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Quantitative, Qualitative and Thermal Aspects of Rainwater Retention on Wetland Roofs

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Abstract: Wetland roofs (WRs) are a multi-functional green infrastructure measure to mitigate the negative effects of climate change. The present work advances knowledge in the field of WRs by analyzing the performance of rainwater management, focused on water sufficiency, water quality and cooling potential. Automatic monitoring, covering weather conditions, temperature and the conductivity of WR water, and the amount of outflow into retention tanks, was supported with automated sampling of water for laboratory analysis of BOD_5, phosphate phosphorus, suspended solids, electrical conductivity (EC), redox potential (Eh), color and pH. From April to September 2022, a precipitation deficit of 395.45 mm and a negative climatic water balance of 267.91 mm were observed. It was necessary to fill up the system several times in order to maintain water at the assumed level. In most cases, the values of EC observed during the monitoring period were higher than those reported for rainwater. Continuous monitoring of EC in the wetland was a useful tool for the observation of operating activities in the system; however, it was not sufficient for system control. BOD_5 values did not exceed 6 mg dm^{-3} and were lower than reported for urban rainwater retention reservoirs. Suspended solids values did not exceed 27 mg dm^{-3}. Color varied between 0 and 101 PtCo, with the highest values noted in July and the beginning of August. The pH value ranged between 7.28 and 8.24. The Eh varied between 155 and 306 mV, with lower values associated with the filling up of the wetland. Peak values of PO_4-P were observed between the end of July and the beginning of September 2022, with a maximum concentration of 232 µg dm^{-3} utilized by the wetland within one month. Monitoring of the water and air temperature showed a thermal buffering effect of the wetland. The results of the research, conducted during the growing season, allow for better management of rainwater on the roof. However, there is a need to expand the scope of the analyzed water quality parameters. Although there are several limitations to the analysis, the present study partially fills the existing knowledge gap and may generate further interest in this topic among researchers and decision-makers.

Keywords: wetland roof; rainwater management; climatic water balance; water quality; temperature

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1. Introduction

Green infrastructure plays an important role in current environmental policies, such as the European Union's (EU) Biodiversity Strategy to 2030 [1] and Climate Adaptation Strategy to 2050 [2]. One of the current problems in urban areas is heavy rain, which can easily flood drainage systems that lack sufficient capacity because of increasing urbanization and climate change [3,4]. Extremely high temperatures are becoming increasingly common in cities, with a negative impact on residents [5]. Rainwater retained by green infrastructure provides a measurable effect, in the form of cooling the surrounding area and building interiors [6,7]. The implementation of rainwater retention, detention and harvesting technologies in urban areas is considered a multi-beneficial strategy for urban flooding control. One common green infrastructure solution that improves the quality of life in cities is an intervention in the form of green roofs. This intervention presents numerous benefits, including delaying runoff, increasing rainwater retention and biodiversity, decreasing internal and external building temperatures, reducing demand for cooling, reducing the urban heat island (UHI) effect, improving air quality and reducing noise. Another well-known intervention for rainwater retention and the treatment of surface runoff are constructed wetlands (CWs), which are characterized by a relatively simple design and low energy requirements and implementation costs. Wetland plants evaporate more water than land vegetation, thus transferring a significant amount of water to the surrounding air [8]. This ecotechnology provides environmental conditions that have become scarce in urban landscapes, where natural wetlands and their biodiversity have been lost [9]. The most important limitation for the implementation of CWs in urban areas is the considerable area that they require. Locating the wetland on the roofs of buildings eliminates this problem, while providing all of the CW benefits. Wetland roofs (WRs) are not a typical structural system of layers performing specific functions, like those seen in green roofs [10]. However, they are a green infrastructure solution, and their benefits combine those of green roofs and CWs.

Interest in WRs is growing slowly and there are currently very few examples of their implementation or of related research. There are two main types of WR, shallow beds with subsurface flow and ponds with floating helophyte mates (also called hydroponic roofs, HRs). Shallow beds with subsurface flow are seen in horizontal subsurface flow constructed wetlands (HSF CWs) and are used for wastewater/grey water treatment or rainwater management. HRs contain open water and are thus used only for rainwater management (Figure 1). The weight of a substrate-based WR is comparable to or less than that of an extensive green roof. The total load depends mainly on the designed retention, which is approximately 100 kg m^{-2} per 10 cm of water layer [11]. As in the case of green roofs, this limits the use of WRs to buildings that have been designed to bear additional loads. Maintenance costs are similar to those of extensive green roofs, but WRs need a sufficient water supply during prolonged periods of drought [12].

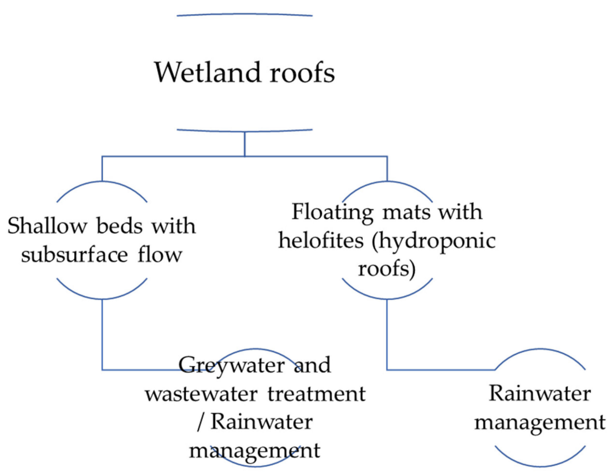

Figure 1. Typical set-up and main functions of WRs.

WRs provide a wide variety of benefits, including enhancing aesthetics and biodiversity [9,13], regulating water runoff [13,14], providing an area for evaporation [15], reducing air pollution and the heat island effect [6], reducing costs of air conditioning and heating [14] and lowering noise pollution [16]. Some authors have also reported their efficiency in wastewater and grey water treatment [16–20]. This can be considered an attractive on-site wastewater treatment solution in the case of limited areas of available land, but this is limited to WRs in the form of shallow beds (Figure 1). Research conducted on HSF CWs, focused on rainwater treatment, has shown that they also have purifying potential [21].

However, a free water surface (FWS) WR, as described in the present study, is filled directly from precipitation, in contrast to CWs, which are fed with polluted surface runoff. The WR analyzed in the present study is unique and its purifying role will be limited to cases in which it will be fed with potentially contaminated water from retention tanks, polluted rainfall or from internal pollution, e.g., via plant decay.

A review of the literature shows that there are some gaps in current WR research, including a lack of understanding of the hydrologic behavior of WRs for rainwater management in different climatic conditions, the impact of wetland water level on the thermal conditions inside a building, and requirements for WR operation and the maintenance of their water quality. The present study contributes to the field by analyzing rainwater management performance, with a focus on water sufficiency, water quality and cooling potential.

2. Materials and Methods

2.1. Site Description

The roofs of the MCER building complex (52.33398367443746, 21.12563478465449) located in Marki (30 km northeast from Warsaw, Poland) are covered with multifunctional roof technology, consisting of WRs, extensive green roofs and gravel roofs with photovoltaic panels. The buildings, which were erected in 2019, comply with sustainable construction practices, according to the Green Building Standard (GBS) [22] and Building Research Establishment Environmental Assessment Methodology (BREEAM) [23] Interim certificates. The area of the WR is approximately 3400 m^2, and extensive green roofs cover 3200 m^2 [11]. The roofs are covered with water and plants to purify the air, suppress noise, create habitats for fauna and flora and to perform recreational and educational functions via footbridges and platforms. The most important functions are rainwater retention and buffering the temperature inside the building.

The rainwater management concept assumes that wetlands are supplied by rainwater via precipitation and that surplus water is drained by gravity through underground retention tanks. During dry seasons and rain shortages, the water supply of the wetland comes from the opposite direction, from the tanks to the roof. The water level in the WR can be regulated by roof drains between 10 and 35 cm in size. The present study was conducted on wetland with a unique construction, as the halophyte mats are lying on the bottom, underlined with 10 cm of mineral substrate (Figure 2), rather than floating. The original species composition included *Iris pseudacorus*, *Lythrum salicaria*, *Caltha palustris*, *Acorus calamus*, *Alisma plantago-aquatica*, *Carex acutiformis*, *Carex acuta* and *Carex pseudocyperus*. In 2022, when the research was conducted, the roof was dominated by sedges (Figure 3).

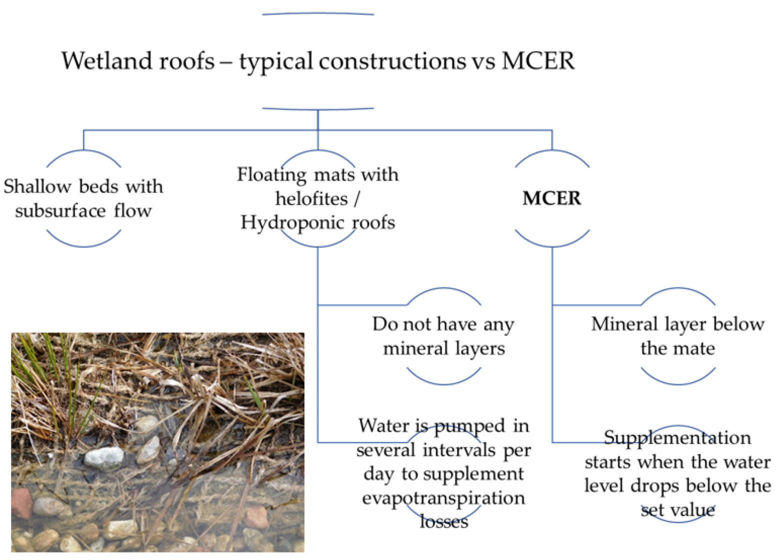

Figure 2. Differences between common WRs and the WR on the MCER building tested in this study. The image shows the helophyte mate underlined with mineral substrate.

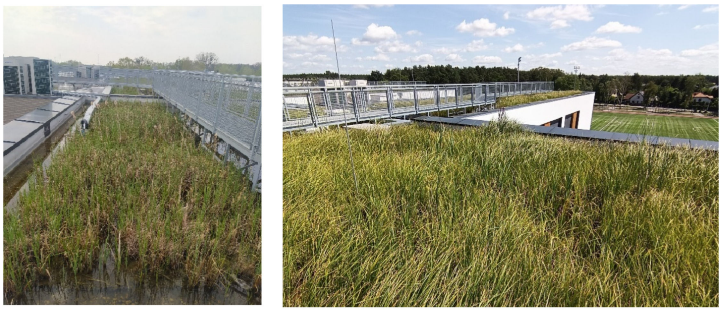

Figure 3. Vegetation on the WR (May and June 2022).

2.2. Automatic Monitoring, Water Sampling and Analysis

The site is equipped with a weather station, sensors for measuring temperature (HOBO U20L-02, Onset HOBO, Bourne, MA, USA) and conductivity (HOBO U24-002-C, Onset HOBO, Bourne, MA, USA) in the wetland, an area velocity ultrasonic flow meter (ISCO 2150, Teledyne ISCO, Lincoln, NE, USA) for measuring the amount of water outflow into the retention tanks from the WR and an automating sampler (ISCO 6712, Teledyne ISCO, Lincoln, NE, USA) to collect water from the wetland for laboratory analysis [24]. Samples of water from the wetland were collected at 48 h intervals, from 14 July to 30 December. Phosphorus concentration, suspended solids, EC, Eh, color and pH were analyzed in each collected sample. For BOD_5 analysis, samples from two consecutive collections were mixed in a volume ratio of 1:1. BOD_5 was measured for five days at a temperature of 20 °C by an OxiTop WTW. The effect of environmental factors on changes in water quality and the performance of the WR were determined during the growing season, from April to September 2022. Data were recorded using the weather station on the WR. Relative humidity, air temperature and atmospheric pressure were measured with an ATMOS-14 sensor (Meter Group, Pullman, WA, USA), wind speed and direction were measured with an ATMOS-22 sensor (Meter Group, Pullman, WA, USA) and total radiation was measured with a SP-110 pyranometer. Precipitation was recorded with a Pronamic rain gauge. The data were registered by a ZL6 data recorder at 10 min intervals. For the vegetation period, the climatic water balance (CWB), defined as the difference between rainfall (P) and reference evapotranspiration (ET_o) according to the Penman–Monteith equation (Equation (1)), was calculated [25–27]:

$$ET_o = \frac{0.408(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where ET_o is reference evapotranspiration (mm), R_n is radiation (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the average daily temperature, measured at a height of 2 m (°C), u_2 is the wind speed at a height of 2 m (m s^{-1}), e_s is the saturated water vapor pressure (kPa), e_a is the current water vapor pressure (kPa), ($e_s - e_a$) is the water vapor pressure deficit, Δ is the slope of the vapor pressure, and γ is the psychrometric constant (kPa $°C^{-1}$), according to the formula given by Hargreaves [28].

The potential evapotranspiration (ETp) from the reservoir overgrown with rush vegetation was calculated based on Equation (2):

$$ET\text{p} = k\text{c}\ ET_o \quad (2)$$

where *ET*p is the potential evapotranspiration from the reservoir overgrown with rush vegetation (mm d^{-1}), ET_o is the reference evapotranspiration (mm d^{-1}) and kc is the crop coefficient [-].

The values of the crop coefficient are presented in Table 1 [29].

Table 1. Values of the crop coefficient (kc) for calculating evaporation from the reservoir overgrown with reed vegetation [29].

Period	kc	Period	kc
April—1st decade	0.51	July—1st decade	1.24
April—2nd decade	0.73	July—2nd decade	1.24
April—3rd decade	0.89	July—3rd decade	1.25
May—1st decade	1.02	August—1st decade	1.28
May—2nd decade	1.11	August—2nd decade	1.32
May—3rd decade	1.17	August—3rd decade	1.40
June—1st decade	1.21	September—1st decade	1.50
June—2nd decade	1.23	September—2nd decade	1.64
June—3rd decade	1.23	September—3rd decade	1.84

3. Results and Discussion

3.1. Weather Conditions of the Growing Season

During the study period, the coolest month was April, with an average temperature of 7.4 °C (1.2 °C lower than the national average) and the hottest was August, with an average temperature of 21.9 °C (3.4 °C higher than the national average). Overall, the average monthly temperatures from May to July 2022 were higher than the national average, while the temperature in September 2022 was lower. June saw the highest temperature amplitude and September the lowest (Table 2). In this period, 63 days of rainfall were noted, with a total rainfall of 258 mm (min. 0.2 mm; max. 19.2 mm; average 4.1 mm; median 2.0 mm). Rainfall values below 5 mm comprised 68% of all noted values. The wettest month was July, with a total rainfall of 79.4 mm (Table 3). The driest month was September (24.6 mm). From May to September 2022, monthly precipitation was lower than the national average (Table 3).

Table 2. Air temperature within the study period (April–September 2022).

Month	Temperature [°C]			
	Minimum	Maximum	Average	Average 1991–2020 *
April	−2.3	21.1	7.4	8.60
May	2.9	27.1	14.2	13.40
June	6.4	33.2	19.9	17.50
July	10.0	34.5	19.7	18.80
August	10.4	32.3	21.9	18.50
September	1.5	21.6	12.2	13.80

* Data for calculation of average from 1991 to 2020 were obtained from national monitoring IMGW_PIB; imgw.pl.

Table 3. Precipitation within the study period (April–September 2022).

Month	Daily Precipitation Minimum/Maximum [mm]	Total Precipitation [mm]	No. Days with Precipitation	Average 1991–2020 *
April	0.2/7.8	41.6	15	36.4
May	0.4/16.0	44.2	12	63.6
June	0.2/10.4	42.6	10	70
July	0.4/19.2	79.4	12	88.1
August	0.2/9.6	25.6	7	66.5
September	0.2/12.2	24.6	8	57.4

* Data for calculation of average from 1991 to 2020 were obtained from national monitoring IMGW_PIB; imgw.pl.

In the analyzed growing season, the highest values of reference and potential evapotranspiration (ETp, Equation (1)) were noted in June and July (Figure 4). The highest value of ETp was recorded on 1 July 2022. This was the hottest day of the research period, with an air temperature of 28.6 °C, radiation of 7095.1 Wm^{-2} and relative humidity of 55.1%.

The lowest value of ETp (37.1 mm) was recorded in April 2022; in May, it was 108.8 mm, in June 151.8 mm, in July 143.6 mm, in August 138.1 mm and in September it was 65.3 mm. The average daily ETp during the summer months was 3.48 mm d^{-1} in May, 5.04 mm d^{-1} in June, 4.67 mm d^{-1} in July and 4.47 mm d^{-1} in August. In the period from April to September 2022, the CWB was negative and amounted to 267.91 mm. The largest monthly water shortages were recorded in June (81.02 mm) and August (75.17 mm) (Figure 4). High evapotranspiration and a negative climatic balance in the summer months meant that there was the need to replenish a large amount of water in the WR.

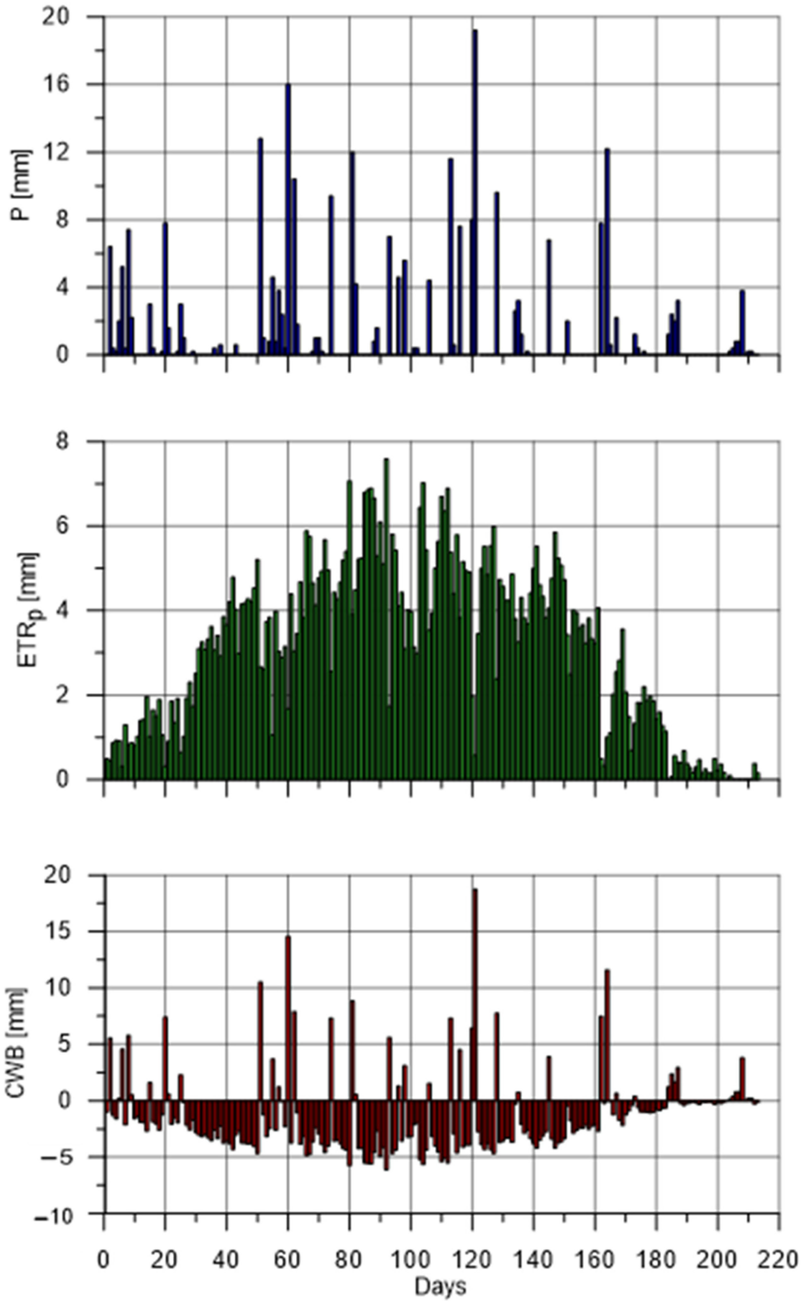

Figure 4. Precipitation (P), potential evapotranspiration (ETp) and climatic water balance (CWB) during the vegetation season, April–September 2022.

According to Zehnsdorf et al. [30], helophytes transpire much more water than the terrestrial plants that are usually used on green roofs. The expected evapotranspiration rate should vary between 3.5 and 3.7 mm per day on an annual basis [31] and can reach values of around 50 mm per day in a hot summer period for the common reed *Phragmites australis* and the common club-rush *Schoenoplectus lacustris* [32]. High evaporation associated with plant transpiration, i.e., evapotranspiration (ET), increases the WR retention capacity between rainfall events [15] and decreases discharge [33,34]. However, during dry periods, it can be associated with large amounts of water being added to the WR to maintain plant health.

3.2. Automatic Water Quality Monitoring

EC is an early indicator of changes in a water system. A significant increase or decrease in EC, whether due to precipitation, evaporation or man-made intervention, can indicate pollution. Water temperature causes conductivity levels to fluctuate daily. Fluctuation can also be due to water level changes and evaporation. The results of EC measurements from the observation period are presented in Figure 5. Daily fluctuations of EC are connected with solar radiation. There is no clear relationship between the EC value and rainfall events. In most cases, the EC value of the wetland water was lowered after rainfall but, in general, each rainfall event appears to be individual. For future analysis of the impact of rainfall on WR water quality, it is necessary to implement rainfall quality measurements into the WR monitoring system. The filling up of the wetland was also reflected by the decrease in EC, which can be clearly seen in August and September (Figure 5). On 6 May, the wetland was refilled with the water stored in the underground tank, which was also reflected by a small decrease in conductivity. Similar EC behavior, triggered by the same activity, occurred in June and July. Each filling was carried out with water from underground tanks, but the administrator of the facility was not able to clearly state whether rainwater collected in the tanks or whether they were already filled with tap water. The results of our monitoring indicate that it is highly probable that the fillings in August and September were carried out via tap water, characterized by lower EC values. The Increase In the daily amplitude of conductivity observed from the middle of May was a result of WR fertilization with ammonium nitrate, using 1.5 kg per m^2 of vegetation. A gap in the data series observed in July was due to a failure of the recorder. The values of EC observed in the monitoring period were in most cases higher than those reported for rainwater [35,36], which may have been a result of the presence of mineral substrate underlying the vegetation and stagnant water conditions. Based on the thus-far automatic EC measurement, it can be stated that EC may be a useful parameter for WR monitoring and, in particular, reflects human interventions such us filling up the wetland (confirmed by records showing water level changes) and fertilization. However, drawing conclusions on the other impacts, e.g., the wet or dry deposition of pollutants and general statements about water quality in the wetland, is rather difficult. Thus, the additional sampling of water for laboratory quality analysis was introduced as a part of a monitoring program from 14 July 2022.

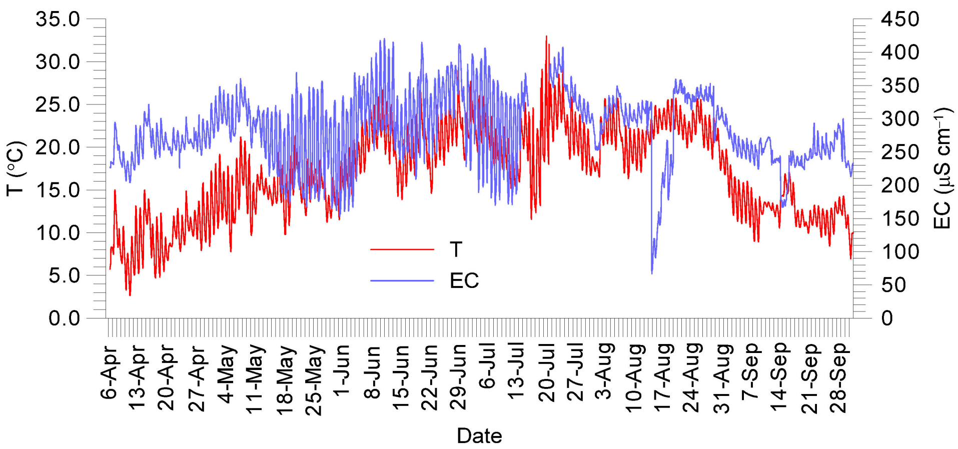

Figure 5. EC and temperature in the WR, April–September 2022.

3.3. Sampled Water Quality Monitoring

The laboratory water quality analyses covered the following parameters: BOD_5, suspended solids, phosphate phosphorus concentration, pH, EC, Eh and color. BOD_5 values did not exceed 6 mg dm^{-3}. In 23% of samples, BOD_5 was not detected and 68% of samples represented values lower than 2 mg dm^{-3}. Observed BOD_5 values were lower than reported for urban rainwater retention reservoirs [37]. Suspended solids values did not exceed 27 mg dm^{-3}, with 85% of samples showing a value lower than 13 mg dm^{-3}. Color varied between 0 and 101 PtCo. Higher color values were noted in July and at the beginning of August. The pH value ranged from 7.28 to 8.24 and EC from 122 to 372 µS cm^{-1} (av. 284 µS cm^{-1}). The typical conductivity range for water in ponds should be between 300 and 1200 µScm^{-1}. In the cases of an EC value lower than 300 µS cm^{-1}, any intervention will result in rapid changes in pH. This was also the case in our wetland when the EC was lowered via water filling. The expected pH range should be between 7.5 and 8.5, which is important to maintain the self-purification mechanisms and friendly conditions for organisms living in the wetland. High pH levels indicate toxic ammonium, while low levels indicate an increase in equally toxic nitrites. The pH can also determine P release from sediments under an oxic condition [38]. The Eh varied between 155 and 306 mV, with lower values connected with the wetland filling up. An Eh value above 200 mV indicates aerobic changes [39]. The values of Eh are usually not interesting in themselves, but they have implications for system behavior [40], as they can indicate transformation reactions of organic pollutants or the occurrence of oxidization or reduction conditions [41]. A moderate correlation was found between pH and phosphate phosphorus concentration (0.66416), pH and Eh (−0.65196), and EC and color (0.73836), at the <0.005 significance level (Table 4). The negative correlation between pH and Eh reflects a dependence between the concentration of hydrogen ions and the Eh; if the pH decreases, the Eh increases. EC, representing the total dissolved solids content, is natural in open waters and affects the color [42].

Table 4. Pearson's correlation coefficients between parameters of water quality in the WR, 14 July–30 September 2022.

	SS	**BOD_5**	**P-PO_4**	**EC**	**pH**	**Eh**	**Color**
SS	1.00000	0.14894	0.23107	0.38730	−0.24847	0.22593	0.30461
BOD_5	0.14894	1.00000	−0.07121	0.11119	−0.44949	0.00662	0.25591
P-PO_4	0.23107	−0.07121	1.00000	−0.03876	**0.66416**	−0.52715	0.12794
EC	0.38730	0.11119	−0.03876	1.00000	−0.22029	0.06229	**0.73836**
pH	−0.24847	−0.44949	**0.66416**	−0.22029	1.00000	**−0.65196**	−0.22260
Eh	0.22593	0.00662	−0.52715	0.06229	**−0.65196**	1.00000	−0.02628
Color	0.30461	0.25591	0.12794	**0.73836**	−0.22260	−0.02628	1.00000

Peak values of phosphate phosphorus were observed between the end of July and the beginning of September 2022 (Figure 6). The maximum P-PO_4 concentration reached 232 µg dm^{-3}. As the decrease in EC suggests, at that time, the wetland was filled up with tap water. This can also explain the detection of phosphorus, which is sometimes added to water supply systems as an anticorrosive agent [43]. Thus, in cases of sensitive water systems, the water used to refill evaporation losses should be tested for phosphorus content. In the case shown in our analysis, the supplied phosphorus was used by the wetland within a month, when its concentration dropped below the detection level (5 µg dm^{-3}).

Apart from the filling water, other sources of phosphorus in WRs can be plant and leaf litter, bird waste and the atmospheric deposition of particles. Sedimentation is often cited as the most important process for the retention of phosphorus in wetlands [44]. Other mechanisms include the adsorption of phosphorus by the substrate [45] and P-uptake by macrophytes [46]. A systematic review of the efficiency of created and restored freshwater wetlands showed that the median removal rate of TP is 1.2 g m^{-2} $year^{-1}$, with a removal efficiency of 46%; both are significantly correlated with the inlet TP concentration, the hydraulic loading rate and the annual average air temperature [44]. Based on our monitoring, it is not possible to state the mechanism of phosphorus removal in the WR. We can only suggest that, based on the main removal processes, it could have been adsorbed by the mineral substrate which underlines the vegetation.

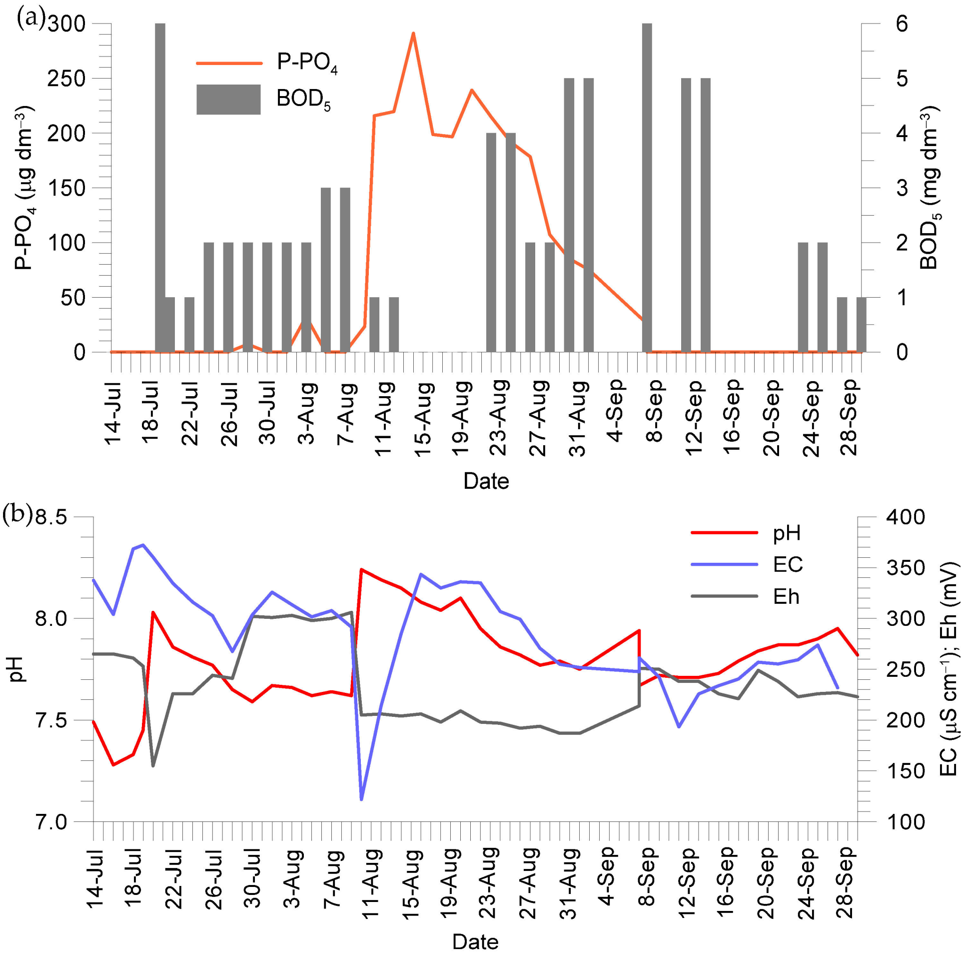

Figure 6. Water quality in the WR, 14 July–30 September 2022: (**a**) $P\text{-}PO_4$ and BOD_5, (**b**) pH, EC and Eh.

3.4. Analysis of the Water Temperature

Temperatures during the 2022 growing season at the bottom of the reservoir did not differ vastly from air temperatures (Figure 7). The average air temperature during the season was 15.95 °C, and the average water temperature in the reservoir was 16.28 °C. In the spring period (April–May), the average air and water temperatures were 10.82 °C and 11.95 °C, respectively. In the summer period (June–August), the distribution of mean air temperatures was similar to that of water; the mean water temperature was 20.30 °C, and the mean air temperature was 20.58 °C. In September, the air temperature (12.36 °C) was slightly higher than the water temperature (12.22 °C). It should be noted that, during days with a temperature above 20 °C, the average daily water temperature was lower than the air temperature.

The data from individual months show that, in April, the mean water temperature (9.17 °C, SD = 3.24 °C) was higher than the air temperature (7.36 °C, SD = 2.04 °C) by 1.81 °C (Figure 8). In May, the mean air and water temperatures were similar (14.2 °C). In July, the mean water temperature was 0.3 °C higher than the air temperature, while the standard deviation was lower in water than in air (SD = 2.5 °C and SD = 3.4 °C, respectively). In June, August and September, the mean water temperature was lower than the air temperature, but the differences were no greater than 0.5 °C (Figure 8).

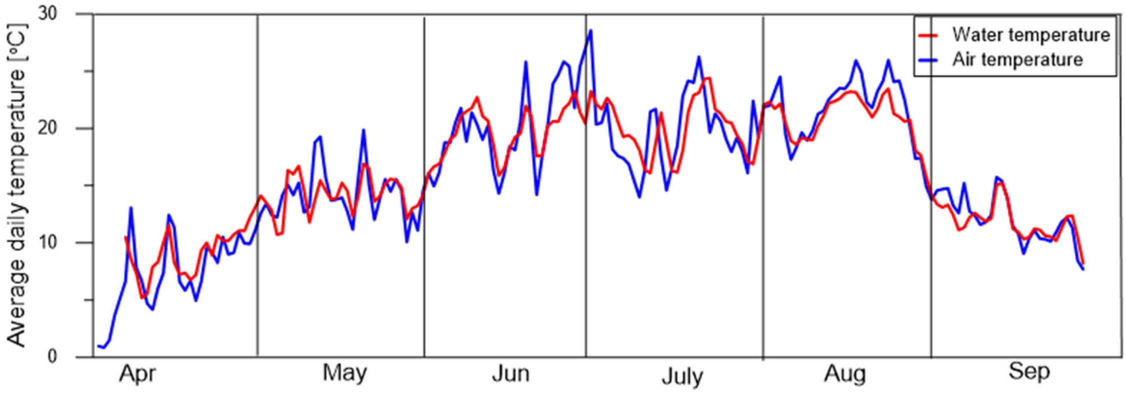

Figure 7. Daily variability of air and WR water temperature, April–September 2022.

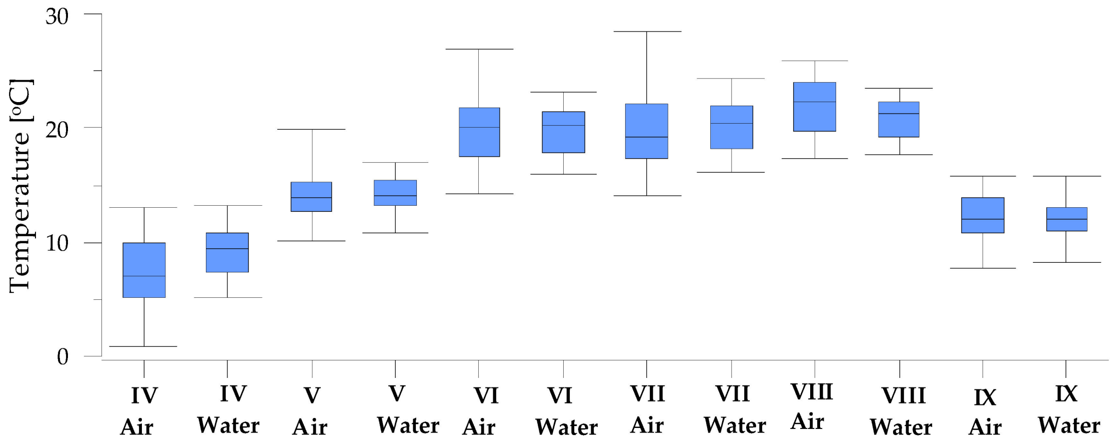

Figure 8. Monthly temperatures of air and water in the WR, April–September 2022.

According to Song et al. [14], WRs provide more stable rooftop temperatures than ambient rooftop air because of the high heat release and insulation capability of water. WRs reduce the daily heat exchange between a building and its surroundings by 43% and 93%, compared to a xeric roof system and a bare roof, respectively [47,48].

These results allowed for a thorough analysis of daily temperature changes in spring and summer, and also on winter days, which are outside the observation period reported in this study. On an example spring day (11 April 2022), at night and in the morning, the air temperature was lower than the water temperature by approximately 2 °C, while in the afternoon, the temperatures were similar (Figure 9a). On the hottest day during the measurement period (1 July), the air temperature increased with the increase in active radiation (the average daily temperature was 28.5 °C), while the water temperature was 5.2 °C lower than the air temperature (Figure 9b). These results indicate that the vegetation and the water bodies were both contributing to cooling and humidifying (Figure 9b). However, on a winter day (22 December 2022; outside the study period), the average temperature difference between the air and water in the reservoir was 2.5 °C (Figure 9c). A greater variation in temperature was recorded for the air temperature (SD = 2.6 °C) than for the water temperature (SD = 0.17 °C). When the air temperature dropped below −5 °C, the water temperature was 0.3–1.5 °C.

This study has some potential limitations. First, prior research relevant to WRs is limited. Thus, during the review of the literature, we needed to draw on additional literature bordering on the topic. This knowledge gap, reinforced by the specific construction and feed type of the analyzed WR, indicates the need for further development in this area of study. Second, during the analysis of collected water quality data, we realized that we were not able to clarify the background or mechanisms of some observations. Therefore, there is a need to use a broader range of tested parameters in future research. Third, for correct conclusions about cause-and-effect relationships, better communication between researchers and the WR operator is necessary. This will likely improve after the owner of the facility takes control of maintenance activities after the end of the warranty period, during which time maintenance activities are carried out by the investment contractor. Fourth, the observations herein covered one growing season, which may not be representative. Nevertheless, this research contributes to the gap in current knowledge and may generate further interest in the topic among researchers and decision-makers.

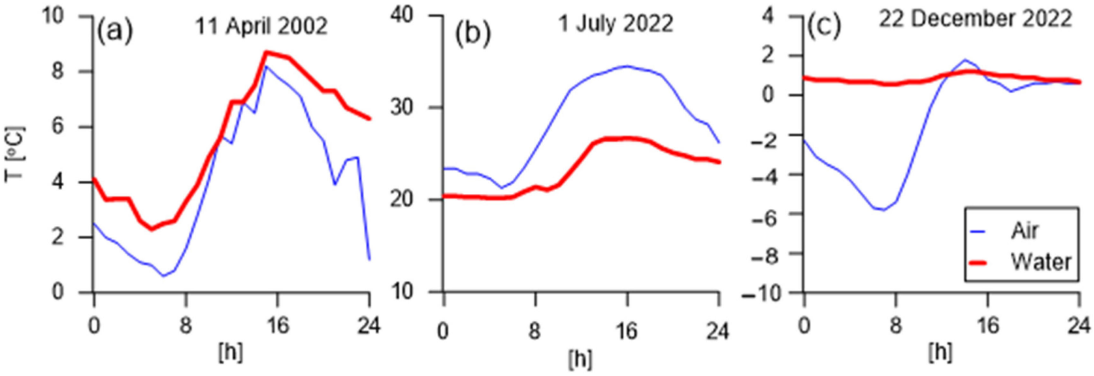

Figure 9. Daily temperature variability on (**a**) a spring day, 11 April 2022, (**b**) a summer day, 1 July 2022 and (**c**) a winter day, 22 December 2022.

4. Conclusions

The aim of this study was to analyze the performance of rainwater management on a WR, with a focus on water sufficiency and water quality. During the vegetation period of 2022, a precipitation deficit of 395.45 mm was observed. The CWB was negative and amounted to 286.10 mm. The WR monitored in this study filled up a few times during the vegetation season, indicated by data about the water level and changes in EC. Our limited access to operational data (we had no data on the amount of tap water used for filling the tank) means that we can only suggest, based on EC monitoring, that the amount of rainwater retained in the underground tank was insufficient for the independent functioning of the system.

The quality of the water in the WR is extremely important from the point of view of aesthetics, habitat conditions and ease of maintenance of the rainwater management system. Continuous EC monitoring indicates basic changes in water condition in the wetland; however, without the support of the continuous measurement of other indicators, it is impossible to clarify the underlying mechanisms of those changes. Additional continuous pH and Eh monitoring and collection of wetland and rainwater water samples for laboratory analysis are recommended.

The existing monitoring allowed the preliminary determination of the role of water on the roof in terms of shaping the building's thermal conditions. Research in this field should focus on air and water temperature measurements, as well as temperature inside the building under roofs with different uses (e.g., wetland, extensive green and gravel roofs). WRs are a multi-beneficial solution with the implementation potential to mitigate the effects of climate change. Our study advances the knowledge in the field of rainwater management in WRs to support the replications of WRs in other locations. The results of monitoring water quantity, quality and thermal aspects can be directly used by WR operators for the optimization of rainwater management.

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