

Should we include drought induced vegetation mortality when modelling long-term retention performance of green roofs?

Devrions nous inclure la mortalité de la végétation induite par la sécheresse lorsque l'on modélise la rétention à long terme des toitures végétalisées ?

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RÉSUMÉ

En période de sécheresse, la végétation des toitures végétalisées peut entrer en état de stress hydrique. Si cet état se poursuit trop longtemps cela peut conduire à la mort de la végétation. Les approches actuelles prenant en compte le stress hydrique de la végétation des toitures végétalisées consistent soit à étudier les stratégies de réponse de la végétation à la sécheresse et en déduire les plantes les plus adéquates pour végétaliser les toitures, soit à proposer des approches d'irrigation pour éviter le stress hydrique. D'autres approches cherchent à modéliser les périodes de stress hydrique directement. Cependant, aucune de ces approches ne s'attarde sur les conséquences de la mortalité induite par la sécheresse sur les performances, et donc sur une approche de risque de défaillance de la rétention par les toitures. La présente étude propose une approche qualitative pour prendre en compte cette perte de performance. Il a ainsi été montré qu'il est pertinent de consacrer plus d'effort à prendre en compte ce processus de mortalité induite par sécheresse étant donné que les résultats suggèrent un impact fort sur les performances suivant les scénarios testés. En revanche la mortalité n'a pas affecté la distribution des débits évacués par les toitures. Il a été jugé pertinent de proposer une approche qualitative car les modèles physiologiques à l'échelle de la plante manquent encore de robustesse. En conséquence, les recherches futures devraient collecter plus de données et s'orienter vers des approches de risques sous fortes incertitudes.

ABSTRACT

In period of drought the vegetation in green roofs can suffer hydric stress. In case drought occurs over long periods, this can lead to drought induced mortality. The current approaches coping with hydric stress on green roofs in the literature consists mainly in focusing on either selecting plants that can face drought or providing irrigation to avoid hydric stress. Other approaches intend to model hydric stress itself. However, none of those approaches models the risk of extreme hydric stress and plant mortality and its consequence as a risk of green roof retention failure. This study proposes a qualitative approach to model the retention performance loss induced by vegetation mortality. It was shown that it is indeed relevant to investigate that process since it can have a strong influence on the hydrological performance of green roofs. The retention loss did not affect the detention performance. It was found relevant to model the influence of that process in a qualitative way as plant scale physiological models still lack robustness. Therefore, future research should focus on gathering more data and on risk approaches accounting for high uncertainty.

KEYWORDS

(Drought-induced mortality, green roofs modelling, retention performance, risk approach)

1 INTRODUCTION

One of the main objectives of urban green infrastructures (GI) is retention, i.e. to reduce the volume of stormwater released from the source to a recipient such as a sewer network or a river in order to mitigate

the effect of urbanization and climate change (Stovin et al., 2013, 2017). Among GIs, some solutions, such as green roofs, rely on evapotranspiration processes to reduce the volume of runoff. The process of evapotranspiration depends on the vegetation, its state, and the available water content in the substrate. During a drought, the vegetation enters a state of hydric stress which prevents from achieving its main function in the green roof: evapotranspiration. If the drought is too severe it can lead to drought-induced mortality of the vegetation which in terms of stormwater infrastructure can be interpreted as a permanent damage to the infrastructure. It is then necessary to do a maintenance or a rehabilitation. After the heatwave in Europe in summer 2022, and the most recent climate change forecasts (Ribes et al., 2022) it appears relevant to include those failure in long term simulations.

Plants mortality has been studied from a physiological perspective (McDowell et al., 2013, Sapes et al., 2019). Based on a model representing coupled xylem and phloem transport, Mencuccini et al. (2015) identified three major drought induced mortality modes: i) carbon starvation, ii) hydraulic failure and iii) phloem transport failure. They acknowledged drought-induced mortality as being challenging to model.

Several studies investigated hydric stress in green roofs (Nagase et al., 2010, Vanuytrecht et al., 2014) or the use of drought resistant species (Szota et al., 2017) and the importance of plant traits for adequate vegetation selection for green roofs (Chu et al., 2022). For example, Du et al. (2019) reported a survival rate between 10 and 100% for different species at the end of a summer where the soil water content dropped to 5%. Nagase et al. (2010) reported, based on a dry watering regime (once every three weeks), survivability after 11 weeks. Many species had a survivability below 25% while sedum species had mostly high survival rate.

However, none to the authors' knowledge, and due to the above-mentioned limitation in drought induced mortality modelling, modelled plant mortality in green roof. Besides, several studies suggest to irrigate green roofs with (Hardin et al., 2012) or without (Van Mechelen et al., 2015) water reuse. More recently some studies investigated strategies with limited irrigation and their effect on the plant physiological performance (Tomasella et al., 2022). However, they do not provide a baseline scenario that include the effect of drought-induced mortality.

Based on the introduction of a qualitative equation to account for drought-induced mortality of vegetation on green roofs, and by considering different climate conditions and climate change scenarios, the objective to that study is to: i) investigate the impact of neglecting this process on long term green roof performances in current and future climate depending on the location, and iii) introduce a risk-based approach based on evapotranspiration.

2 METHODS

2.1 Climate location and climate change scenarios

The chosen locations are Trondheim, Lyon and Marseille. The choice was based on the dry climate conditions for Lyon and Marseille, while Trondheim is used as a reference where drought is expected to occur less frequently. Additionally, the availability of a statistical temporal downscaling model generating time-series at 6-minute resolution based on daily resolution time-series (Pons et al., 2022) was another decision criterion.

2.2 Green roof models

The green roof models used in that study are similar to the ones used in Pons et al. (2022). They were chosen because the extensive green roof (E-green roof) and the detention-based extensive green roof (D-green roof) have different behaviours and storage layers. They were modified as detailed in the following section.

2.3 Qualitative model for drought induced mortality

The survival rate of the vegetation in dry conditions depends directly on the species and their drought response (e.g., isohydric that avoid drought by closing their stomata to keep water, or anisohydric that tolerate drought allowing their internal water content to drop). The combination of species, through biotic interactions, can also play a role and improve their response.

To account for this variability between studies, plants and conditions, several scenarios were introduced based on the duration under hydric stress (stress duration – sl): between 2 weeks and 8 weeks (2, 4, 6, and 8 weeks) associated with a decreasing survival rate (sr) from 90 to 20 % (90, 70 and 50 %) with increment during time. Maintenance operations were assumed to be carried out in the following spring

season to restore the survival rate to 100%. It is acknowledged that hydric stress solely does not lead to mortality. However due to the conceptualization of the actual evapotranspiration that linearly decrease with water content in the models, it was chosen to consider hydric stress only. Notations are as follows: the scenario noted srX_slY is a scenario with a survival rate of X/10 after a stress period of Y weeks.

2.4 Performance estimation

The annual retention fraction was estimated with a moving window with a 2-week step computed for each time-series as a retention fraction distribution.

To compare drought and climate scenarios, the Kolmogorov-Smirnov distance (KS distance) was used. A value of zero shows that the distributions are similar, a value of 1 is the maximum. A value of X between 0 and 1 shows that when estimating the probability to have a retention fraction with the baseline scenario compared to another scenario the difference in estimation can be up to X. In the hypothesis that a drought scenario represents accurately the processes, the difference can be interpreted as an error in the probability estimation of the performance.

3 RESULTS AND DISCUSSIONS

3.1 Shift in performance based on drought-induced mortality

For each of the location the KS distance between the calculated retention distributions was computed. For instance, on figure 1 in the case of Lyon, the baseline scenario estimates that the retention will be higher than 40% with a probability of approx. 0.7, while with the scenario sr7_sl2 the probability is slightly less than 0.2. It means that the error in estimation is of 0.6, the KS distance exhibits the highest error that can be made if the drought scenario is accurate. It showed that in Trondheim scenarios based on a stress duration sl equal to or longer than 6 weeks did not affect the performance. In Lyon, scenarios with sl \geq 8 weeks, and in Marseille all scenarios, influenced the retention distribution. Those results highlight that the greater the exposure to drought, the higher the risk of having the retention performance altered.

The change in performance for the scenarios srX_sl4 and srX_sl2 compared to the baseline scenario shows that the shift is not linear with the stress length (not shown in figure 1). It also suggests that extensive green roofs are more sensitive in terms of performance which is expected since their thin substrate layer cannot store enough water for prolonged dry periods.

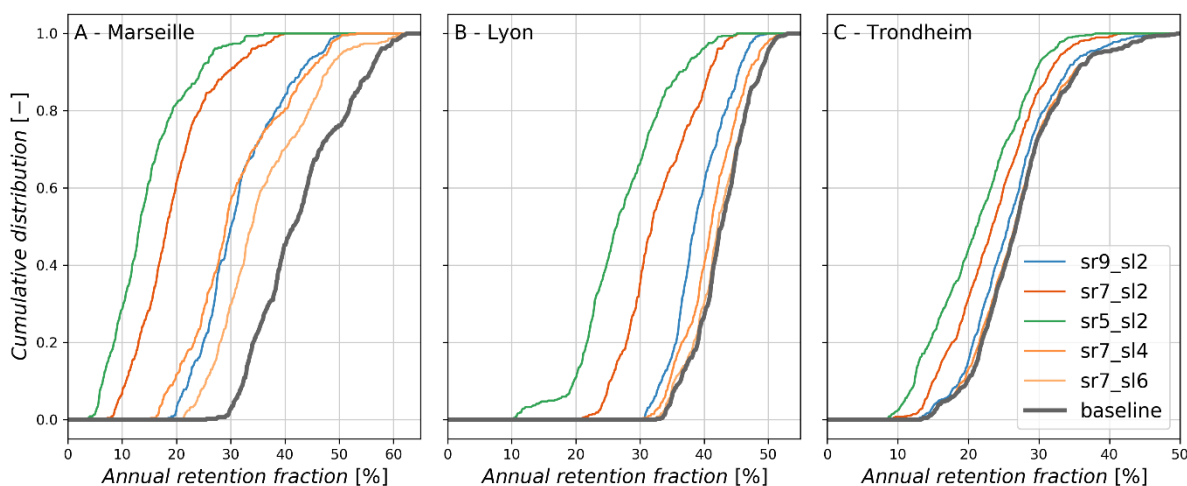


Figure 1 : Cumulative distribution of retention fraction for the D-green roof for each location. The baseline is the reference scenario without drought mortality.

3.2 Shift in performance between current and future climate

To evaluate the effect of climate change on the use of a qualitative equation for drought mortality, the KS distance between the cumulative distributions in current and in future climates was used. For the moderate drought induced mortality scenario and the baseline without drought mortality the distance was estimated close to 0.4 in the city of Lyon. Only scenarios with severe drought mortality had a lower distance to current conditions with 0.3. It means that the shift in performance is similar, with and without drought mortality. The lower distance in case of severe drought can be explained by the fact that during

summer only low performance are reached so the difference between current and future climates remain moderate.

4 CONCLUSION

Including a qualitative equation to account for the drought-induced vegetation mortality had a clear effect on green roof retention performance. It was possible to show that the performance loss due to retention failure depends on both the location and plant selection. Based on the input range for the simulation that was drawn from literature values, it can be concluded that this process deserves more attention for a risk-based perspective. It was found that retention failure did not affect the detention performance of the green roof. The divergence of the retention failure scenario to the baseline scenario was not affected by climate change. Using those scenarios as baseline would lead to a better estimation of risks and of benefits of irrigation scenarios.

The current approach is acknowledged as being limited due to the qualitative nature of the equations used to represent drought mortality. In order to strengthen the results a multi-model approach should be used since the equations used to compute potential evapotranspiration, actual evapotranspiration and hydric stress influence the modelling outputs. If experimental data are gathered, it should become possible to derive an empirical quantitative equation.

LIST OF REFERENCES

- Chu, H.-H., and Farrell, C. (2022). *Fast plants have water-use and drought strategies that balance rainfall retention and drought survival on green roofs*. *Ecological Applications*, 32(1). doi: 10.1002/eap.2486.
- Du, P., Arndt, S., and Farrel, C. (2019). Is plant survival on green roofs related to their drought response, water use or climate of origin? *Science of The Total Environment*. 667, 25-32. doi: 10.1016/j.scitotenv.2019.02.349.
- Hardin, M., Wanielista, M., and Chopra, M. (2012). *A Mass Balance Model for Designing Green Roof Systems that Incorporate a Cistern for Re-Use*. *Water*, 4(4), 914-931. doi: 10.3390/w4040914.
- McDowell, N. G., Fisher, R. A., Xu, C., Domec, J. C., Hölttä, T., Mackay, D. S., ... and Pockman, W. T. (2013). *Evaluating theories of drought-induced vegetation mortality using a multimodel–experiment framework*. *New Phytologist*, 200(2), 304-321. doi: 10.1111/nph.12465.
- Mencuccini, M., Minunno, F., Salmon, Y., Martínez-Vilalta, J. and Hölttä, T. (2015). *Coordination of physiological traits involved in drought-induced mortality of woody plants*. *New Phytol.* 208, 396-409. doi: 10.1111/nph.13461.
- Nagase, A., & Dunnett, N. (2010). *Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity*. *Landscape and Urban Planning*. 97(4), 318-327. doi: 10.1016/j.landurbplan.2010.07.005.
- Pons, V., Benestad, R., Sivertsen, E., Muthanna, T. M., and Bertrand-Krajewski, J.-L. (2022). *Forecasting green roof detention performance by temporal downscaling of precipitation time-series projections*, *Hydrol. Earth Syst. Sci.*, 26, 2855–2874. doi: 10.5194/hess-26-2855-2022.
- Ribes, A., Boé, J., Qasmi, S., Dubuisson, B., Douville, H., and Terray, L. (2022). *An updated assessment of past and future warming over France based on a regional observational constraint*, *Earth Syst. Dynam.*, 13, 1397–1415. doi: 10.5194/esd-13-1397-2022.
- Sapes, G., Roskilly, B., Dobrowski, S., Maneta, M., Anderegg, W. R., Martinez-Vilalta, J., and Sala, A. (2019). *Plant water content integrates hydraulics and carbon depletion to predict drought-induced seedling mortality*. *Tree physiology*, 39(8), 1300-1312. doi: 10.1093/treephys/tpz062
- Stovin, V., Poë, S., and Berretta, C. (2013). *A modelling study of long term green roof retention performance*. *Journal of Environmental Management*. 131, 206-215. doi: 10.1016/j.jenvman.2013.09.026.
- Stovin, V., Vesuviano, G., and De-Ville, S. (2017). *Defining green roof detention performance*. *Urban Water Journal*. 14(6), 574-588. doi: 10.1080/1573062X.2015.1049279.
- Szota, C., Farrell, C., Williams, N., Arndt, S., and Fletcher, T. (2017). Drought-avoiding plants with low water use can achieve high rainfall retention without jeopardising survival on green roofs. *Science of The Total Environment*. 603-604, 340-351. doi: 10.1016/j.scitotenv.2017.06.061.
- Tomasella, M., De Nardi, E., Petruzzellis, F., Andri, S., Castello, M., & Nardini, A. (2022). *Green roof irrigation management based on substrate water potential assures water saving without affecting plant physiological performance*. *Ecohydrology*, 15(4). doi: 10.1002/eco.2428
- Van Mechelen C., Dutoit T., and Hermy M. (2015). *Adapting green roof irrigation practices for a sustainable future: A review*. *Sustainable Cities and Society*. 19, 74-90. doi: 10.1016/j.scs.2015.07.007.
- Vanuytrecht, E., Van Mechelen, C., Van Meerbeek, K., Willems P., Hermy, M., and Raes, D. (2014). Runoff and vegetation stress of green roofs under different climate change scenarios. *Landscape and Urban Planning*. 122, 68-77. doi: 10.1016/j.landurbplan.2013.11.001.