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Review

Wetland Roofs as an Attractive Option for Decentralized Water Management and Air Conditioning Enhancement in Growing Cities—A Review

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Received: 8 July 2019; Accepted: 2 September 2019; Published: 5 September 2019

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Abstract: While constructed wetlands have become established for the decentralized treatment of wastewater and rainwater, wetland roofs have only been built in isolated cases up to now. The historical development of wetland roofs is described here on the basis of a survey of literature and patents, and the increasing interest in this ecotechnology around the world is presented. In particular, this article describes the potential for using wetland roofs and examines experience with applications in decentralized water management in urban environments and for climate regulation in buildings. Wetland roofs are suitable as a green-blue technology for the future—particularly in cities with an acute shortage of unoccupied ground-level sites—for the decentralized treatment of wastewater streams of various origins. Positive "side effects" such as nearly complete stormwater retention and the improvement of climates in buildings and their surroundings, coupled with an increase in biodiversity, make wetland roofs an ideal multi-functional technology for urban areas.

Keywords: (irrigated) wetland roof; wetroof; decentralized water management; water treatment; natural air conditioning; greywater recycling; wet green roof

1. Introduction

Increasing numbers of people around the world now live in cities. Just 30% of the global population lived in cities in 1950, but this figure had risen to 55% by 2018 and is predicted to reach almost 70% by 2050 [1], (see Figure 1). This trend is placing increasing demands on infrastructure for the supply of water and energy and on the hygienic removal and treatment of wastewater. In many cities that have developed over a long period of time, wastewater is collected in sewer systems and routed to wastewater treatment plants. However, increasingly long periods with little rainfall in temperate climate zones are creating as many problems (sedimentation in sewers) as heavy precipitation within short periods of time (overflowing of sewers). As heavy precipitation can potentially cause serious damage in urban areas, possible methods of predicting such events and of retaining water are being sought worldwide [2–4]. The idea of decentralized treatment of different wastes and water streams (greywater, rainwater) at the location, where they arise, was proposed for discussion a number of years ago [5]. Constructed wetlands have become established as a robust, close-to-nature ecotechnology for decentralized treatment of water streams of various quality levels, from rainwater to municipal wastewaters [6,7]. In subtropical zones, constructed wetlands are already being used for rainwater retention and treatment on a large scale [8]. However, land-use conflicts often occur in growing cities, where ground-level sites are in strong demand and are therefore expensive. An increasingly attractive method for harnessing the advantages of constructed wetlands without causing competition for ground-level sites is offered by "wetland roofs" that are planted on the roofs of suitable buildings in order to retain and treat water, where it arises.

Wetland roofs are constructed on available roof surfaces, therefore it can be assumed that the area used does not compete with other uses, which may be the case at ground level [9]. The following discussion will present the current status of applications and research in this specific area of roof greening.

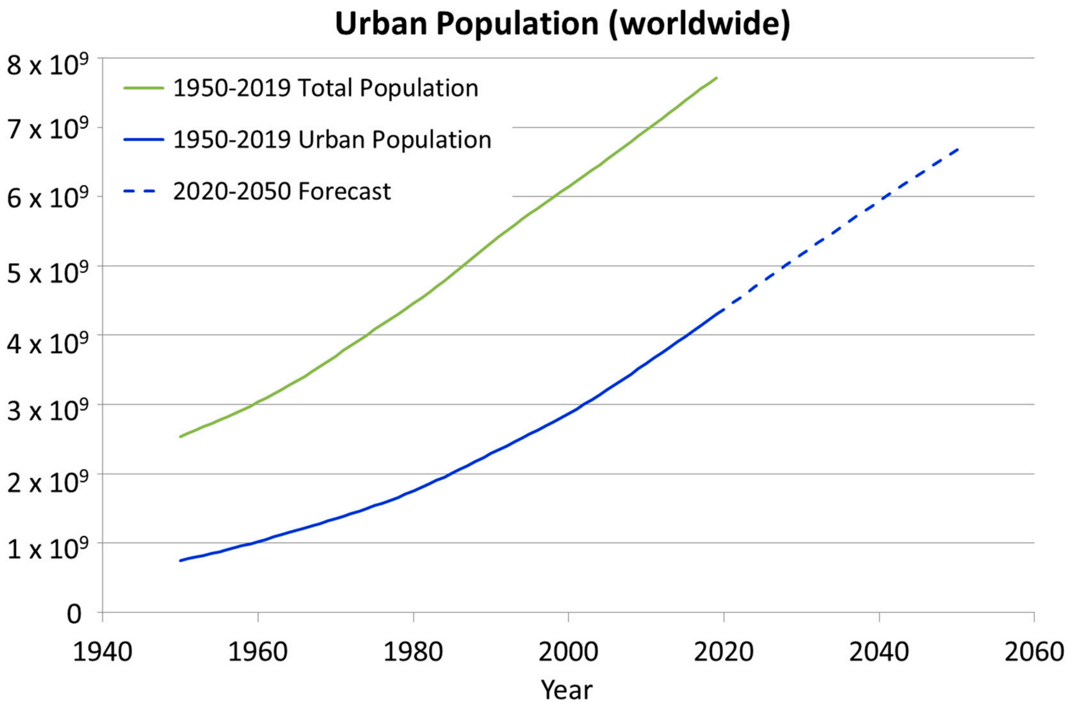

Figure 1. Development of the global population in cities [1].

2. Methods

A literature search was carried out in all databases of the Web of Science (WoS) and Google Scholar for the topics of "wetland roof" and "wetroof" on 6 June 2019. Alongside the twelve publications found, there were also articles—already known to us, and mainly in German—from the course of development of wetland roofs, contributions to books, students' theses and contributions to the proceedings of academic conferences. The German-language articles were particularly significant in this context, as the first wetland roof was built in Germany back in 1991, while interest in this technology has only begun to emerge internationally in recent times. In addition to this literature search, we carried out a patent search using "Orbit Intelligence—Questel" on 19 February 2019 and also considered patents that were already known to us (Table 1).

Table 1. Patents on wetland roofs (search with "Orbit Intelligence—Questel", date 19 February 2019).

Patent Number	Title	Applicant	Priority Date	Status
CN108640290 (A)	Roof wetland structure applicable to southern China	Univ. of Electronic Science and Technology of China, Zhongshan Institute	20 July 2018	In examination. Publication date 12 October 2018
US2017113956 (A1); US9884780 (B2)	Wetland roof technology for treating domestic wastewater	Bui Thanh Xuan (VN); Ton Duc Thang Univ.	21 October 2015	Granting USA 06 February 2019
CZ20150423 (A3)	A roof wetland purifier	Liko-S A S (CZ)	13 June 2015	In examination. Publication date 25 January 2017
CN204588825 (U)	Constructed wetland device for roof	Duan Lipeng	26 March 2015	Publication date 11 March 2015
CN204198545 (U)	Roof landscape wetland device capable of purifying and recycling sewage	Li Yingjun	25 July 2014	Publication date 11 August 2015
CN202391027 (U)	Roof wetland system	Dehua Ecological Technology Company LTD	24 November 2011	Publication date 22 August 2012
US2008245714 (A1)	Plant-based sewage treatment system for purifying wastewater	Deere & Company	7 May 2004	Granted EP 14 January 2015 Patent March 2015 US 13 July 2010
GB2375761 (A)(B)	Green roof water recycling system—GROW	Christopher Jon Shirley-Smith	7 April 2001	Granted 23 June 2004
DE19630830 C2	Dachbegrünung und Verfahren zur Herstellung (Roof greening and installation procedures)	Heinrich Dernbach, Mühlheim	31 July 1996	Granted 7 March 2002 Expired August 2016

3. Results and Discussion

The publications and patents that were identified were sorted here based on the purpose that the described roof greening with wetland plants was intended to serve. The physical construction and design of wetland roofs was identified as an essential component in realizing the two focal areas that emerged: water treatment and climate regulation for buildings. The construction and applications of wetland roofs are summarized in the following sections.

3.1. Construction of Wetland Roofs

Several publications have outlined design considerations for wastewater treatment and passive air conditioning applications of wetland roofs and these are discussed in the following sections. Examples of materials used in literature are provided in Table 2.

Table 2. Examples of wetland roof component materials from literature.

Component	Purpose	Implementations	Reference(s)
Non-permeable root barrier	Protect the roof structure from excess moisture and root infringement	Ethylene propylene diene monomer liner	[10]
		Bituminous waterproofing membrane	[9]
Substratum	Provides storage depth, hydrolysis, growing media for vegetation and biofilm, and appropriate hydraulic residence time	Gravel, soil, sand, polylactic acid (PLA) beads	[11]
Water Retention	Provides water storage, can act as growing media	Polyethersulfone water storage mat (Repotex D)	[12]
		Physical substratum bed depth	[11]
Vegetation	Increase the rate of evapotranspiration for flood control and temperature reductions	*Carex acutiformis* *Juncus inflexus* *Juncus effuses* *Lythrum salicaria*	[12]

3.1.1. Overview of Wetland Roof Design

Wetland roof design follows an adapted multi-layered construction to that of an extensive green roof and is comprised of (from bottom to top): an impermeable root barrier liner protects the roof structure from excess moisture and root intrusion, substrata with water retention capability, and a top helophyte vegetative mat across the entire surface of the roof that must be regularly irrigated (Figure 2) [11,12].

To supplement rainwater, additional stored water from a storage cistern or alternatively domestic wastewater should be pumped back and distributed onto the roof surface daily via an irrigation pipe [12]. Water percolates through the wetland roof via horizontal subsurface flow [9]. In cases of overflow, inclined roof constructions may employ rain gutter drainage (Figure 2) while flat roof constructions may employ discharge chambers calibrated to the desired wetland roof water level [13]. Overflow may be directed towards an overflow cistern or directly back to the sewers or local septic holding tank [9,13].

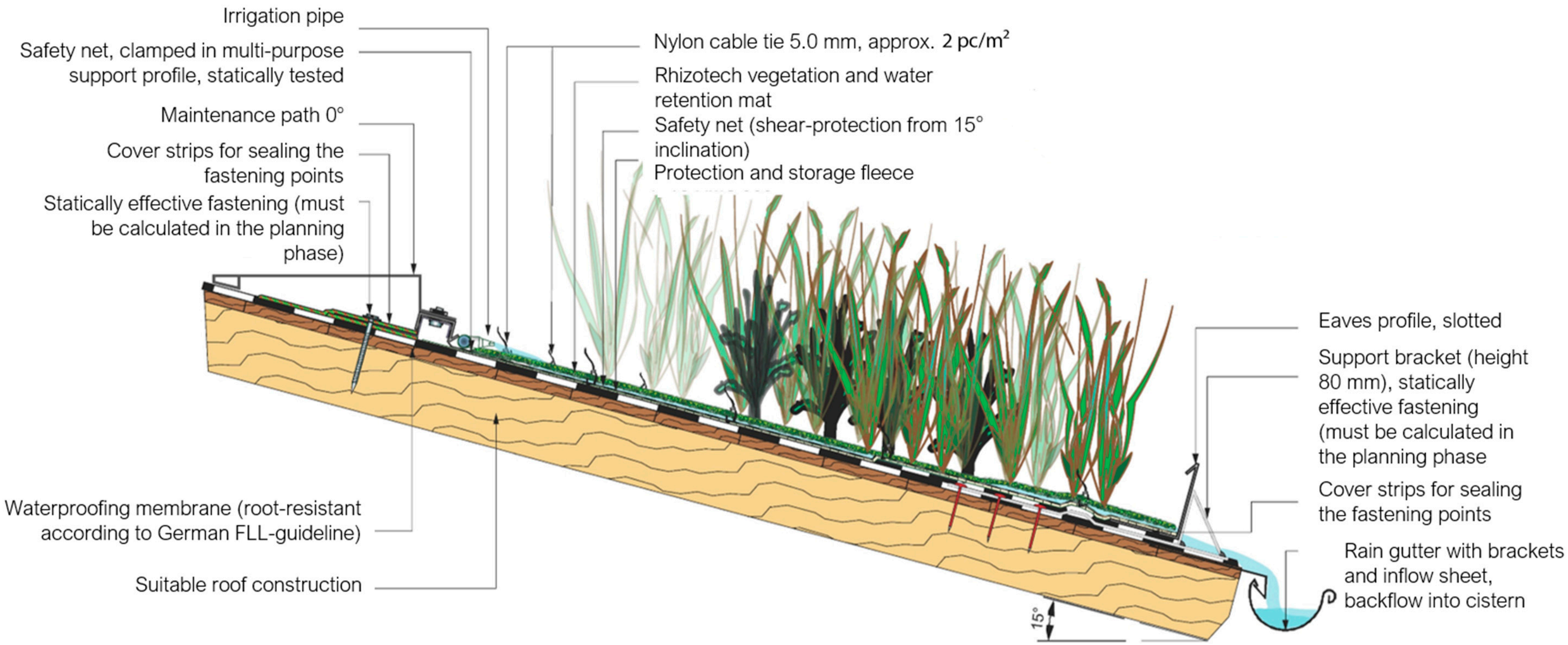

Figure 2. Basic structure of a wetland roof, as already realized in practice (graphic: Michael Blumberg).

3.1.2. Substrata Considerations

The substrata mix chosen should be of minimal weight so as not to exceed the load bearing capacity of the roof structure while providing the necessary hydraulic residence time in water treatment applications [11]. Realized wetland roof designs have previously implemented solid substrata combinations to provide both water retention and a reaction space for nutrient and contaminant removal from water [11]. A vegetative helophyte mat is installed above the substrata and held in place with the aid of stabilization plates to protect against shear resulting from roof inclination and weight application [11].

Solid substrata can be composed of a variety of materials notably soil, sand, and gravel; though polylactic acid beads and light expanded clay aggregates have also been investigated due to their high surface area for biofilm development and low weight [11]. The choice of substratum is important for providing the appropriate hydraulic residence time for the treatment of influent water as well as providing adequate surface for biofilm development [11]. While finer particles may provide greater hydraulic residence times, preferential flow has been observed in systems with too small hydraulic conductivities, which could lead to bed damage as well as short circuiting, which reduces the hydraulic residence time [11]. To reduce this effect, a selective mix of substrata materials of varying diameters can be used [11]. Alternatively, Thanh et al. employed five consecutive channels to decrease short circuiting effects [14]. Short circuiting was also reduced in the construction of a green rooftop incorporating troughs fitted with baffles and weirs to promote a plug flow regime and wastewater contact with substrata in the Green Roof-top Recycling System (GROW) [15].

Adapted realized designs have instead opted for integrated vegetative and water retention fleece mats in place of solid substrata media as this provides the necessary root zone and water retention capabilities at a lesser weight and volume relative to the roof load bearing capacity [12]. Plant roots grow into the fleece textiles, which additionally stabilize the helophyte mat [12]. Recent designs have further employed multipurpose support profiles and statically effective fastening mechanisms such as nylon cables to support and attach the wetland roof construction onto the roof surface (Figure 2) [13].

To prevent clogging and blockages within the wetland roof and pump, gravel is often employed at each end of the wetland roof construction [16]. Additionally, a free hanging metal strainer with small perforations can be integrated onto the suction side of a sump pump to prevent blockages from coarse particles and suction of rooftop sediments [12].

3.1.3. Vegetation Considerations

Wetland roof systems tolerate permanent flooding conditions and oversaturated soil, therefore flood-tolerant macrophytes that are composed of the appropriate biomass and height that satisfy the roof load bearing capacity requirements are recommended as the best choice for rooftop wetlands [10]. For long term maintenance reasons, these plants are preferred to be perennial such that they are capable of regeneration each season without need for replanting [10]. It is recommended that the selection of plants meet the criteria such that they are: easy to grow, can thrive in harsh conditions, possess the ability to treat wastewater, offer aesthetics, provide broad roof coverage, are locally available, and are low cost [17]. Particularly large plants, such as *Phragmites australis* should not be used given that their height results in greater wind stress than low lying plants. Because different regions possess differing climatic conditions and native plant species, plant selection cannot be derived directly from published literature, but should instead be based on long term local climate and resource characteristics, or alternatively introduced from the neighboring regions of similar climatic conditions [18].

Plant species may be pre-cultivated under water saturated conditions with the use of vegetative and water retention storage mats [12]. Pre-cultivation such that the root zone is fully developed at the time of construction provides for greater structural integrity and an effective reaction zone necessary for water treatment applications. However, pre-cultivation in a nursery is time intensive and can require one or two vegetation periods to achieve a cover ratio of the plants of up to 100% [11,12].

Upon installation, vegetative mats can adapt to wetland roof conditions via irrigation using tap water prior to the introduction of wastewater or greywater for water treatment [16,17]. Nutrient removal rates in wetland roof systems treating domestic wastewater have been observed to vary between different plant species [16]. This suggests that wetland roofs may be designed to optimize nutrient and contaminant removal from influent waters. Optimization of wetland species for the purpose of meeting specific removal efficiencies is an area of potential future research.

Greater rates of evapotranspiration result in greater cooling effects as more heat is dissipated by the system in the form of water vapor. Helophytes possess greater evapotranspiration capabilities than common green roof terrestrial plants and thus offer a greater capacity for passive air conditioning applications [12].

It was found that different wetland plant species exhibit varying rates of survival under extended drought and flooding conditions [10]. This suggests that wetland plant species may be selectively chosen based on tolerance for drought conditions in climates that experience drought conditions as well as heavy rainfall. Further research regarding the maximum duration of drought conditions at which plants may be revived should be considered.

MacIvor et al. compared three coastal barren species (considered wetland species) and three dryland plant species performance on extensive green roofs over two growing seasons in Halifax, Nova Scotia based on the criteria of plant survival rate in subsequent growing seasons, vegetation roof cover, roof surface temperature, water capture, albedo, and water loss as a proxy to estimating evapotranspiration rates [19]. Dryland species were found to be overall more effective in performance criteria than wetland–dryland species combinations however dryland species may not be suitable in subtropical or tropical climates experiencing greater flooding than Halifax [19]. There was no apparent correlation in survival rates between wetland and dryland species (all species were observed to have survival rates >75% between growing seasons) despite observed winter temperatures from November to April of −8.6–1.2 °C which suggests that plant survival performance in cold climates is comparable between wetland and dryland species [19]. This study further suggests that increasing vegetation cover improves thermal reduction effects due to greater albedo and evapotranspiration rates thus wetland plant species capable of high growth rates and growing density may provide greater thermal mitigation effects [19].

3.1.4. Suitability of Wetland Roof Implementation

Many wetland roofs are designed to not operate in winter months when bed temperatures drop below 2 °C resulting in the freezing of wastewater within the system [9]. At this time, wastewater is instead directed immediately back into sewerage systems, or in cases of off grid systems, back to the septic holding storage tank [9]. If neither option is available, then the implementation of wetland roofs is limited by climate and should not be implemented in areas that wish to use this system for treatment of waste waters full time throughout the year or hold seasons during which temperatures drop below 2 °C. While facilitating a deeper bed depth has been proposed as a means of preventing wastewater freezing, this design modification is generally less preferable due to its increased weight of implementation for roof load bearing capacities [10]. For this reason, wetland roofs may be more viable for more temperate climates.

Climates that are susceptible to long periods of drought may not be suitable for wetland roof systems and irrigation of the wetland roof may require supplementation with domestic waters to maintain a hydraulic loading rate that keeps the bed saturated and active while sustaining wetland plant species [12]. Greater ability for long term water storage and water retention volumes can prevent deterioration of wetland roof aesthetics and treatment function and should be planned for prior to wetland roof construction. Degradation of wetland roof aesthetics due to plant drought as a result of short-term complete evapotranspiration of influent water has been observed though plants were capable of revival with increased supplemental irrigation and lessened sun intensity [9]. Research has yet to be conducted regarding maximum extended periods of drought wetland roof systems can endure and still be revived to the necessary operating capacity.

Pilot constructed wetland roofs have previously demonstrated the capability of reaching the strict removal efficiencies required for water discharge into an infiltration pond by local legislation [9]. Future implementation of constructed wetland roof for water treatment and subsequence water reuse applications will be dependent on the wetland roof's ability to meet local discharging guidelines which may be stricter for organic matter and solids depending on the location and governance of implementation.

3.2. Water Treatment

Dr. Käthe Seidel carried out pioneering work on the use of wetland plants for (waste)water treatment in Germany in the mid-20th century [20]. While wetland plants in constructed wetlands quickly became established as a close-to-nature solution for decentralized wastewater treatment, wetland roofs are still considered somewhat "exotic" to the present day [21,22]. In the context of worldwide population growth in cities and conurbations and of the resulting increase in building densities in urban areas, wetland roofs have the potential to serve as innovative tools for ensuring the sustainability of urban water management structures. It is increasingly being accepted that building roofs can perform additional functions apart from merely protecting the interiors of buildings against precipitation (see Figure 3). In addition, the investment for roof areas has generally already been made, when the buildings on the site have been constructed.

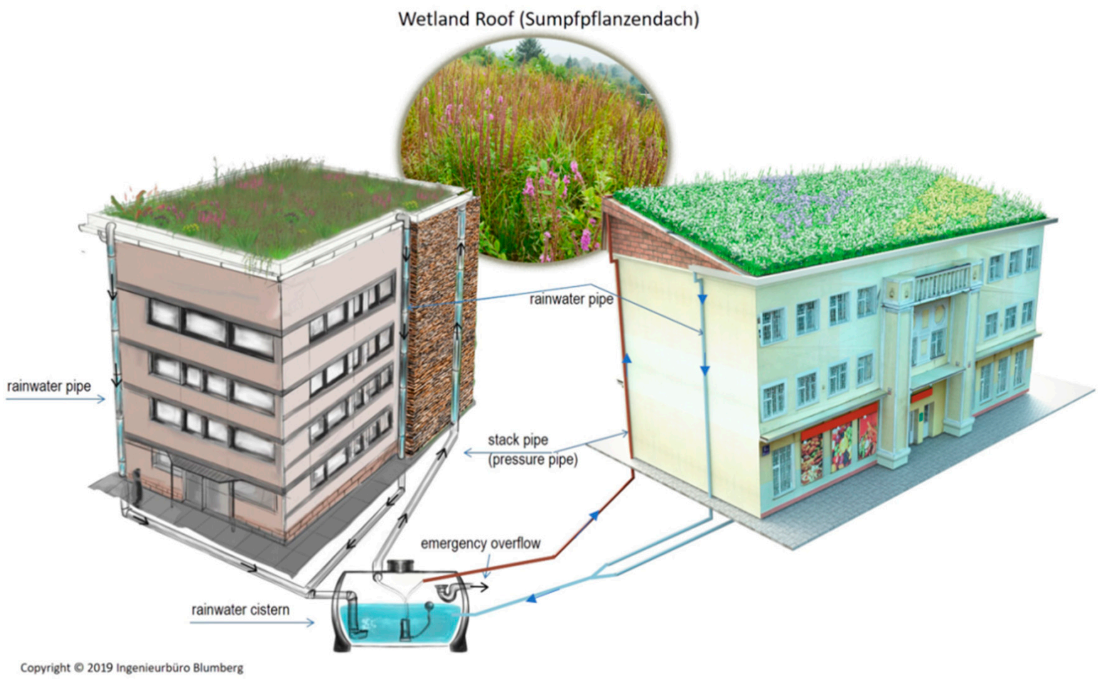

Figure 3. Buildings with wetland roofs for rainwater retention, evapotranspiration or for greywater treatment (graphic: Michael Blumberg).

3.2.1. Greywater and Rainwater

Decentralized treatment of greywater (water that arises in households with the exception of that from toilet flushes) is currently attracting increasing attention, particularly in growing cities. This approach would reduce the burden on existing wastewater removal systems and avoid the need for expensive expansions. As ground-level sites are generally expensive and usually already reserved for other land uses, greywater treatment using helophyte mats on the roofs of buildings has now become an attractive option, for economic reasons, too. As well as treating water, this process also has a positive effect on climate regulation inside buildings [23–25]. In a test carried out under realistic conditions, it was shown with the aid of a pilot plant that a helophyte mat with a root-layer thickness of 0.1 m is capable of treating typical greywater from a residential building during the growing season at hydraulic loads per unit area of up to 15 L/m^2 × d [26–28]. Zapater-Pereyra et al. found that a constructed wetland roof was capable of meeting up to the strictest treatment level (60 mg L^{-1} fortotal suspended solids (TSS), 40 mg L^{-1} for 5-day biochemical oxygen demand (BOD_5), 200 mg L^{-1} for chemical oxygen demand (COD), 4 mg L^{-1} for NH_4^+-N, 60 mg L^{-1} for total nitrogen (TN), and 6 mg L^{-1} for total phosphorus (TP)) required by Netherlands guidelines for discharge into water bodies given that the overflow water was directed to an infiltration pond [9]. It should be noted that water reuse guidelines such as for toilet flushing in other parts of the world (such as in the USA and Canada) are stricter for organic matter and solids removal and additionally require microbial removal parameters [9]. Pradhan et al. suggests pathogens remain the largest risk in green roof greywater treatment and thus toilet flushing should be the preferred reuse option, which has low water quality requirements and low pathogen risks [29]. In reuse applications where microbial pollution is to be monitored, additional supplemental treatment such as by UV may need to be applied following initial treatment within the wetland roof.

With the simultaneous treatment of greywater, systems of this type can also be used for the treatment and evapotranspiration of rainwater as they are able to withstand even longer periods without precipitation thanks to the continuous inflow of greywater [12]. Additional promising areas of application for wetland roofs include their use on "Tiny House"—projects that are self-sufficient for water and also on mobile homes—an area that is currently attracting increasing attention [30]. Another application of wetland roofs for residential and hotel development was proposed in 2014 as a means of blending urban development with the natural beauty aesthetics of the surrounding Hanalei River Ridge for the Hanalei Plantation Resort in Hanalei, Hawaii on the island of Kauai while providing a means of passive cooling, pollution mitigation, and habitat supplementation [31]. Entire buildings have also been fitted with these types of roofs (see Figure 4).

Figure 4. Building with half the roof area covered by a wetland roof (photo: Michael Blumberg).

In recent times, an increasing number of retention roofs have been built to store rainwater and evaporate it through the vegetation on green roofs in cases where the building has a sufficient reserve load-bearing capacity. With these retention roofs, the rainwater storage is located underneath the actual green roof structure, so as to ensure a good air–water balance in the root zone. Supply to the terrestrial vegetation is based on the capillary effect. Blue–green roofs of this type can achieve a significantly higher cooling effect as a result of the better availability of water relative to simple extensive green roofs [32], and they can also contribute significantly to rainwater retention [33]. In the case of wetland roofs, rainwater can be stored partly within a special plant carrier and water storage mat (see Figure 3), since these plants can actively supply oxygen to their root zones [34] via their aerenchyma tissue.

3.2.2. Municipal Wastewater

The treatment of municipal wastewater using wetland roofs is not very feasible in Germany due to a lack of acceptance. However, tests with pilot plants have already been carried out in Vietnam [14,35–37]. It was found that wetland roofs can treat municipal wastewater streams to such an extent that the treated water fulfils the requirements of regional wastewater treatment standards. Comparisons of potentially suitable typical regional plants revealed that there were indeed differences in the treatment performance and efficiency of nutrient removal for the species investigated [16].

As conventional constructed wetlands, which have now become established around the world for the decentralized treatment of municipal wastewater, are generally too heavy to be located on a roof, a concept for a corresponding constructed wetroof has been developed in the Netherlands [38]. As part of these efforts, various substrates have been tested with regard to their hydraulic residence time, long-term stability, and the necessary reserve load-bearing capacity of the roof [11]. The influence of the weather—and particularly of precipitation and dryness—on the treatment performance was analyzed and it was found that the water-treatment efficiency of a constructed wetroof is not influenced by the weather even though the hydrology of these roofs is strongly weather-dependent [9].

3.2.3. Industrial (Waste) Water

Wetland roofs are particularly well-suited for the treatment of industrial process waters if the desired purification process involves the removal of plant nutrients. The tractor manufacturer John Deere has been successfully using a wetland roof with a surface area of 160 m^2 in Mannheim, Germany, since 2001 to remove phosphorous from water streams that arise during production [39–41].

3.3. Natural Climate Regulation for Buildings

Alongside their potential for environmentally sustainable and space-saving water treatment, wetland roofs also have a positive influence on the climate in the buildings underneath them and in the immediate surroundings, which is discussed in the following sections.

3.3.1. Municipal Buildings

The temperature in a building can be reduced efficiently on hot summer days, because of the high evapotranspiration rate of the wetland plants used on these special extensive green roof systems. In Berlin, Germany, two-year measurements in a rainwater retention basin using Phragmites and Schoenoplectus resulted in mean daily evapotranspiration rates at this inner–city site for *Phragmites australis* between 7.8 mm/d and 9.2 mm/d, and 6.9 mm/d for *Schoenoplectus lacustris* [42]. In contrast, the wetland roof has an insulating effect in winter, which reduces heat losses through the roof [10].

Tests on the cooling effect of a wetland roof have been carried out on a pilot plant system in Leipzig, Germany, during the growing season in 2017. In these tests, 10 liters of water per square meter were added to the wetland roof four times each day. At this water amount, the run-off from the pilot roof never ran dry during the test period and there was always water available for evapotranspiration through the wetland plants for the entire roof surface. The temperature at the center of the root zone was measured and recorded from the start of August to the start of September. A gravel roof with white gravel served as the reference case. The maximum temperature difference between the two roofs was 25 K [25] (see Figure 5).

Figure 5. Pilot plant system of a wetland roof (planted area 4.5 m^2) (photo: Andreas Zehnsdorf).

3.3.2. Industrial Buildings

The largest wetland roof in Germany, with a size of 3000 m^2, has been in operation at the Possmann cider winery in Frankfurt am Main, Germany, since 1991. The roof is used to collect rainwater, which is then used to cool apple wine in the storage cellar [43,44]. Thanks to the use of evaporative cooling, chemical coolants are no longer necessary, and there is also no need for the cooling towers that would otherwise be required—which represents significant cost savings. The wetland roof has developed into a biotope and also improves the visual appearance of the irrigated green roof. The Possmann company received an Honorary Award from the city of Frankfurt as "Water-saver of the year 1996" for this innovative application [45].

3.3.3. Stable Buildings

Another interesting application is the planting of wetland plants on the roofs of cowsheds used in dairy farming [46]. Initial tests were carried out under realistic conditions by the German Federal Research Institute for Agriculture (FAL) back in 2006 (see Figure 6). The aim was to identify a solution that would cool a dairy livestock stable in an energy-neutral manner and avoid summer temperature peaks in particular [47,48]. With the installation of a wetland roof on the cowshed, the temperature in the stable with the wetland roof was reduced by 5 K compared to a cowshed building without a green roof [47].

Figure 6. Wetland roof on a cow barn of the Federal Research Institute for Agriculture (FAL) in Braunschweig, Germany (roof surface 834 m^2, photo: Michael Blumberg).

3.3.4. Urban Microclimate

Beyond the direct effect on various different types of buildings, wetland roofs contribute to the improvement of the urban microclimate and to the reduction of the "heat island effect" by increasing air humidity and through the associated regional reduction in air temperature in dense urban environments [49]. According to model calculations using the assumption that 50% of the roofs of a city are equipped with intensive green roofs, this will lead to a temperature reduction of up to 3 °C [50]. Wetland roofs have been observed to provide more stable rooftop temperatures than that of ambient rooftop air due to the high heat release and insulating capability of water [10]. It was found that wetland roofs possess the greatest capability for heat flux reduction of rooftops compared to xeric green roof systems and bare roofs for subtropical climates such as Southwest Florida [51]. Wetland roof systems were found to reduce the daily heat exchange between a domestic house and its surroundings by 43% and 93% compared to the xeric roof system and bare roof respectively [51].

The evapotranspiration rates of the plants used on green roofs are of great importance for rainwater evaporation as well as for building cooling. Evapotranspiration data for green roofs have so far been determined in many cases only under laboratory conditions and for short periods of time [52], but evaluating the evapotranspiration performance of different plants on green roofs requires year-round data. In comparison of the evapotranspiration values of wetland plants and grass areas (see Table 3), it can be seen that a much higher cooling effect may result from a marsh plant vegetation by wetland roofs.

Table 3. Mean evapotranspiration capacity (ET) and resulting calculated daily ET and energy demand of different types of vegetation.

	Mean ET	**ET/Day**	**Energy Demand for ET**
	(mm/a)	**(mm/d)**	**(kJ/m^2 × d)**
Reference Value		1	245 [2]
Wetland Plants	1100 [1]–2000 [3]	3–6	735–1470
Grass Area	400–500 [1]	1–1.4	245–343

ET in mm/year according to: [1] [53], [2] [54], and [3] [42].

The combination of green roofs (and especially wetland roofs) and artificial wetlands, such as ponds or pools, could be particularly attractive in this context. However, little research has been carried out up to now on the effects of the spatial proximity of these two ecotechnologies of "green roofs" and "wetlands created by humans" and the possibly resulting interactions, particularly with regard to urban microclimate and biodiversity. The deliberate combination of these two ecotechnologies and their widespread use in urban areas could potentially deliver significantly more positive impacts in the future as compared to the sporadic, isolated use of green roofs and wetlands.

Interestingly, MacIvor et al. investigated combinations of both native wetland and dryland plant species in reducing surface temperatures on extensive modular green roof systems over two growing seasons in Halifax, Nova Scotia [18]. While dryland plant modules recorded greater temperature reductions than wetland plant combinations, plant type (marshland and dryland) or plant species combinations had no significant difference on mean surface temperature reduction capability however, plant coverage area had a significant effect suggesting the importance of implementing plant species capable of greater roof area coverage [18].

Further microclimate temperature reduction effects for water tolerant plant species have been discussed and modelled in publications on "hydroponic roofs" which result from a keyword search for "wetland roof" in Google Scholar. While extensive roofs make use of solid type growth media to promote plant growth, hydroponic roofs are composed of plastic-planters floating on pure water substrate operating under flood like conditions [55]. The microclimate effects of hydroponic green roofs specifically with respect to rooftop temperature reductions have been measured and modelled using heat balance analyses and programs such as ENVI-met [56,57]. While temperature reductions by hydroponic roofs have been observed, the individual impact of reducing temperature effects over large distances above a single hydroponic roof structure is small [57]. A comparison of extensive and hydroponic green roofs suggested that hydroponic green roofs are an effective means of reducing roof top temperatures and heat amplitudes and though extensive green roof slightly outperform hydroponic roofs in roof top temperature reductions, the reduced irrigation needs, stormwater storage capability, low maintenance, and superior weed control among other benefits make hydroponic roofs an attractive option with many benefits comparable to wetland roofs [55]. Further research could delve into microclimate effects of wetland roofs over greater distances and comparisons in microclimate effects of wetland roofs to hydroponic green roofs.

4. Conclusions and Outlook

If water is available in sufficient quantities and is to be removed by evaporation at the location it arises, wetland roofs are a promising addition to already established ecotechnologies, particularly in urban environments. Irrigated green roofs of this special type achieve a range of positive impacts, such as improved building air conditioning and cooling effects for the microclimate as well as an increase in biodiversity. Despite the increasing international interest in wetland roofs, a range of open questions still remain. The examples presented here will hopefully encourage readers to consider the area of wetland roofs in more detail.

Funding: This publication was created as part of the project for a research green roof titled "Forschungsgründach" which is funded by the European Regional Development Fund (ERDF) and co-financed by tax revenue on the basis of the budget enacted by the members of the Saxon state parliament.

Acknowledgments: The authors would like to thank the staff of the library of the Helmholtz Centre for Environmental Research—UFZ for their support in the procurement of publications and Matthias Remmler from the Knowledge and Technology Transfer (WTT) department of the UFZ for patent search assistance. We dedicate this article to the memory of Peter Kuschk, who recognized the potential of water treatment using root mat filters at an early stage.

Conflicts of Interest: The authors declare no conflict of interest.

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