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A Green Roof Segment for Monitoring the Hydrological and Thermal Behaviour of Anthropogenic Soil Systems

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Abstract

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Green roofs and similar anthropogenic soil-plant systems in conurbations have a high relevance for society, especially in a changing climate. Understanding the hydrological performance of green roof substrates is a significant task in the framework of sustainable urban planning and water/energy management in urban areas. Potential retention and detention capabilities of anthropogenic, light weight, highly permeable soil systems and their continued performance over time are of major importance. A green roof test segment was designed to investigate the benefits of such anthropogenic systems. This adaptable low-cost system allows for long-term monitoring of preferred characteristics. Temperature and water balance measurements complemented with meteorological observations and studies of physical properties of substrates provide a basis for a detailed analysis of thermal and hydrological regime in green roof systems. The very first results obtained from the test segment have confirmed the green roof systems benefits. Reduced temperature fluctuations as well as rainfall runoff were attained compared to the traditional roof systems. Depending on numerous factors including the substrate material or vegetation cover, in the green roof tested the temperature amplitude for a selected period of non-freezing days (with minimum ambient air temperature of 2.8°C) was suppressed by about 6.5°C on average. The ability to completely prevent (light rainfall events) or reduce and delay (medium and heavy rainfall events) the peak runoff was demonstrated, too.

Keywords: continuous monitoring; heat island effect; microclimatic conditions; thermal regime; vegetation cover; water balance

The continual growth of urban areas contributing to the loss of greenery and extension of impervious surfaces leads to the increase of stormwater runoff (Shuster *et al.* 2005), microclimate environmental impairment, elevated air pollution, and reduced water quality. The above mentioned aspects known as the heat island effect have been treated in a number of studies (e.g. Pickett *et al.* 2001; Rizwan *et al.* 2008; Kodešová *et al.* 2014).

Rooftops represent a great percentage of impervious areas. Green roofing may be an attractive choice in highly developed urban areas with limited options for green space recovery.

The effectiveness of green roof systems may vary with climate (Dvorak & Volder 2010; Ascione *et al.* 2013), plant species selection (Nagase & Dunnett 2010), and materials used for the green roof construction (Savi *et al.* 2013). Reliable performance of a green roof system depends on the roof inclination and substrate depth (Heim & Lundholm 2014).

Thermal behaviour of green roof soil systems under atmospheric forcing has repeatedly been studied. Dvorak and Volder (2010) described thermal functioning of green roofs in areas ranging from subtropical prairie over coastal lowland and moraine to intermountain semi-desert or temperate regions.

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The use of highly diverse vegetation had a positive effect on the thermal functioning of green roofs (Kolb & Schwartz 1993).

There are several plant species suiting this purpose, e.g. succulents or gramineous plants. The benefit from a green roof system is directly associated with the proper choice of the vegetation cover which should meet the actual needs and local climate conditions.

Depending on the geographic region, the green roof benefits involve the runoff mitigation, reduction of pollutant loading and heat island effect.

The reduction of stormwater discharge is considered the greatest environmental benefit of green roofs. In this context, the effect of the green roof slope on water retention (in terms of precipitation that did not run off the system) is often studied. However, contradicting results have recently been registered, Getter *et al*. (2007) or Villarreal and Bengtsson (2005) found that green roof retention decreased with the increased slope, while Liesecke (1999) and Schade (2000) concluded that the slope effect on the roof system retention is more or less negligible. This is probably due to different experimental conditions, green roof construction, and functional shift in definition of the roof system retention. Large unirrigated green roofs, when subjected to another extreme condition – the drought, were examined by Thuring *et al*. (2010) who concluded that herbaceous perennials planted in a 30 mm thick substrate layer did not survive.

The most important part of the green roof systems in respect to hydrological and thermal behaviour is the growing medium. Besides the living roof greening materials mentioned e.g. by Ondimu and Murase (2007), the most frequently used media are Technosols, i.e. redeposited soils made of a large amount of technogenic material like rubble (Rossiter 2007). The water and thermal regime of these highly heterogeneous soils mainly depends on the climatic forcing, presence of vegetation cover, and soil properties. Technosols are often characterized by extreme permeability (Nehls *et al*. 2007) and unsettled water capacity (Berndtsson 2010; Young *et al*. 2014). Studies on thermal properties of Technosols are sparse and their results are frequently contradictory due to a strong dependence on the composition of the technogenic material used. In general, the bulk soil thermal conductivity as a function of soil water content exhibits a distinct behaviour (Jim & Peng 2012) from traditional estimation methods (e.g. Chung & Horton 1987). Therefore, a careful description of soil constituents and a detailed knowledge of the soil moisture regime in Technosols are of major importance (Sun *et al*. 2013).

The objective of the present study was to introduce a newly designed, low-cost, durable green roof segment because the existing reports considering the conditions of the Czech Republic are sporadic and often bringing ambiguous results. The basic requirements for the green roof functionality were reviewed. The main characteristics of the green roof segment were discussed in respect to testing the technical solutions involving anthropogenic soil systems for sustainable urban drainage applications. The presented experimental data proved the ability of the segment to fulfil the declared functions. Advanced performance testing of different anthropogenic soil materials suitable for this purpose should follow.

MATERIAL AND METHODS

Test segment design. The green roof test bed (segment) with a top view dimension of 1 × 1 m and a depth of 0.1 m is made of a 1 mm thick galvanized steel sheet. The impervious box is supported by a rectangular steel tubing system that prevents deflection of the segment. The supporting base system also provides the slope setting and weighing option. Threaded rods mounted on each of the four legs allow the slope adjustment in the range of 0–5°. Weighing option is provided by four high accuracy and watertight load cells (LCMAD-100, Omega Engineering Ltd., Manchester, UK), one per each leg. Note that the presented results were obtained for not weighed roof segments. The segment is situated ca. 20 cm above ground to allow the water outflow rate measurements. The outlet face made of iron mesh is connected with a drain gutter that collects the outflow water and leads it to the tipping bucket flowmeter. The flowmeter is protected by a plastic shelter that has two open sides to allow the water to flow out freely. The outflow gauge was calibrated to provide one tip per 0.064 mm of outflow corresponding to the effective volume of 64 ml. The flowmeter thus can register outflow intensities of approximately 0.06–75 mm/h.

The segment is heavily insulated from circulating ambient air (10 cm of extruded polystyrene insulation) with the exception of soil surface and outlet face (Figure 1). Furthermore, it is equipped with a temperature probe 107-L (Campbell Scientific Ltd., Shepshed, UK) measuring the substrate temperature at the depth of

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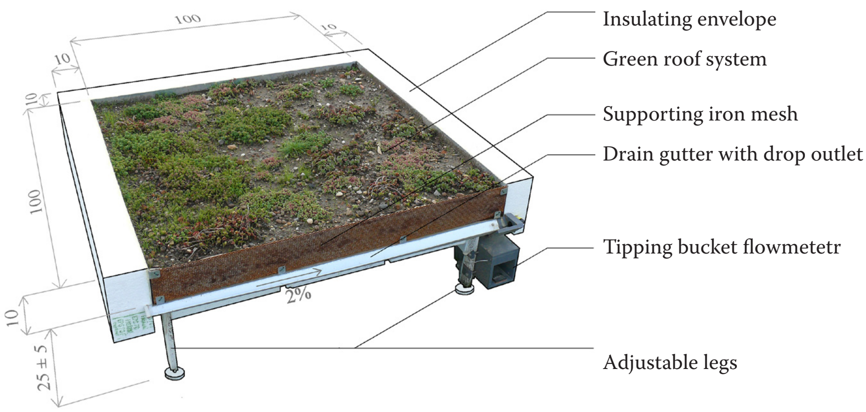

Figure 1. Green roof test bed filled with soil and plants

about 3.5 cm. The segment weight at maximum load is about 150 kg (including all construction parts, substrate etc.). The raw test bed (the green roof segment without the components dedicated for greening, i.e. the protective layer, substrate, and plants) weighs 43 kg.

A typical cross-section of the green roof segment layers is presented in Figure 2. The segment includes a vegetation layer (e.g. stonecrops or herbaceous perennials), a substrate layer (Technosol or special extensive green roof substrate), a roof drain consisting of the filter mat, drainage board, and protection mat, a waterproof layer (galvanized steel sheet), and an insulation layer (extruded polystyrene foam).

The main advantages of the segment construction are:

– Exact measurement of water outflow (built-in tipping bucket flowmeter);
– Adjustable green roof slope;
– Exact measurement of temperature (built-in temperature probe);
– Heavily insulated walls and bottom;
– Weighing option.

The system moreover enables to evaluate the effects of the green roof slope and soil depth on the storm water retention, plant species alternation, technology and materials testing for the use in the system construction and finally the thermal effect of green roofs.

Experimental site and data. Two green roof segments (S1 and S2) are currently being tested at the experimental site established by the University Centre for Energy Efficient Buildings (UCEEB), the Czech Technical University research centre facility in Buštěhrad, Czech Republic (50°9.41797'N, 14°10.19195'E, 355 m a.s.l.). Local climate is classified as temperate (average annual rainfall and temperature ca. 500 mm and 8°C, respectively).

The advantage of the experimental site is the possibility to directly compare the model systems – test segments S1 and S2 with the already existing building green roof system facing the same weather conditions. The site was fully equipped by June 2014 and is located on a green roof of the main building elevated by 10 m. The building green roof is square-shaped with the total area of 941 m^2 and it was designed as an extensive one with a shallow 5-cm thick substrate layer. To get all relevant information to evaluate the green roof performance, the test site is designed to collect the meteorological data including air temperature, wind speed and direction, net radiation, relative humidity,

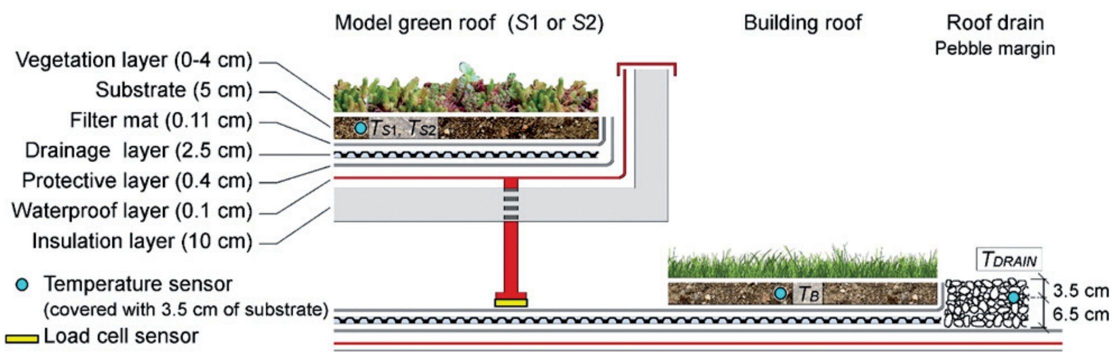

Figure 2. Typical cross-section of the green roof segment and its surroundings at the experimental site

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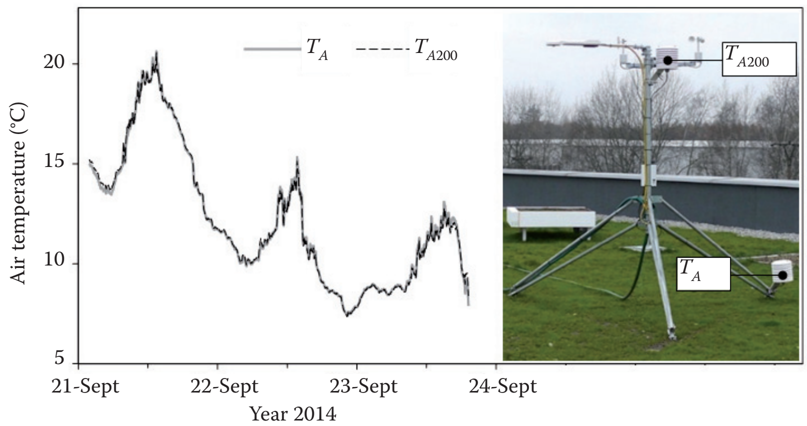

Figure 3. Weather station placed at the building green roof (right-hand side). Air temperatures measured at 200 cm (T_{A200}) and 23 cm (T_A) above the green roof (left-hand side)

and rainfall intensity (Figure 3). The meteorological information on the site is completed by temperature and water balance measurements. The temperature sensors are situated as depicted in Figure 2 in the green roof segment substrates (T_{S1} and T_{S2}), building roof substrate (T_B), pebble margin (T_{DRAIN}) and two ambient air temperature sensors (T_A and T_{A200}) are situated 23 cm and 200 cm above the building green roof surface. Local microclimate of the building green roof system is rather limited due to its size and wind exposure. Results of three-day temperature measurements at 23 cm above the green roof surface (Figure 3) clearly demonstrate that the air temperature measured is almost unaffected by the presence of the system. Root-mean-square deviation of air temperatures measured at 200 cm and 23 cm above the green roof was 0.13°C, individual differences did not exceed 0.74°C.

As the first approximation of the latent heat fluxes at the site we used the Penman-Monteith method (Monteith 1965) to estimate the daily potential evapotranspiration from short-cut grass. To estimate the effective values of the aerodynamic and surface resistance parameters, we followed the methodology of Allen *et al.* (1998).

Plant cover and substrates. To study the green roof performance, two segments with identical typical cross-section were constructed. The only difference lies in the class of the substrate used. The substrate depth is 5 cm in both cases.

The first segment (designated as S1) is filled with the soil comprised of the stripped topsoil from a road construction with admixed low-density inorganic components (crushed expanded clay and bricks). This mixing method became very popular with the Czech building industry due to lower costs and non-existence of a relevant legal regulation. Analyzing the fine earth fraction, i.e. soil particles smaller than 2 mm in size, the substrate in segment S1 was recognized as sandy loam.

The second segment (S2) is filled with lightweight Optigreen green roof extensive substrate Type E. The product datasheet is available at http://www.optigruen.de (Optigrün International AG, Krauchenwies-Göggingen, Germany). Main components of the technogenic substrate of S2 are expanded shale, lava, pumice, expanded clay, crushed bricks, and green waste compost. The substrate, classified as loamy sand, is designed to be lightweight, highly permeable, and capable of notable water storage.

The building green roof substrate is structurally similar to the substrate in segment S1, i.e. local stripped topsoil with crushed bricks and green waste. The substrate comprises a significant proportion of very fine particles and thus it is prone to clogging up of soil pores and forming of fissures on the surface. The textural class is loam.

Selected physical and chemical properties of the substrates are shown in Table 1. Soil substrates S1

Table 1. Physical and chemical properties of soil substrates based on laboratory testing

Substrate	Total organic carbon in solid (% C)	pH (–)	Electrical conductivity (mS/m)	Dry matter content (%)	Bulk density (g/cm^3)
Segment S1	2.30	8.5	15.40	51.2	1.15
Segment S2	0.73	8.5	4.93	78.5	0.77
Building roof	3.99	8.4	18.80	68.5	1.00

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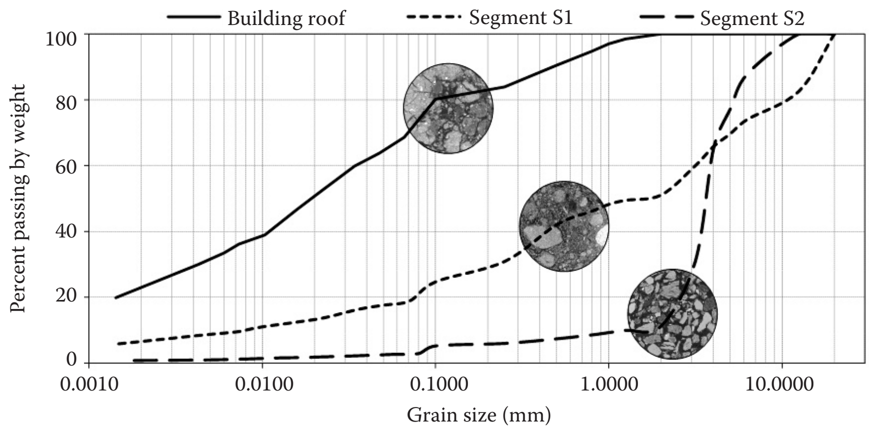

Figure 4. Grain size distribution curves supplemented with typical internal structure visualized by microCT for green roof substrates used

and building roof demonstrate similar properties. The technogenic substrate (S2) exhibits significantly lower electrical conductivity and total organic carbon in the solid sample analyzed. On the other hand, this substrate contains a higher percentage of dry matter. Bulk density for the technogenic substrate (S2) is by about 30% lower than for the substrate in segment S1. Generally, the bulk density value indicates actual soil compaction, significantly affects infiltration, rooting, porosity, plant water/nutrient availability or activity of soil microorganisms.

Table 2 summarizes hydraulic parameters of substrates estimated with help of the neural network model Rosetta (Schaap *et al.* 2001) using mass fractions of sand, silt, and clay, and bulk density value. The estimates were further adjusted using information available from technical sheets. Relatively slight differences in hydraulic parameters between the building roof and segment S1 indicate that the building roof is reasonably well approximated by the test segment. Saturated hydraulic conductivity for substrate S2 is by one order of magnitude higher than hydraulic conductivities estimated for S1 and the building roof.

The grain-size distribution curves demonstrate soil texture differences of selected substrates (Figure 4). Soil substrates S1 and building roof contain significantly higher proportion of fine-grained elements compared to technogenic substrate S2.

Test segments were planted with a mixture of stonecrops (*Sedum album* L., *Sedum hybridum*, *Sedum spurium*, *Sedum acre* L.). The S1 segment was established on July 9, 2014, the S2 segment two months later, on September 4, 2014. The building roof has been planted with herbaceous perennials since September 2014. The development of the vegetation cover in the model systems was monitored by a digital camera (Figure 5). Three months after planting, the segment S1 vegetation covered 53% of the soil surface. The vegetation cover of segment S2 one month after planting reached only 8%.

RESULTS AND DISCUSSION

To study the attenuation of temperature fluctuation in the test segments, a set of data measured continuously for a long time was used.

Figure 6 shows diurnal patterns of the temperature fluctuation measured in the segment substrates (T_{S1} and T_{S2}) and in the air 23 cm above the surface (T_A) on September 21–24, 2014. The temperatures in the segments differ significantly by daylight (up to 2.6°C at noon on

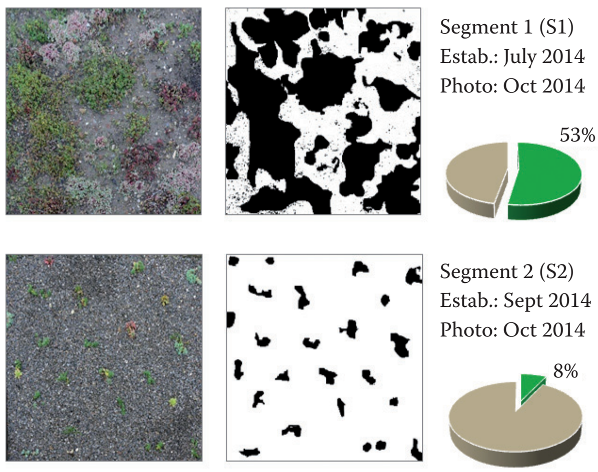

Figure 5. Soil cover fractions representing the proportions of green and bare cover for segments *S*1 and *S*2

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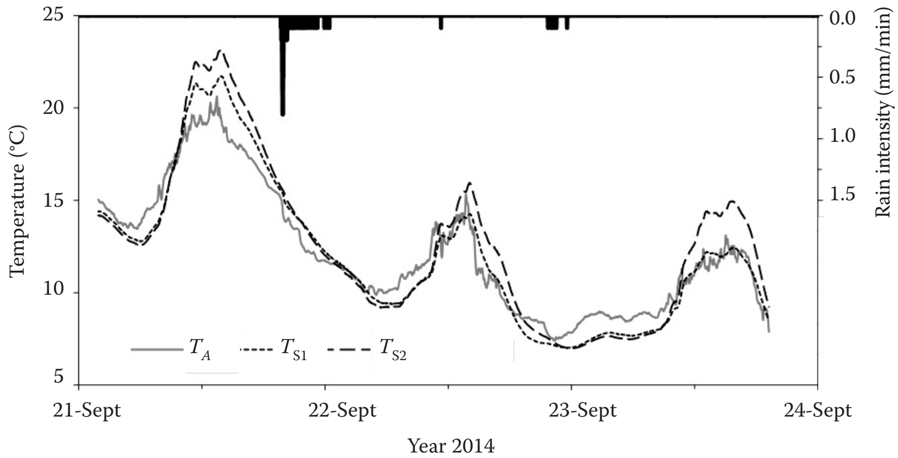

Figure 6. Comparison of temperature readings from green roof segments (T_{S1}, T_{S2}) and ambient air (T_A) during two rain episodes

September 23). During the night the temperatures of the test segments dropped to the similar value. Two short rainfall events registered by the tipping bucket rain gauge are displayed in Figure 6 – medium rain on September 21 (total depth 12.1 mm) and light rain or drizzle on September 22 (total depth 0.5 mm). Medium rain of 5 h duration caused a quick respond of the substrate temperature followed by the occurrence of outflow registered by the tipping bucket flowmeter (shaded area in Figure 8). The equation $T_{S1} = T_{S2} = T_A$ (i.e. rainwater temperature was approximately equal to air temperature and temperature of the segment substrates) was valid at this moment. The drizzle on September 22 was a typical episode that did not cause outflow and substrates temperatures as well as air temperature remained diverge.

The ability of the green roof systems (T_{S1}, T_{S2}, and T_B) to reduce temperature fluctuation in comparison with pebble drain T_{DRAIN} (which is assumed to approximate temperatures of traditional roofing such concrete tiles) is expressed by daily temperature variance (Figure 7). The variance was calculated as the difference between the daily temperature maximum and minimum. The warmer the conditions, the more prominent the temperature fluctuation difference between the respective systems. The lowest temperature variances were achieved in the green roof system with a higher plant cover (T_{S1}). Maximum temperatures in roof system S1 were reduced by 7.1°C on average, minimum temperatures by 1.2°C compared to pebble drain (T_{DRAIN}). For the newly established test systems this benefit is probably

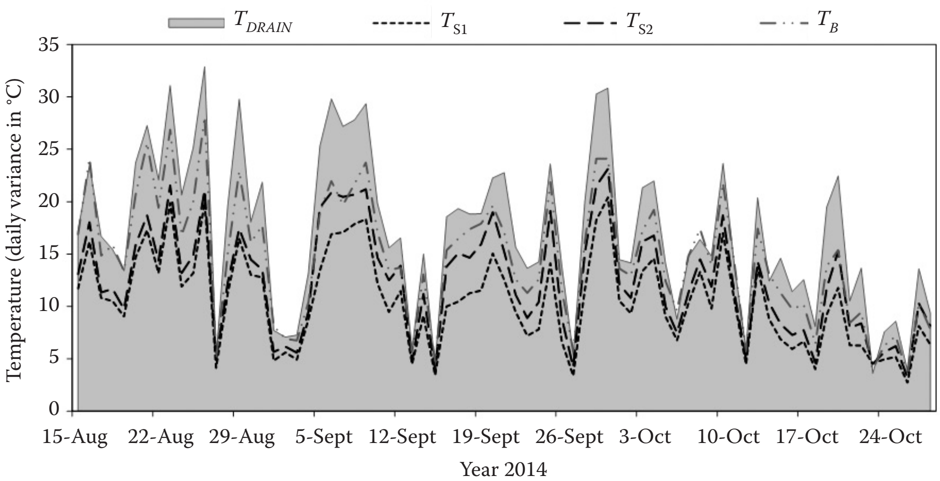

Figure 7. Daily temperature variance in three green roof systems – test segment *S*1, test segment *S*2, and building green roof *B*, compared with the temperature variance in roof drainage filled with pebble T_{DRAIN}

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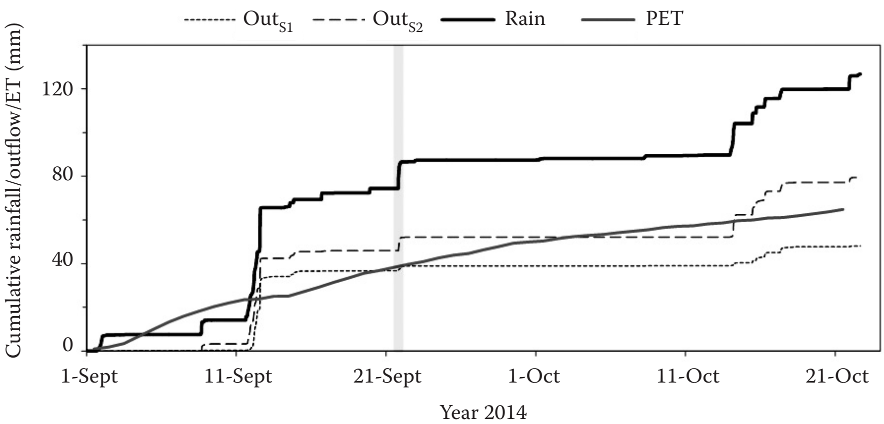

Figure 8. Components of the green roof segments water balance for the period September 1–October 28, 2014; solid lines represent rainfall (black) and potential evapotranspiration (grey), dashed lines correspond to segment outflow; potential evapotranspiration (PET) was calculated independently; shaded rainfall episode from September 21, 2014 is discussed with Figure 6; note that the presented results are obtained for not weighed roof segments, therefore closure of the segment water balance is unfeasible

slightly reduced due to sparse vegetation cover since the temperature reduction is caused by evaporation and the associated latent heat flux (Denardo *et al.* 2005). Another explanation of the dissimilar thermal regime in the segments is associated with the soil substrates characteristics. Lightweight substrate S2 tends to exhibit greater temperature fluctuations than Technosol used in S1.

Water balance components are measured to estimate the combined effect of storm water retention and evaporation. Figure 8 shows the cumulative outflow from the two segments compared to rainfall at the experimental site and calculated Penman-Monteith potential evapotranspiration. The two segments differ in substrate material properties and vegetation cover, thus outflows and retention capacities of the green roof segments naturally differ. It is evident that the segment S1 is able to mitigate more rainfall runoff and so it makes the outflow line flatter and later. It is partly caused by a better developed plant canopy in segment S1. As mentioned above, S2 was planted two months later and its green coverage is therefore substantially less developed (compare green cover fractions in Figure 5 – 53% and 8% for segments S1 and S2, respectively). The second reason for more intense mitigation in segment S1 partly consists in hydraulic properties of the soil substrates tested. The technogenic substrate in S2 is characterized by significantly higher saturated hydraulic conductivity and smaller retention space (Table 2) than the soil in S1. Therefore, substrate in S2 shows smaller retention performance for water associated with its shorter residence in the segment and subsequent lower actual evapotranspiration.

When analyzing the precipitation record in detail, it is important to distinguish between the individual events in respect to the amount precipitated. In light rainfall events (< 4 mm), water was completely evaporated back to the atmosphere in both segments. Calculated potential evapotranspiration was 64.8 mm, comprising 51% of total rainfall (126.6 mm). This quite well corresponds with the measured components of water

Table 2. Hydraulic parameters of substrates used

Substrate	θ_r	θ_s	α_{VG}	n_{VG}	K_s
	(cm^3/cm^3)		(1/cm)	(–)	(cm/day)
Segment S1	0.12	0.54	0.0225	1.437	36.0
Segment S2	0.05	0.35	0.0382	1.362	313.3
Building roof	0.15	0.56	0.0071	1.576	36.0

θ_r – residual soil water contents; θ_s – saturated soil water contents; K_s – saturated hydraulic conductivity; α_{VG} and n_{VG} – empirical parameters of van Genuchten (1980)

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balance – outflow depths in segments S1 – 48.2 mm and S2 – 79.7 mm comprising 38% and 63% of received rainfall, respectively. Differences in the water balance closure lie in an unknown proportion of potential to actual evapotranspiration and only rough approximation of the evaporative surface with short-cut grass.

CONCLUSION

Durable green roof segments were established by the UCEEB, the Czech Technical University research centre facility in Buštěhrad, Czech Republic. The newly designed system for automatic continuous monitoring of temperatures and outflow allows for investigating the thermal and hydrological effects of green roofs. Moreover, the system itself requires minimum maintenance and it is simple and robust for diverse purposes. One of the main application areas is the performance testing of different anthropogenic soil materials.

The very first results confirmed the benefits of green roof systems. Compared to the reference temperature (roof drainage filled with pebble), the green roof systems reduce temperature fluctuations by about 6.5°C on average. Moreover, outflow was reduced at least to 63% of rainfall.

The green roof segment developed seems to be a useful tool for better understanding anthropogenic soil systems functioning.

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