Helophyte mats (wetland roofs) with high evapotranspiration rates as a tool for decentralised rainwater management – process stability improved by simultaneous greywater treatment

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ABSTRACT

Redensification of the housing stock is also creating challenges for the drainage of wastewater and rainwater in existing sewer systems, particularly in growing cities. One alternative here is the evaporation of rainwater, which reduces hydraulic loads on sewers. Rainwater evapotranspiration using helophyte mats on building roofs is a possible approach. Helophytes are able to transpire considerably more rainwater than extensively planted green roofs. Other than conventional green roofs helophyte mats in the form of wetland roofs require a permanent water supply on a daily basis. Greywater application can be an additional advantage in terms of nutrient supply of the wetland roof after being treated microbiologically within the plant carrier mat. The treatment of greywater using a helophyte-planted roof can help to meet the water and nutrient requirements of the helophytes even during rain-free periods. However, it must be ensured that the root mat treats the greywater to a sufficient extent. It was shown under practical conditions that a 0.1 m-thick helophyte mat is suitable for treating typical domestic greywater at loads of up to 15 L m^{-2} d^{-1}.

Key words | decentralised rainwater management, greywater treatment, helophyte mat, helophyte-planted roof mats, root mat filter, wetland roofs

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INTRODUCTION

Initial situation

The global trend in massive urban development provides new challenges in urban landscape management. Over the years, land use pressure led to an increase of paved and impermeable areas that currently contribute 50% of total land area within city centers. The reduction of green and permeable areas take a toll on economical, social and ecological functions of urban areas (McPhearson *et al.* 2014). Urban development has locally considerably altered one of the most dominant environmental cycles, namely hydrological cycle. That, in turn, generates several chain effects that make living in cities more and more problematic. The most challenging problems concerning urban landscape architecture and development are urban flooding and the heat island phenomenon. Flood risk is typically the problem affecting the infrastructure and causing considerable threat to citizens' life. Existing drainage systems are less and less capable of dealing with stormwater due to further increase of catchment areas which are characterised by little water retention. Regarding the climate change they may be even more exposed to bigger loadings and failures in the future since increased frequency and intensity of massive rainfall events is expected to come (Radojevic *et al.* 2010).

Capacity problems can occur with regard to the drainage of rainwater when feeding it into existing sewer systems and wastewater treatment plants, particularly when new

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residential neighbourhoods are being built or when redensification of existing housing stock is being carried out on a large scale. As the expansion of sewer systems is very cost-intensive, decentralised rainwater treatment close to its collection point is an alternative worth considering. Decentralised rainwater treatment is becoming increasingly important – particularly in connection with the continuous increase of intensive precipitation events with high volumes of water in a short period – as a response to the resulting dilution of wastewater and the range of volumetric flow rates to be treated, which can lead to temporary overloading of sewer systems and wastewater treatment plants. Unlike the traditional flood management approach, application of ecologically engineered systems provides non-structural measures that are predominantly implemented to minimise the peak discharge and delaying runoff formation by increasing water capacity storage within the urban landscape (Ashley *et al.* 2007).

Innovative solution

The separation of wastewater streams into partial streams with different levels of contamination (blackwater, yellowwater, greywater) and separate treatment of these partial streams are currently attracting major attention internationally (Ochoa *et al.* 2015). The separate collection and treatment of wastewater streams that contain energy and nutrients (blackwater) can significantly increase the efficiency of treatment systems (Kjerstadius *et al.* 2015). Weakly contaminated greywater from baths, showers, washing machines, dishwashers and kitchen sinks (Ghaitidak & Yadav 2013) can often be treated cost-effectively close to its collection point.

The use of fleece mats that are intertwined with helophyte roots represents an innovative method of rainwater management at the level of residential neighbourhoods or buildings. This type of structure is easy to work with and is relatively light. In this way, it becomes possible to shift rainwater retention and treatment to the roofs of buildings and to keep ground-level areas free for other, more economically attractive uses.

A wetland roof is a form of extensive roof greenery, where helophytes are planted on the entire surface of a roof and are watered at regular intervals each day (Blumberg 2011). The use of helophytes is particularly attractive as they have reduced the stomata regulation of their transpiration over the course of evolution. As a result, helophytes evapotranspirate much more water than terrestrial plants that are usually used on conventional green roofs. Depending on the size and type of the helophytes, the evapotranspiration rate can be expected between 3.5 and 3.7 mm per day on an annual basis (Abtew 1996) and can reach peak values of around 50 mm per day on hot summer days using aquatic macrophytes like common reed *Phragmites australis* (Cav.) Trin. ex Steud. and common club-rush *Schoenoplectus lacustris* (L.) Palla (Kraft 1984).

Root zone of the helophyte mat as a retention and reaction space

The root zone of the helophyte mat serves as a retention space for rainwater, delays and reduces the flow of this water. However, as helophytes also require water during rain-free periods, excess water should be temporarily stored in a cistern and pumped back on the roof top 6–8 times on a daily basis (10 mm per day). It is also feasible to collect greywater from the households of building separately and to treat it using the helophyte mat with its microbiological biofilms. In this way, the plants will have a permanent basic supply of water and nutrients even during periods with no precipitation. In the case of combined treatment of rainwater and greywater, it must be ensured that the undiluted greywater is treated to a sufficient degree, when it passes through the plant carrier and water storage mat; this was tested as described below.

The limit values applicable in Germany for wastewater treatment plants of size class 1 (less than 60 kg BOD_5 per day) were used as quality criteria for the outlet water from the helophyte mat. These treatment plants correspond to population equivalent values of up to 1,000 and it is assumed that helophyte-planted roots will initially remain within this range. The legal limit values for the outlet water from treatment plants of this size class are $\leq$150 mg L^{-1} for chemical oxygen demand (COD) and $\leq$40 mg L^{-1} for 5-day biochemical oxygen demand (BOD_5) in Germany (German Wastewater Ordinance, Annex 1 Domestic and municipal wastewater).

Plant-substrate mats made of fleece materials or other engineering textiles, which may have a high specific area depending on their structure, and the plant roots themselves serve as growth surfaces for water-purifying microorganisms. These attached biofilms contribute significantly to the wastewater-treating ability of wetlands, whereas the plants are responsible for only around 15% of the water-treatment capacity depending on the time of year. The plant roots grow into the structure of the textile, which helps to stabilise the entire helophyte mat (Zehnsdorf *et al.* 2016).

It was shown under realistic operating conditions that helophyte mats are suitable for treating greywater, which is an important prerequisite for the use of these systems in decentralised rainwater management. Microbial hygienisation has not been taken into account so far, as this can be implemented in an effective manner using simple additional engineering measures (Maimon *et al.* 2014; do Couto *et al.* 2015).

MATERIALS AND METHODS

Helophyte mat

The *Repotex D* water-storing mat, which was developed by the Saxon Textile Research Institute (Sächsisches Textilforschungsinstitut, STFI, Germany) and was made of polyethersulfone, was used as plant carrier for the helophytes and served mainly to fix the plants in place. The mat used was 4.35 m long and 1.10 m wide, and had a water-storage capacity of 8.5 L m^{-2} in an unplanted state.

Lesser pond sedge root mats (*Carex acutiformis* Ehrh.) that had been pre-cultivated for two years and had a thickness of approx. 0.1 m were provided by nursery Rhizotech (Rosdorf, Germany) in September 2014. The helophytes (marsh plants) were placed on the polyethersulfone textile mat at the site of the experiment and further cultivated under water-saturated conditions. Alongside the main plant species *Carex acutiformis*, the accompanying vegetation also included the European meadow rush (*Juncus inflexus* L.), the common rush (*Juncus effusus* L.), the greater pond sedge (*Carex riparia* Curtis) and the purple loosestrife (*Lythrum salicaria* L.) in lesser amounts. The mat was already well intertwined with roots by 16 April, 2015; the mat was then inserted into the experimental system and feeding with greywater was started.

At the end of the experiment in July 2015, the mat was divided up into pieces, each 1 m^2 in size. The following data were determined for three of these pieces. The average thickness of the root zone was 0.11 ± 0.04 m; however, the thickness of the root zone formed differed from place to place. The mass of the helophyte mat that contained 0.1 m of water was 117.04 ± 1.32 kg m^{-2}, with a drained mass of 44.58 ± 14.31 kg m^{-2}. The drained mass was considered to be reached when the rate of ongoing mass reduction was less than 0.05% min^{-1}. The experimental method was validated by repeating the measurement three times with the mat that had developed to the greatest extent; the result was 55.30 ± 0.71 kg m^{-2}. To determine the water-storing capacity, a water-saturated cube of well-developed root zone with a side length of 0.1 m was dried at 105 °C for each mat until constant mass was achieved. The average water-storing capacity was 62.24 ± 2.05%.

Experimental system

The test was not conducted on a real roof so as to make it easier to carry out the experiment and take samples. A close-to-realistic experimental set-up at ground level with a custom-made wooden structure (4.4 m length, 1.1 m width, 15 ° slope, see Figure 1) was used. The test rig corresponded

Figure 1 | Experimental set-up with helophyte mat, at the end of three months in service treating greywater (photograph: A. Zehnsdorf).

to the design specifications already tested in practice with rainwater by Rhizotech (Rosdorf, Germany).

A 0.1 m-high raised edge on both sides, the inclusion of sheeting on the base underneath the mat, and carefully considered orientation of the structure ensured targeted flow of water from the inlet to the outlet that was evenly distributed over the entire width. The greywater used came from the bathroom and kitchen of a four-person household in Döben, close to Grimma in the state of Saxony in Germany. This greywater was drawn from a sump present beside the house. On the suction side, a freely hanging strainer made of perforated metal with a hole diameter of 3 mm was used to avoid blockages due to coarse particles and to prevent the suction of sediment. The greywater was pumped using a peristaltic pump (ECOLINE VC-280, Ismatec) that was activated for 40 min every 4 h using a timer. The greywater was distributed across the entire width of the helophyte mat at its highest point using a PVC pipe with 10 drilled holes, each 3 mm in diameter. The distribution pipe was submerged in the helophyte mat so as to avoid aerosol formation. Greywater treatment was carried out between the end of April and the start of July 2015. The hydraulic load per unit area was increased from 10 $L\,m^{-2}\,d^{-1}$ to 15 $L\,m^{-2}\,d^{-1}$ and then to 20 $L\,m^{-2}\,d^{-1}$ over this period.

Sample removal and analysis

Samples were taken at the inlet and outlet of the experimental rig in quick succession, which ensured there was only a minimal time delay between these samples. The water from the inlet and outlet was analysed using the methods described in Table 1.

Table 1 | Parameters and methods for investigation of the inlet and outlet water

Parameter	Method
Chemical oxygen demand (COD)	Cuvette test Hach/Lange LCI 400
5-day biochemical oxygen demand (BOD_5)	Differential pressure measurement WTW OxiTop C
Total nitrogen ($N_{tot} = \sum NH_4\text{-}N, NO_2\text{-}N, NO_3\text{-}N$)	TOC-VCSH/CSN analyzer with a TN unit (Shimadzu, Japan) as per DIN EN 38409
Total phosphorus	Cuvette test Hach/Lange LCK 349

RESULTS AND DISCUSSION

The plant stock in the helophyte mat developed continuously during the experimental period and did not exhibit any signs of deficiencies or damage. The growth height reduced from the inlet to the outlet, which can be ascribed to the reduction in the nutrient content of the water. Over the course of the experiment, the average plant height measured each month increased continuously from 0.1 m to 0.55 m to 0.75 m. The plants on the first metre of the flow path had an intensive green colour due to the better supply of nutrients.

As a result of the horticultural pre-cultivation, the root zone was fully developed, which means that an effective reaction zone for water purification was already present at the start of the experiment. The textile mat was fully intertwined with roots on its underside and was thus able to fulfil its function of stabilising the plants.

The wastewater ordinance currently valid in Germany (Abwasserverordnung 2004), which defines the minimum requirements for releasing treated wastewater into water bodies, was used to compare the results achieved with the experimental outcomes. Values less than the legal limits specified in this ordinance of $COD \leq 150\,mg\,L^{-1}$ and $BOD_5 \leq 40\,mg\,L^{-1}$ were achieved consistently for the tested hydraulic loads per unit area of 10 and 15 $L\,m^{-2}\,d^{-1}$ for BOD_5 (Figure 2). The outlet values of COD exceeded the limit value twice (178 $mg\,L^{-1}$ and 156 $mg\,L^{-1}$) after increasing the load per unit area in each case. The effluent values subsequently stabilised again (Figure 2). This is due to the adaptation process that is necessary for the microorganisms when the system is working at optimal performance. This effect can be avoided by providing a slightly larger reaction zone (mat surface area × height of root zone) or reducing the hydraulic load per unit area (litres of water to be treated per square meter of wetland roof mat). The low number of samples taken for the 20 $L\,m^{-2}\,d^{-1}$ loading rate ($n = 3$) means that no definitive statement can be made about the purification performance of this hydraulic loading rate.

The evapotranspiration of the system was always lower than the inlet volumetric flow. At a hydraulic load per unit area of 10 $L\,m^{-2}\,d^{-1}$ the evaporation loss was

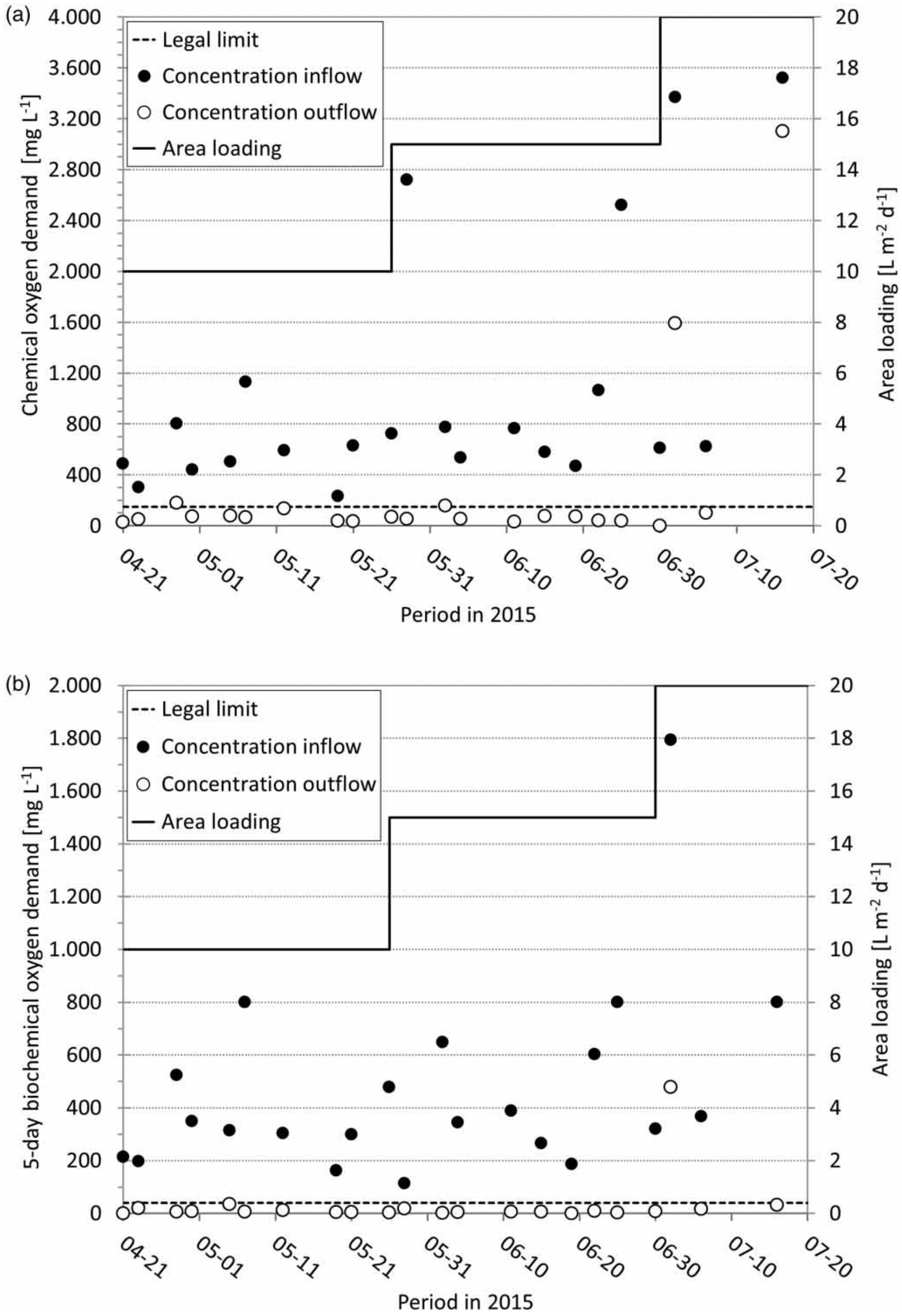

Figure 2 | Treatment efficiency of the helophyte mat for greywater with increasing load per unit area. a = COD, b = 5-day BOD.

3.9 L m^{-2} d^{-1}, respectively 4.9 L m^2 d^{-1} on average at a load per unit area of 15 L m^{-2} d^{-1}. Thus, there was always water present in the outlet and the marsh plants never dried out. The increased average evapotranspiration loss at a hydraulic load per unit area of 15 L m^{-2} d^{-1} can be explained by the advanced plant growth (leaf area index) and the summer temperatures between the end of May and the end of June. A significant exceedance of the legal limit value for COD occurred at a hydraulic load of 20 L m^{-2} d^{-1} (Figure 2). This can be attributed to the start of cheese production in the household, which led to significantly higher inlet concentrations.

Table 2 | Efficiency of the helophyte mat as a function of the hydraulic load per unit area

	COD			BOD_5			TN			TP		
	Concentration[a] [mg L^{-1}]			Concentration [mg L^{-1}]			Concentration [mg L^{-1}]			Concentration [mg L^{-1}]		
Hydraulic load per unit area [L m^{-2} d^{-1}]	Inflow	Outflow	Efficiency[b] [%]	Inflow	Outflow	Efficiency [%]	Inflow	Outflow	Efficiency %	Inflow	Outflow	Efficiency [%]
10 ($n = 6$)	635.2	69.1	93.5	393.3	10.6	98.9	16.7	1.2	96.2	1.2	0.4	77.6
15 ($n = 9$)	1,115	61.3	94.7	407.7	5.9	98.2	16.3	1.1	95.2	2.6	0.3	88.0

[a]Average.
[b]Average efficiency, calculated on the basis of the loading rate [g m^{-2}].

The dynamic profile of greywater correlates primarily with drinking water use in the bathroom and kitchen areas. In terms of load, greywater is strongly dominated by habits in the kitchen. The pollutant load increases for the various house connections as following: hand washbasins < showers < bathtubs < washing machines < kitchen wastewater (Arbeitsblatt DWA-A 272 2013). Sievers *et al.* (2014) quote the following typical concentration ranges for greywater (including kitchen wastewater) on the basis of a survey of the literature: COD 102 to 1,583 mg L^{-1}, BOD_5 56 to 427 mg L^{-1}. As a result of the inlet loads from mid-July onwards that were significantly above typical values for greywater, the experiment with the helophyte root mat was ended early.

The results presented in Figure 2 and Table 2 show that a well-developed helophyte mat can treat greywater with typical concentrations of COD and BOD_5 in a reliable manner in spring and summer operation at hydraulic load per unit area of up to 15 L m^{-2} d^{-1}.

The helophyte mat is not sensitive to short-term interruptions of water inlet feed due to the water-storage capacity of the root zone (see Section 'Helophyte mat'), and this helps to increase the stability of the purification process.

SUMMARY AND OUTLOOK

It was demonstrated under real application conditions for greywater with typical concentrations of COD and BOD_5 from a four-person household that a well-developed helophyte mat can treat this type of water to the quality level necessary for a receiving body of water at a hydraulic load per unit area of up to 15 L m^{-2} d^{-1} in spring and summer operation. Overloading of the system first occurred with the start of cheese production in the household, which resulted in untypically high organic and nutrient concentrations in the greywater.

Using this combination of greywater and rainwater treatment, planted roofs modified to act as 'irrigated helophyte-planted roofs' can serve as efficient tools for local rainwater management in urban environments. This adds an attractive and innovative option to the range of conventional rainwater management systems already available for urban areas. This type of method for the treatment of greywater and rainwater could also be attractive as a source of water that could be used (respectively reused) for gardening and other green areas in climate zones that are frost-free all year round and have regular high heat loads caused by the temperatures during summertime.

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