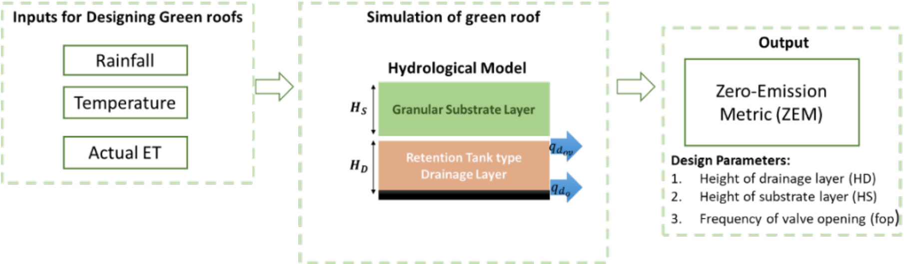

Figure 1. Overall framework of the hydrological modelling of the green roof

The temperature data at 6-minute resolution was downscaled from the daily resolution climate data using the structure function (Schertzer and Lovejoy 1991). The temperature was further used to generate the potential evapotranspiration (PET) data for the time period 2031-2050 using an empirical relation given below:

$$PET = \left(\frac{1}{2^{k+h}}\right) a \left(\frac{T}{\langle T \rangle}\right)^{b(T/\langle T \rangle)^{c}} \qquad (1)$$

where T is the temperature in Kelvin, a =211.25 mm, b = 26.59 mm, c = -7.29, h = 7.9, and k =6 are the empirical parameters estimated through the curve fitting of the observed daily temperature and evapotranspiration values from the datasets of Météo-France for the Paris region. It was observed that the PET losses for the climate scenario SSP5-8.5 (1344 mm) are higher when compared to SSP2-4.5 (1339 mm). This can be attributed to the high temperatures that are likely to occur in the SSP5-8.5 scenario with fossil fuel–based development.

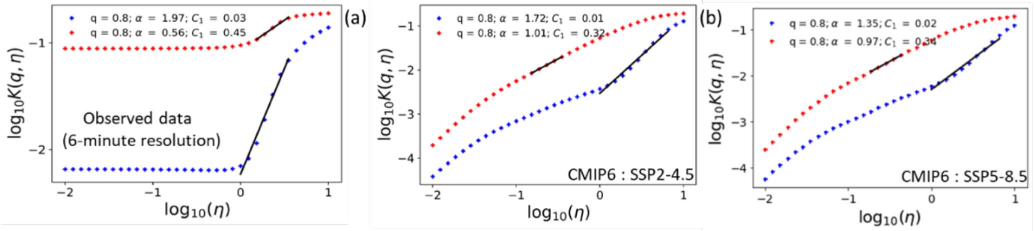

Figure 2. Estimation of UM parameters from (a) Observed data, (b) SSP2-4.5 and (c) SSP5-8.5 climate data (blue and red colours indicate coarse and fine scaling regimes, respectively).

2.2 Hydrological Modelling of green roof

The hydrological model used in the study conceptualises green roofs with a substrate layer and a drainage layer (Figure 1). The substrate layer is composed of soil media, and the drainage layer functions like a tank to store water. Precipitation that enters the green roof must pass through the substrate layer to reach the drainage layer. The movement of water through the green roof from one layer to the other is modelled using a non-linear reservoir model. To estimate the discharge from the substrate layer, the hydraulic conductivity and subsequently the water retention should be estimated at each computational time step. Utilising the PSD model (Ramanathan et al. 2023) offers a physically realistic approach to simulating water retention in the substrate layer. The water discharged from the substrate layer enters the drainage layer, which is fitted with an overflow drain and an outlet discharge. The opening and closing of the outlet discharge are controlled, while the overflow drain is always kept open to discharge runoff when the water storage capacity of the drainage layer is exceeded. The hydrological modelling enables the simulation of the overall discharge produced by a green roof during precipitation events. The efficiency of green roofs can be estimated based on the discharge (or water storage capacity) from the green roofs. In this study, effectiveness is measured using a zero-emission metric (ZEM). ZEM has been defined to assess the efficiency of green roofs so that they comply with the zero-emission (zero-discharge) rules of Paris. The ZEM is expressed as: $ZEM = \frac{1}{N}\sum_{me=1}^{N}\frac{N_{me,0}}{N_{me}}$, where N_{me} indicates the total number of reference rainfall events, $N_{me,0}$ indicates the number of reference rainfall events that comply with the zero-emission rules specific to Paris, and N indicates the total number of ensemble rainfall series generated from the multiplicative cascade model. A green roof is at its maximum efficiency when ZEM =1. The zero-emission rules divide Paris into 4 zones. During the occurrence of a reference rainfall event, the anticipated storage in the green roof (for a duration of 24 hours) in different zones is as follows: 4mm (zone 1), 8mm (zone 2), 12 mm (zone 3), and 16 mm (zone 4).

3 RESULTS AND DISCUSSIONS

The impact of future climate (2031-2050) was evaluated for a sample green roof in the Paris region using simulated reference rainfalls, temperature, and evapotranspiration scenarios. The green roof was modelled with a surface area of 12 m^2 and a surface slope = 0. The simulations were carried out for HS values varying between 170 mm and 300 mm, and HD values = 50, 80, and 100 mm. The results presented in Figure 3 depicts the efficiency of green roofs for zone 1 (Rule 1) in Paris (results for other zones are not presented due to the limitation in page count). In the figure, HD denotes the drainage layer depth, HS denotes the substrate layer depth, fop denotes the frequency of opening of the outlet discharge pipe present in the drainage layer. When fop = 0 days, it means that the outlet discharge pipe is kept closed, and the discharge from the green roof is through the overflow pipe. It can be observed that the efficiency of the green roof (ZEM) decreases in the future scenarios when compared to the past because of the increase in precipitation extremes in the future. Between the two future scenarios, SSP5-8.5 (52-62%) has better ZEM values than SSP2-4.5 (48-60%). This is because the evapotranspiration losses in SSP5-8.5 are higher due to the temperature rise induced by the exploitation of fossil fuels. This could lead to more water evaporating from the substrate and drainage layers in the green roof, thereby increasing its water storage capacity. Therefore, under the SSP5-8.5 climate scenario, water losses from the green roof will be higher due to evapotranspiration, which reduces the overflow discharge that happens during precipitation events.

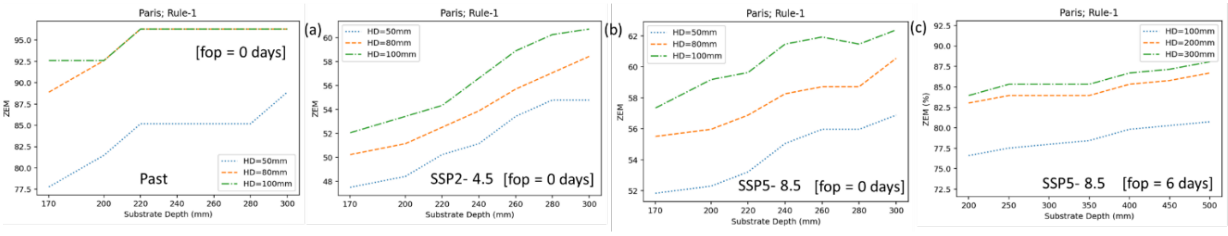

Figure 3. ZEM values obtained for (a) past climate, (b) SSP2-4.5 scenario, (c) SSP5-8.5 scenario, and (d) SSP5-8.5 scenario with improved green roof parameters

The ZEM values were found to improve for SSP5-8.5 when the HS and HD values were increased (Figure 3d), along with the operation of the outlet discharge pipe at a frequency of 6 days. This implies that to improve the efficiency of green roofs to withstand the future extremes, the design configurations (substrate and drainage layer depths), and the operational parameter (frequency of discharge pipe opening) have to be higher than the parameters used for past climate scenarios. This necessitates detailed hydrological modelling specific to various regions when green roofs are to be designed for integration with the developmental plan. The methodology proposed in the study has also been extended to study the efficiency of green roofs in other regions of France with different climate conditions (Nantes, Marseille, Strasbourg, and Lyon), complying with the zero-emission rules specific to them. The authors also intend to carry forward the assessment of the efficiency of green roofs for Paris by considering the future regulations planned from 2026.

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