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Green roof performance potential in cold and wet regions

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ABSTRACT

Extensive green roofs have become a frequently used option for stormwater retention across many different climates including cold and wet regions. Despite the extensive documentation of green roof technology for stormwater management, the knowledge about their function and potential use in wet and cold regions is deficient. Using historic data on daily temperature and precipitation in a green roof water balance model coupled with the Oudin model of evapotranspiration (ET), we evaluated the effects of maximum green roof storage capacities (S_{max}) and ET on stormwater retention along climatic gradients in Northern Europe. Large differences in potential annual stormwater retention were found between locations, driven by differences in temperature and precipitation amounts. Highest retention in absolute values was found for the wettest locations, while the warmest and driest locations showed highest retention in percentage of annual precipitation (up to 58% compared to 17% for the lower range). All locations showed a considerable retention of stormwater during summer, ranging from 52% to 91%. Storage capacities accepting drought conditions once every 3.3–3.9 year were found to be about 25 mm in the cold and wet locations increasing to 40–50 mm in the warmer and drier locations. Corresponding storage capacities to prevent wilting of non-succulent vegetation was on average a factor of 1.5 larger (not including Sheffield and Malmö). Annual retention increased both with an increase in plant water use (specific crop factors, K_c) and with an increase in S_{max}, but was found to be more sensitive to changes in K_c than to changes in S_{max}. Hence, ET was the limiting factor for green roof retention capacity in the cold and wet locations, but relatively large changes in evapotranspiration would be needed to have an impact on retention. The potential to use vegetation with higher water use to better restore the storage capacity between storm-events in these regions was however limited by the risk of permanent wilting of non-succulent vegetation, even on the wettest locations. A considerable increase in roof storage capacity and substrate thickness would be required to reduce this risk; still the increase in stormwater retention would be marginal.

1. Introduction

Green roofs are widely used to improve urban stormwater management, and extensive work has been carried out to understand, predict, and improve their function (Berndtsson, 2010; Li and Babcock, 2014). A majority of the reported research has been carried out in temperate climates with warm summer, while there is a lack of knowledge about green roof performance and function in cold and wet climates. Climatic conditions and prediceted climate changes lead to large stormwater runoff volumes and higher stormwater peaks that must be handled, and together with urbanisation, cities in cold and wet regions face large stormwater challenges. Recently there has been an increasing interest in the use of extensive green roofs for stormwater management in cold and wet climates. A green roofs ability to hold back and use water is closely connected to the local climate, and direct transfer of knowledge form drier climates is therefore not sufficient. As a consequence, implementation of green-roof-technology in these regions so far faces challenges of undocumented function, resilience and operational benefits.

Green roofs can retain (permanently remove) or temporarily detain (hold back) stormwater, to reduce and delay both total runoff and peak flows (Voyde et al., 2010). Green roofs retain stormwater by storing water in the vegetation, substrates, and other specially designed layers. Stored water can be removed from the system by evapotranspiration (the combined effect of evaporation from surfaces and plant transpiration). Evapotranspiration (ET) is highly influenced by environmental conditions like temperature, irradi-

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ance, wind, and water availability, showing both short- and long term variation due to daily variations and seasonal fluctuations in weather conditions (Allen et al., 1998). In addition, the ET potential differs between vegetation types depending on their water use strategies (Starry et al., 2014; Wolf and Lundholm, 2008), often approximated by specific crop coefficients (K_c) (Allen et al., 1998).

Stormwater retention of extensive green roofs is affected by climatic conditions, notably the effects of precipitation amounts and patterns, and temperature on the water balance (Sims et al., 2016; Nawaz et al., 2015). The frequency and amount of precipitation determine input to the roofs, while temperature together with wind and irradiance drives both evaporation and plant transpiration. The seasonal variation in temperature and other important climate variables is large, and possible covariation between ET and precipitation patterns can influence the performance of a green roof.

Climatic conditions determine the type of vegetation that will be suitable for the system, which again have consequences for the ET. Plant survival during summer drought is a key factor for vegetation use on extensive green roofs, however ice burn and winter frost are expected to be as important in cold climate regions (Durhman et al., 2007). Succulent vegetation based on species from the *Crassulaceae* family is commonly used for extensive green roofs. Many of these *Sedum* species used for green roofs in Northern Europe use both the C_3 and Crassulacean acid metabolism (CAM) carbon fixation pathways. Depending on C_3 metabolism under moist conditions and switching to the less efficient CAM metabolism under prolonged dry periods (Starry et al., 2014; Sayed, 2001). This makes them flexible, using more water than strict CAM succulents during wet periods, while having better survival than non-CAM plants under drought (Monterusso et al., 2005). These metabolism changes impacts ET as a relatively high transpiration during wet and moist conditions is reduced as water availability decreases. ET may drop 3–5 folds during drought, but with considerable differences between species (Al-Busaidi et al., 2013; Starry et al., 2014). Succulent species still have their limitations as they are low to moderate water consumers in cold and wet climates (Stovin et al., 2013) Alternative vegetation with a higher transpiration may better maintain water management efficiency under such conditions (Macivor and Lundholm, 2011). The use of non-succulent species is however at a risk. Succulents can survive long periods without available soil water (Monterusso et al., 2005), while many non-succulent species reach a point of no return and permanent wilting when no plant available water remains in the substrate.

To evaluate the potential for green roof technology in cold and wet conditions, answers are needed to questions of how green roof function varies among climates. Do cold and wet climatic conditions call for other design criteria, and what climatic constraints are there in the use of green-roof vegetation? To close some of these knowledge gaps and contribute to improved performance of green roofs in cold and wet conditions, this study addresses climate impacts on green roof function using historic weather data for selected locations in Northern Europe.

Our objectives were to (1) document how a roofs storage capacity and the vegetation's water use (crop coefficient) influences retention, and risk of drought in different climates; (2) evaluate required storage capacities and provide estimates for retention of stormwater by extensive green roofs in different climates; (3) evaluate the impact of environmental conditions on the vegetation of extensive green roofs in the colder and wetter regions.

2. Materials and methods

A green roof water balance model was applied to estimate retention performance and risks of drought for extensive green roofs for a variety of Northern European cold and wet climates. The model was based on historic records of daily temperature and precipitation data in order to make the method commonly applicable, using only readily available meteorological data. The first step was to find the best fit temperature based evapotranspiration model (ET-model) for the chosen geographical locations. Secondly, the chosen ET-model was applied in the green roof water balance model studying retention and risk of drought as a function of maximum storage capacity and ET characteristics of the vegetation (as determined by crop coefficients). The last step was to apply a chosen crop coefficient and storage capacity to the green roof model in order to estimate the annual and seasonal retention of stormwater at the different climatic locations. Local climate indices were defined, and computed, as a basis for discussing limitations and possibilities for extensive green roof plant species in Northern European climates. All modelling and estimation of climate indices were done in Matlab R2015b (MathWorks, Inc. Massachusetts, USA).

2.1. Sources of historic climate data

Ten Northern European locations, representing a span in temperature and precipitation along a north-south gradient (53–70°N) and coastal-inland gradient were selected (Fig. 1, Table 3). The locations ranged from temperate to cold climates, all fully humid and with warm or cold summers according to the Köppen-Geiger climate classification (Peel et al., 2007). The most northern locations were close to the definition of polar climates. National meteorological offices provided data for daily precipitation and daily average temperature, together with monthly average maximum and minimum temperatures. Data for Oslo, Grimstad, Sandnes, Bergen, Trondheim and Tromsø were obtained from the Norwegian Meteorological Institute, data for Reykjavik from the Islandic Metorological Office, data for Sheffield from the National Meteorological Library & Archive (United Kingdom) and data for Malmö and Umeå from the Swedish Meteorological and Hydrological Institute. Monthly reference Penman-Monteith evapotranspiration values, for the purpose of evaluating other less data intensive evapotranspiration models, were obtained from the World Water and Climate Atlas (IWMI, 2011), where values are given for a 10 min grid (1/6°) for the normal period of 1961–1990. Values were not provided for the exact position of Sheffield and Reykjavik, here the nearest available values of approximately 30 km south of Sheffield and 15 km east of Reykjavik were used.

Two different study periods were used. The normal period of 1961–1990 was used for comparison between different evapotranspiration models since this was the period for which reference evapotranspiration rates were available. The most recent 30-year normal period of 1986–2015 was used for all other analysis in order to gain an as accurate and up to date picture of the local climates as possible.

2.2. Evapotranspiration estimates

ET-models estimate ET for a reference crop under abundant water supply and standard conditions (ET_o) or potential evapotranspiration for any vegetation under sufficient soil water availability (PET). ET_o or PET can further be adjusted for the type of vegetation by a crop coefficient (K_C), and for other stresses and environmental constraints (Allen et al., 1998). Reduced evapotranspiration caused by limited water availability in dry periods can be included as a soil moisture extraction function (SMEF). SMEFs have been applied and recommended in several green roof studies (Zhao et al., 2013; Poë et al., 2015; Digiovanni et al., 2013; Marasco et al., 2015; Hakimdavar et al., 2016; Berretta et al., 2014). The resulting estimated ET after the chosen correction procedures is called actual evapotranspiration (AET).