A practical tool for designing vegetated roofs to optimise rainfall retention

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Un outil pratique pour optimiser la rétention des eaux pluviales dans les toitures végétalisées

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RÉSUMÉ

Les toitures végétalisées (TVs) sont de plus en plus utilisées pour diminuer les rejets urbains par temps de pluie. Les concepteurs de toitures végétalisées ont besoin d'outils d'aide à la décision pour choisir les végétaux et le substrat en vue d'optimiser la performance hydrologique. Le bilan hydrique et donc la performance hydrologique d'une toiture végétalisée dépendent principalement de la capacité des plantes à restaurer la capacité de stockage après chaque pluie. Toutefois, la plupart des TVs utilisent actuellement des plantes sélectionnées pour leur résistance à la sècheresse, avec une faible consommation d'eau, ce qui donne à ces plantes la capacité de survivre pendant des périodes sans pluie, mais qui limite leur performance en termes de mitigation de ruissellement. Nos études précédentes ont montré qu'il existe des plantes (provenant d'habitats semblables aux toitures végétalisées, tels que les affleurements en granite) qui ont une forte capacité à varier leur consommation d'eau selon le teneur en eau du substrat. On présente, dans cette communication, un modèle simple qui simule le bilan hydrique de toitures végétalisées, en prenant en compte l'effet de cette variation sur la performance hydrologique sur le long terme. Le modèle permet au concepteur d'optimiser la sélection du végétal et du substrat pour atteindre les objectifs hydrologiques du système, ainsi que d'évaluer les risques dus à la sécheresse pour ces plantes. On propose d'intégrer le modèle dans une application-web accessible aux concepteurs et urbanistes.

ABSTRACT

Green roofs are increasingly being designed to reduce the volume of polluted stormwater generated by cities. Green roof designers therefore need tools to help them select an appropriate combination of plants and substrates which will maximise rainfall retention. The rainfall retention capacity and therefore the hydrological performance of green roofs are largely determined by the ability of plants to replenish the water storage capacity of the substrate between storm events. Most green roofs, however, are planted with drought-tolerant species with inherently low water use which, while limiting their rainfall retention capacity; ensures persistence of the vegetation during drought. In previous studies, we showed that plants from habitats analogous to green roofs, e.g., granite outcrops; can show adaptive water-use strategies; facilitating high water use when it is available, while retaining the ability to survive periods of drought. In this paper, we outline a simple green roof water balance model which describes how these alternative plant water-use strategies can affect the long-term hydrological performance of green roofs. The model allows the user to determine the best combination of substrates and plants to achieve given long-term runoff reduction targets; as well as quantifying the incidence and severity of drought stress. We intend to develop this model into a simple, user-friendly web application which can be used directly by urban planners and green roof designers.

KEYWORDS

Evapotranspiration, green roof, plant physiology, rainfall retention, stormwater reduction

1 INTRODUCTION

Rooftops represent a significant proportion of the impervious surface area in cities. Therefore, green roofs can potentially make a valuable contribution to reducing stormwater runoff volumes. These hydrological benefits have led to green roofs being increasingly adopted worldwide, with many cities legislating or encouraging their adoption through other policy mechanisms.

Green roofs have been installed across temperate regions, where they typically have a shallow substrate (30-150 mm) and are planted with low water-using succulent species with high tolerance to drought as well as freezing temperatures. In hotter cities such as those in Mediterranean areas, low-water using succulents are also highly valued for their drought tolerance. The need for drought tolerance is increased by the fact that substrates are often shallow as buildings in Mediterranean climates have largely not been constructed to cope with extra loads such as snow.

However, the exclusive use of low water-using plants potentially limits the hydrologic performance of green roofs; as evapotranspiration is the major process by which the rainfall retention capacity of a green roof is determined (Poë et al., 2015). In an earlier study, we found that plants from shallow soil areas (such as granite outcrops) can have high rates of water use when it is available, but are able to limit water use under drought conditions (Farrell et al., 2013). Selecting plants with these water- use strategies may therefore improve rainfall retention, without increasing the likelihood of drought death.

The hydraulic processes and rainfall retention capacity of shallow-substrate/succulent plant green roof configurations have been well described by a number of models. However, few attempts have been made to compare how different plant species may influence the hydrologic benefits of green roofs. In this paper, we present a simple water balance model to assess the trade-off between hydrologic performance and the incidence of drought stress for plants with different water use strategies. This model can be used to select the most appropriate combination of substrate type/depth and plant water use strategy. We intend to develop into a web application to be used by urban planners, policy makes and green roof designers to help them both set and meet stormwater reduction targets.

2 MATERIALS AND METHODS

2.1 Structure of the water balance model

Our water balance model is coded in R (R Core Team, 2014) and the structure follows many previous studies by using: $dS/dt = P – R – ET$; where the change in soil moisture stored in the substrate per unit time (dS/dt) is equal to precipitation (P) minus runoff (R) and evapotranspiration (ET). As a daily time-step rainfall retention model, the order of operations begins with the depth of water stored in the substrate on the previous day (S_{t-1}). Our model runs an initial simulation to determine the starting storage value (S_{t-1}); where we first set starting storage equal to 50%; then the model runs the first year of the supplied climate data 5 times, to equilibrate storages and eliminate any artefacts of setting the initial storage. The storage value at the end of this ‘pre-simulation’ run is then used as S_{t-1}. Rainfall on the day (P_t) is then applied to the substrate as a single dose (i.e., S_{t-1} + P_t) and any water exceeding the maximum storage capacity of the system (WHC) is converted to runoff (R_t); whereas the remainder is retained by the substrate.

Evapotranspiration on the day (ET_t) is then calculated in a two-step process; following the method of Allen et al. (1998). Firstly, reference evapotranspiration (ETo_t; determined using the Penman-Monteith equation) is converted to crop evapotranspiration by applying a species-specific crop factor (K_c); representing the depth of water that species would use if the water content of the substrate was maximised. Secondly, ET_t is adjusted according to the available moisture in the substrate after rainfall (S_{t-1} + P_t); using the relationship between stomatal conductance (g_s; indicative of maximum water use where all but SWC are non-limiting) and soil moisture content for each species. ET_t is then simply subtracted from S_{t-1} + P_t to calculate the depth of water in the substrate at the end of the day (S_t). At present, there is no ‘death function’; i.e., even if substrates have zero water for an indefinite period, the plants will start using water again as soon as rainfall occurs. This is of course not realistic and will be the subject of specific experiments to describe recovery of ET after extended periods of drought.

The outputs generated include the size, frequency and number of runoff events; as well as the incidence of plant stress. Interpretation of the output allows the user to design a green roofs system; i.e., select the best combination of substrate type, depth and plant species to achieve runoff reduction targets while minimising the risk of dieback or death of the vegetation.

2.2 Required model inputs

2.2.1 *Substrate properties: water holding capacity and depth*

Both the water holding capacity (*WHC*) and the depth (*D*) of the substrate are required to run the model; however, the user can enter as many different values of both inputs to determine the optimum combination of substrate type and depth to achieve reduction targets and minimise plant water stress. In the example here, we simply take the *WHC* of three green roof substrates we have used in previous experiments: roof-tile, scoria and bottom ash (46, 44 and 52% *WHC*) (Farrell et al., 2012) and test a range of depths from 0 (i.e., no green roof) to 300 mm.

2.2.2 *Meteorological data: precipitation and reference evapotranspiration*

Daily precipitation (*P*) and reference evapotranspiration (*ETo;* according to Allen et al. (1998)) data are required to run the model. For this example simulation, 1 year (2014) of *P* and *ETo* data were sourced from SILO (Jeffrey et al., 2001) for the Melbourne Regional Office meteorological station (086071).

2.3 Plant-related model parameters

2.3.1 *Determining plant water use and water stress*

Two parameters are required to calculate *ET* on any given day in our model: (i) the relationship between *ET* and *ETo* under well-watered conditions (i.e., a 'crop factor') and (ii) the relationship between soil water content (*SWC*) and g_s to determine the reduction in water use during soil drying. We derived these functions in a terminal drought (glasshouse) experiment for 18 species, including: geophytes, grass-like monocots, herbs and shrubs, selected from drought-prone and/or shallow soil habitats around Victoria, Australia. Plant water stress is also calculated by the model and was determined from the same experiment by relating *SWC* to predawn leaf water potential (Ψ_{PD}); a standardised method of determining relative water status. Pressure-volume curves were generated for all 18 species which also allowed us to determine the water potential at which each species loses turgor, or 'wilts' (Ψ_{TLP}).

2.4 Outputs generated by the model

2.4.1 *Hydrological and plant physiological performance metrics*

The model generates critical hydrological metrics, including: the number of runoff events, total runoff volume and rainfall retention (i.e., runoff reduction). Many green roof models report these statistics; however, our model also reports on the status of the vegetation, specifically with regard to the frequency and duration where plants are exposed to significant water stress and are therefore at a high risk of dieback/death.

3 RESULTS AND DISCUSSION

Figure 1 compares the performance of two contrasting plant species: (i) *Arthropodium milleflorum*; a medium-level water user with high sensitivity to drought and (ii) *Ficinia nodosa*; a high-water user with very little sensitivity to drought. Figure 1A and B indicate how green roofs planted with these species would differ with regard to rainfall retention, in relation to increasing substrate depth, for three different substrates. To achieve ~80% rainfall retention, a roof planted with the medium water-using plant (*Arthropodium*) would need a substrate of 150 mm deep; whereas a similar reduction could be achieved with half that depth (75 mm) for a roof planted with a high water user (*Ficinia*). This estimate does not take into account the impact of drought stress which could lead to death of the vegetation and therefore a reduction in rainfall retention. Figure 1C and 1D illustrate this risk by showing the number of days each species is exposed to 'critical' water stress (i.e. number of days where Ψ_{PD} is less than the Ψ at which the different species wilt (Ψ_{TLP})). As well as using less water, *Arthropodium* is also highly sensitive to declining soil water content; therefore it does not experience significant water stress even when planted in very shallow substrate. Conversely, the high water user (*Ficinia*) is less sensitive to drought and continues to use water at a high rate as the substrate dries. As a result, the *Ficinia* would need to be planted in >150 mm scoria substrate to avoid significant water stress;

whereas the *Arthropodium* could survive well even at very shallow substrate depths. Shallow-substrate green roofs in Mediterranean climates will almost certainly need irrigation during drought; therefore Figures 1C and D can also be used to estimate when irrigation would be required to alleviate drought stress and avoid plant dieback. The final decision on the best combination of substrate type, depth and plant species (strategy) based on such outputs will depend on the requirements of the user with regard to their set rainfall retention targets, weight loading restrictions and other considerations.

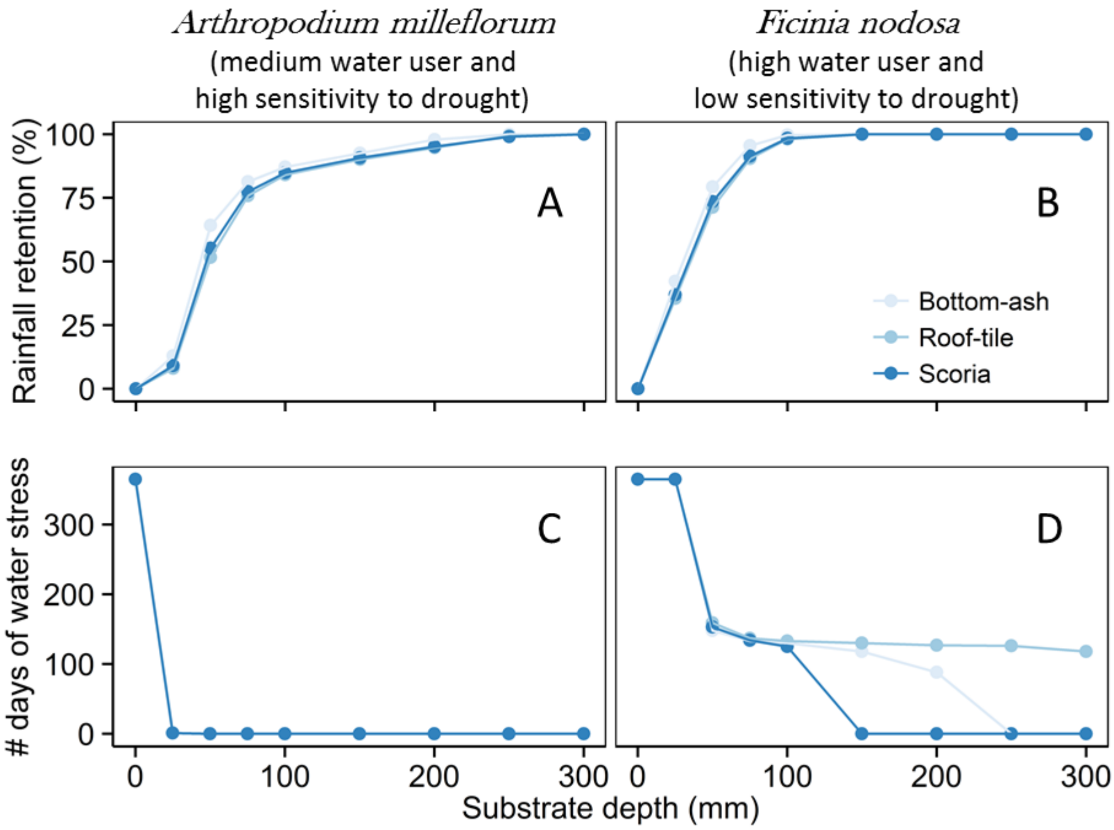

Figure 1. Rainfall retention (A and B) and number of days where plants suffer significant water stress (C and D) for two species with contrasting water use strategies in relation to substrate type and depth.

4 CONCLUSIONS

We suggest that our green roof model could be used by designers to select the combination of plants species and substrates which will maximise rainfall retention and minimise the incidence of drought stress. The model is still in development and will improve over time as we gather more information on specific responses to drought and recovery and validation data; however, we expect to convert it from a research tool into a simple web-based interface in the near future to develop its practical usefulness at the same time we are improving its accuracy.

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