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Demonstrating the Use of Below-Substrate Water Storage as a Means of Maintaining Green Roofs - Performance Data and a Novel Approach to Achieving Public Understanding.

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ABSTRACT

Green roofs are becoming increasingly important in the challenge of dealing with climate change and urbanisation. One of the challenges for green roof design and construction is the need to trap large volumes of water on roof structures with limited load bearing capacity. If this is attempted by using increased volumes of mineral substrate the ratio of water volume stored to total load can be insufficient to achieve the water attenuation aims of the system within the limited load constraints. This paper reports on the performance aspects of the approach of closely integrating stormwater capture, storage and reuse within a green roof and reports some preliminary data which indicates the effectiveness of the capillary feeding device used to supply water from relatively deep void forming drainage, conveyance and water storage layer into the overlying substrate of a green roof. A case study is presented where a roof park is formed on the first floor deck of a former bus station and includes a modelling exercise to demonstrate the value of the stored water for maintaining the "urban roof park" environment. A unique demonstration project is also presented.

Keywords Green roof, capillary irrigation, urban cooling, rainwater reuse

INTRODUCTION

Cities currently face many weather related challenges including increased rainwater runoff (leading to pluvial flooding), the urban heat island effect and reduction in green space with associated loss of both amenity and biodiversity. Much of this is being exacerbated by climate change and numerous approaches aim at resolving these challenges. A contribution to the mitigation of such problems highlighted is to utilise the roof spaces of buildings to create green roofs. The potential of green roofs to contribute to the mitigation of rainwater runoff is well established (e.g. Stovin, 2009, Carson *et al.* 2013) and has been the subject of studies in a range of environments including Mediterranean (Fioretti *et al.* 2010) and tropical climates (Wong *et al.* 2003). Green roofs reflect incoming sunlight and evaporate water which helps to reduce the urban heating effect, but increasingly, in the Netherlands, more emphasis is being put on the capacity of green roof to store large amounts of rainwater during the ever less frequent but more intense summer rainstorms. Green roofs providing extra functionality to trap and manage larger amounts of water (50 mm or more) in open drainage layers are referred to as blue-green roofs. Green roofs are also reported to be capable of mitigating air pollution (e.g. Berghagee et al. 2007, Baik et al. 2012). The cooling potential of green roofs on individual buildings is widely reported (Palomo Del Barrio,1998, Castleton et al., 2010, Alexandri and Jones, 2008). The Castleton et al. paper is a review, which highlights a range of literature associated with winter heat retention as well as the passive summer cooling potential. The contribution to combating the urban heat island effect is also recognised (Takebayasi and Moriyama, 2007, Susca *et al.* 2011) and a recent review paper by Santamouris (2014) also references other means of urban heat island mitigation such as reflective roofs. Green roofs are also important in improving biodiversity within cities (Brenneisen 2006, Kadas, 2006, Cola *et al.* 2009), and, although potentially in conflict with biodiversity aims (Dunnet 2006), the aesthetic value of the green roof can often be a dominant factor (Matsuoka, and Kaplan, 2009). Where the green roof is intended to be accessible and provide, in part, the function of an urban park, as is the case with both examples of installations presented here, it is important that the provision of water, to maintain adequate growing conditions (for a wide range of plants), during dry periods is recognised. This helps to enhance the amenity value. One of the factors is the maintenance of an adequate soil moisture content. The limited load bearing capacity (LBC) of the roofs of (existing) buildings often dictates the amount of water that can actually be safely retained on the roof. Building rainwater storage tanks inside or next to the building and using pumps and irrigation systems is of, course, an option which will provide both runoff attenuation and on-site rainwater reuse; however, the running costs, capital costs and building space/land-take combined with the need for maintenance and the propensity for active systems to break down are factors which would mitigate against their choice. Designing green roofs to match the LBC involves finding a careful balance between storing as much rainwater as possible, maintaining a suitable substrate layer for plant growth and respecting the LBC of the roof construction (Molineux *et al*. 2009, McIntyre and Snodgrass, 2010). Adding more substrate, aiming at increasing the amount of water stored, achieves a water-stored-to-weight- ratio (WSWR) of just 0.2 l of water per added kg of soil (excluding the mass of water itself) for loamy sand, or 0.4 l/kg for a typical, specialised, extensive green roof substrate (table 1). Table 1 also shows data for two types of systems that store water below the substrate. The Zinco Floradrain FD 40-E drainage system stores water with a WSWR of 3 l/kg, but due to its limited height, has a maximum storage capacity of 6 l/m^2. The Permavoid 85SC void forming drainage and water storage layer has a WSWR of 9.1 l/kg, due to its lightweight design, which provides a large open void volume and a height of 85 mm. Here we report initial results from a preliminary experiment to compare the variability of soil moisture content between adjacent conventional green and capillary-fed blue-green roofs, a modelling exercise to show that, in the Netherlands at least, the proposed system is capable of providing irrigation water throughout the summer months and examples of two demonstration installations.

Table 1: Water-stored-to-weight ratios for sand (as a comparison), an average extensive green roof substrate,the Zinco Floradrain FD 40-E and Permavoid 85SC void forming drainage systems (data from www.zinco.nl and www.permavoid.co.uk).

	Water Storage in Soil		Water Storage in Drainage Layer	
	Loamy Sand	Extensive green roof substrate	Zinco Floradrain FD 40-E	Permavoid 85
Specific density (kg/m^3 dry weight)	1350	1000	50	106
Water storage at field capacity (l/m^3)	300	400	150	960
Water-stored-to-weight ratio (WSWR l/kg)	0.2	0.4	3.0	9.1

THE SYSTEM

The system highlighted here is based on 85mm or 150mm load bearing void forming units (Permavoid, Netherlands). Further details of the units themselves are presented in the relevant patent (Van Raam *et al.* 2014). Figure 1 illustrates the typical cross section of the system. The roof is sealed with a waterproof membrane upon which the units are laid. A capillary geotextile is applied to prevent the loss of the substrate

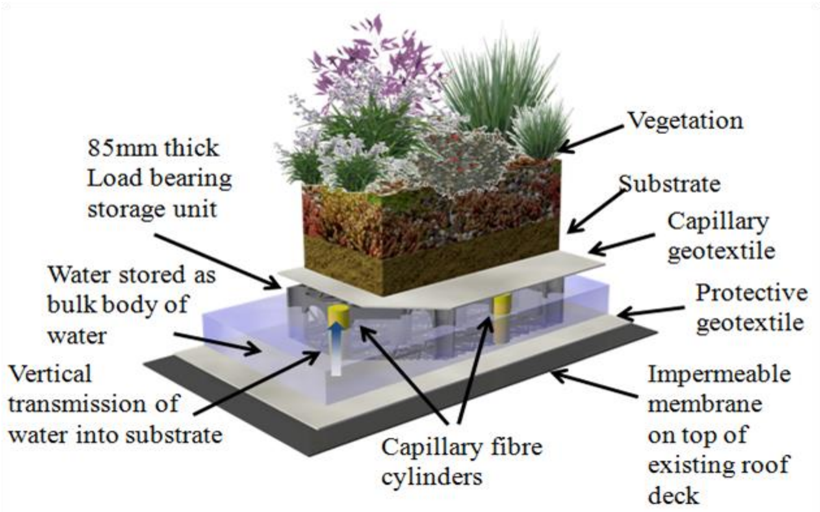

Figure 1**:** Cross Section of green roof using 85mm void formers as subbase with capillary fibres in vertical cylinders to transport water from the storage layer to the substrate.(modified with permission Permavoid Ltd)

into the void forming box. The substrate is applied to a depth consistent with the load bearing capacity of the roof (taking into account also the volume of water to be stored). The key development in the use of these units in green roofs, is the capillary fibre cylinder insertions located in the hollow load bearing columns of the units. This is because the volume of water that can be stored within the load bearing boxes will always leave an air space between the water body and the overlying substrate. These capillary fibre cylinders allow the passive transmission of water into the substrate. In effect, an equivalent volume of water is being stored within the void space of the box rather than in the interstices of the substrate of a traditional green roof; thus reducing the load on the roof for the same volume of stored water.

A Preliminary Investigation Of Variability in Soil Moisture Content.

This section represents a very preliminary investigation, which was aimed at addressing technical problems before progressing to a much more comprehensive study. The two comparable systems are located on a rooftop in Renkum, The Netherlands. Shown in figure 2a., the system provided with storage and capillary irrigation below the substrate was a single model constructed in a 700 x 350 mm marine ply and Perspex box, incorporating the Permavoid 85mm drainage unit, Permatex capillary geotextile and 0.1m of Zinco (Zinco Benelux BV, Amsterdam, The Netherlands) green roof substrate beneath mixed sedum vegetation.

(a) (b)

Figure 2: (a) The capillary irrigated green roof on top of the void forming drainage units. b) Standard mixed sedum green roof used for comparison(August 2015) (author’s images)

The performance of the capillary-fed model was compared with the standard installation (figure 2b). This comprised a mixed sedum green roof on a 25 mm drainage layer (Zinco Floradrain FD 25-E with Zinco SF Filter with 0.1m of Zinco substrate). In each installation, one Delta-T W.E.T. sensor was placed at 50mm depth to record soil moisture content, electric conductivity and soil temperature. Weather data was collected on site with the Delta T RHT2 shielded relative humidity and air temperature sensor and an AN4-05 Anemometer. All data was logged with a Delta-T GP1 logger at 5-minute intervals. Precipitation data was obtained from the Netherlands Royal Meteorological Institute from a nearby (7 km) weather station in Oosterbeek. When the abstract for this paper was submitted it had been intended that an extensive period of monitoring would be carried out over the spring and summer of 2015. However, due to some technical difficulties only 2 months of data, August and September 2015 are presented (Figure 3). The intention is to continue to monitor over a 12 month period, to present a more complete dataset that will include the 2016 growing season and to use the experience obtained to inform the design of a more substantial replicated study. Figure 3 suggests that the capillary-fed system essentially maintains a consistant soil moisture content during the period of study, including the dry spell in early August and the extreme rainfall events of mid-August and mid-September. Essentially, whilstever there is water stored in the subbase, the continuous feed of water rationalises the variability in soil moisture, which is apparent in the plot for the traditional green roof, which is seen to be responding to the prevailing precipitation.

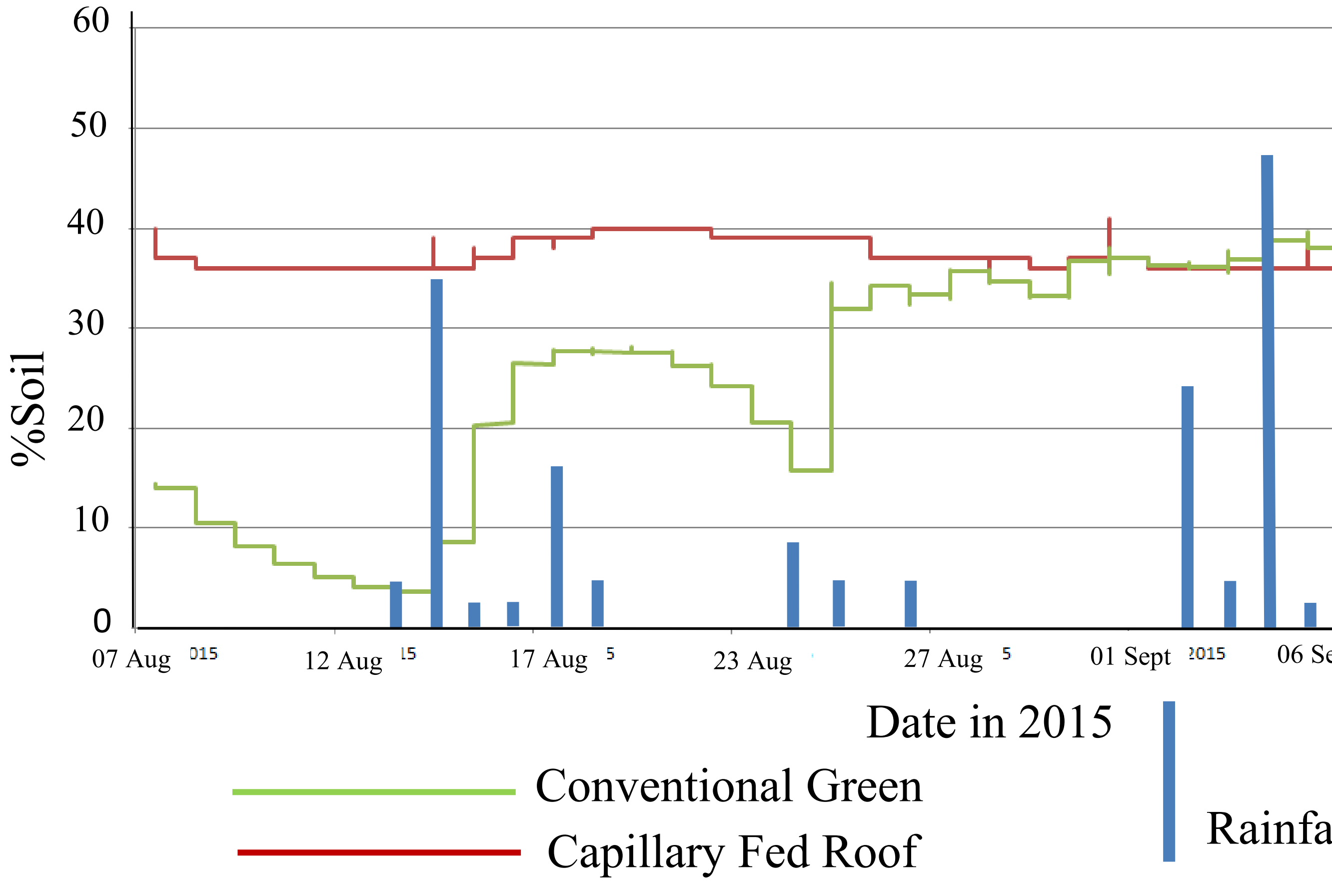

Figure 3:-Soil Moisture content for conventional and capillary-fed green roofs and rainfall recorded during August and September 2015 – Renkum, The Netherlands

Modelling the Roof Park at Orlyplein

The Orlyplein roof park was constructed on a former bus station, located on an elevated deck adjacent to a Railway Station at Amsterdam-Sloterdijk in The Netherlands. It contains a subbase of Permavoid 85 units, fitted with capillary fibre cylinders, to act as a rainwater drainage, storage and irrigation layer and has an overlying layer of 300 mm of fine sand with 8% organic matter acting as growing medium. The sub-base is able to store up to 60 mm of rainfall (currently controlled by a fixed depth overflow). Figure 4 shows photographs of the site before, during and after the installation of the roof park. Funding for this project was provided by the City of Amsterdam and was part of an initiative to transform ‘Grey’ into ‘Green’ to improve liveability, safety and the economic viability of this area of the city. The installation was completed in February 2015. A modelling exercise was carried out to give an indication of the potential performance of this installation with respect to providing sufficient storage for the driest periods of the year. The hydrological behaviour of the installation was studied by applying the general water balance equation:

$ET = P - Q +/- \Delta S$; where:-

ET is the evapotranspiration, P is the precipitation, Q is the amount of discharge (runoff) and ΔS represents the change in water storage. Both the evapotranspiration and precipitation data were provided by the Royal Dutch Meteorological Institute (KNMI) weather stations (De Bilt and Amsterdam). The model utilises the maximum storage capacity as an input value (from an overflow set at 160mm total storage, including both sub-base and in the substrate) and uses this value to set the initial water level in January. Assuming that evapotranspiration stagnates in the non-growing season, it was assumed that the drainage layer of the green roof would always be filled to the maximum capacity in January. An assumption was made that the substrate layer is able to store moisture up to approximately 33%. The planted areas contain a variety of different plant species and the evapotranspiration calculated by the KNMI was assumed to be representative for this green roof. In fact, the uncertainty in the accuracy of the evapotransporation data is probably the greatest source of uncertainty in the whole model and the model would certainly benefit from a period of calibration to establish a relationship between KNMI reported ET and the locally recorded ET.

The model was constructed to assess the roof park's efficacy in reusing stored rainwater for plant growth, aiming at minimising both the amount of water overflowing into the sewer system and the potential amount of (potable) water

(a) (b) (c)

Figure 4**:** (a) 'before' image of the bus station, (b) during construction and (c) the same location, now in use as a roof park (images courtesy Permavoid Ltd).

needed for irrigation. Using average monthly evapotranspiration and precipitation data, the model showed no water deficiency in the system. To increase resolution, the model was expanded to utilise actual recorded daily values of precipitation and evapotranspiration, to calculate the amount of water in storage at the end of every day. In total, for the period 2000-2014, some 15 annual models were constructed and compared, showing a simulation of how the roof park installed at Orlyplein would have performed if it had been built 15 years ago. The total storage capacity of the system in the model could be easily manipulated so as to illustrate the effect of reduced or increased storage capacity.

Three examples of the model outputs (using 160mm maximum storage) are presented as figure 5, which presents the total amount of water stored in the system for 2010 (which is considered typical of the rainfall regimes of that period), 2012; an exceptionally wet year, and 2003, which is both an unusually dry year and one of only two years in which there is a period where the predicted stored water falls to zero (the other was for a single day in 2006), representing a period where replenishing the storage and capillary irrigation system with water from other sources (most likely potable water) would have been necessary. The 2003 "dry period" included 27 days with zero water in storage. Even in the typical years there were extensive periods where the water storage capacity was fully utilised indicating a need for a system to dump stored water prior to predicted storm events. An automated real time control system is currently under development.

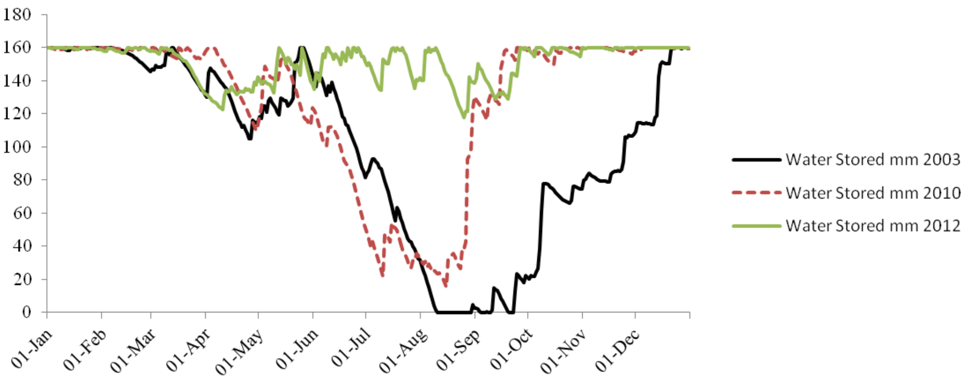

Figure 5: Calculated values of total amount of water stored in the system (60 mm maximum in the drainage layer and 100 mm in the substrate) for every day of the year for the years 2003 (very dry year), 2010 (typical year) and 2012 (wet year).

A Unique Demonstration Project

Clearly, if local authorities and other supporters of expanding the use of green roofs in cities are to get the message across there is a need for projects which catch the public imagination. One such project, which took a highly imaginative approach to this, has been instigated by the City of Ghent in Belgium as part of its plans to "climate proof" the city. This system used 150mm void forming units to form a "roof garden" complete with open water and wetland plants, constructed on a restored, vintage, rail flatcar. The goal was to demonstrate the possibilities and value of green roofs, visible at ground level. The system can store up to 135 mm of rainfall in the void forming drainage system. Details of how the system was constructed are available as a video (https://www.youtube.com/watch?v=Zj9En5iM0y4). The system was completed in April 2015 and since then it has been located at Voorhavenlaan, Ghent, in the former cotton harbour district. Public access is encoraged and the planting includes several edible species. Despite being located in an area, which might be expected to attract vandalism, anecdotal evidence is that minimal damage has been experienced and the locals have shown great interest in the system. Figure 6 shows photographs of the system just after completion of planting and the arrangement of the sub-base units to allow the construction of the open water area. The white circular objects visible on the black plastic units are the capillary fibre cylinders.

CONCLUSION AND FURTHER WORK

The experimental assessment of the comparative difference in soil moisture content, between traditional drainage layers and a combined water storage/capillary irrigation drainage layer, illustrates a very stable soil moisture content in the latter during both dry spells and severe rain events. The consistent soil moisture content enables plants

(a) (b)

Figure 6: (a) the void former drainage layer visible during construction and (b) the rail flatcar demonstration garden after completion. The stairs, the viewing deck and the pathway allow people to enter and view mixed vegetation up close. (images courtesy Permavoid Ltd)

to grow better because water is not a growth-limiting factor. By storing water immediately beneath the green roof substrate and making it available for the plants by capillary action, more water can be stored on the roof without adding more soil or substrate to the system; effectively shifting the weight balance on the roof from ‘storing soil’, to storing rainwater and effectively retaining water for plant growth rather than discharging it to the sewer. In addition, a significantly wider planting choice is possible, without having to increase substrate depth because the plants no longer need to be selected based on drought tolerance. The latter of course assumes that the green roof is designed to provide a continuous supply of supplementary water on the rare occasions when irrigation is required.

The results of the modelling exercise at Orlyplein show that the current storage capacity of 160 millimetres is sufficient to prevent water shortage in the green roof, except for the exceptionally dry summers in 2003 and 2006 (one day only). Based on these predictions, one can conclude that the Orlyplein green roof has been built with near-optimum capacity to prevent water shortages in the growing season. During operation of earlier versions of the model, based on monthly averages, no years were found to show a period where the system ran out of water. This illustrates the importance of using high resolution data for the calculation of the water balance of green roofs, if modelling is to be used to allow the design of green roofs that fit the climate in a particular area, whilst minimizing the production costs, sewer-loading (especially during peak rain events) and the use of potable water for irrigation purposes during prolonged dry periods. The average precipitation and evapotranspiration data referred to by the green roof industry as a reference for green roof designs, needs to be interpreted very carefully.

The model demonstrates that there is a direct correlation between the decrease in storage within the roof attenuation layer and an increase in discharge to the sewer and this corresponds with an insufficiency in water available for irrigation of the green roof vegetation (1 year in 3 if available storage is set at 110mm). Suggested further research includes a monitoring study where actual precipitation and evapotranspiration are carefully measured over a long time period, in order to get insight into the reliability of the results of the current study. This information would contribute to the development of green roof optimization regarding water management and plant species selection options. A green roof research project, where growth, transpiration, evapotranspiration, irrigation and run-off will be carefully monitored for 2 full years is currently under design by KWR in the Netherlands, to be constructed on the rooftop of the ANDAZ Hotel in Amsterdam, The Netherlands, in early 2016 and green roof research projects are proposed in Coventry and Blackburn UK.

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