Article

The Efficiency and Reliability of Pollutant Removal in a Hybrid Constructed Wetland with Common Reed, Manna Grass, and Virginia Mallow

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Abstract: In this paper, the pollutant removal efficiency and the reliability of a vertical and horizontal flow hybrid constructed wetland (CW) planted with common reed, manna grass, and Virginia mallow were analyzed. The wastewater treatment plant, located in south-eastern Poland, treated domestic sewage at an average flow rate of 2.5 m$^3$/d. The tests were carried out during five years of its operation (2014–2018). The following parameters were measured: biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), total suspended solids, total nitrogen, and total phosphorus. The results showed that more than 95% of BOD$_5$, COD, and total phosphorus was removed in the tested CW system. The average effectiveness of removal of total suspended solids and total nitrogen exceeded 86%. A reliability analysis performed using the Weibull probability model showed that the removal reliability in the tested CW was very high for BOD$_5$, COD, total suspended solids, and total phosphorus (100%). The probability that the total nitrogen concentration in the treated effluents would reach the limit value (30 mg/L) established for effluents discharged from a treatment plant of less than 2000 PE (population equivalent) to standing waters was 94%. The values of all the pollution indicators in wastewater discharged to the receiver were significantly lower than the limit values required in Poland. The investigated hybrid CW system with common reed, manna grass, and Virginia mallow guaranteed stable low values of BOD$_5$, COD, total suspended solids, and total phosphorus in the treated wastewater, which meant it was highly likely to be positively evaluated in case of an inspection.

Keywords: efficiency; horizontal flow; hybrid constructed wetlands; pollution removal; reliability; vertical flow; wastewater treatment

1. Introduction

An important indicator of the civilizational development of a society is the state of the sanitary infrastructure [1,2]. Sewage treatment plants are becoming a common feature in rural areas, especially those where the construction of a traditional sewerage network is not economically or technically viable [1,3,4]. According to the latest data, there are around 217,000 domestic wastewater treatment plants in Poland and the number is still growing [5]. Among the solutions applied in household wastewater treatment plants, the most commonly used ones are drainage systems and systems using conventional methods of wastewater treatment—biological beds, activated sludge chambers, and facilities with a hybrid reactor [2]. However, due to the huge variability of hydraulic loads, pollution loads, and operating conditions, they do not guarantee high pollutant removal
efficiencies [6–8]. An alternative to these solutions is constructed wetlands (CWs), which are characterized by simple operation, low operating costs, and resistance to changes in technological conditions [9–14]. These systems, mainly comprising vegetation, substrates, soils, microorganisms, and water, utilize complex physical, chemical, and biological processes to remove various contaminants or improve water quality [9,15–17]. Constructed wetlands for wastewater treatment are classified into two types: free water surface (FWS) CWs and subsurface flow (SSF) CWs [9,16]. FWS systems are similar to natural wetlands, with shallow flow of wastewater over saturated substrate. In SSF systems, wastewater flows horizontally or vertically through the substrate which supports the growth of plants. Depending on the direction of the flow, SSF CWs are divided into vertical flow (VF) and horizontal flow (HF). Another type of structure is hybrid CWs, which consist of various combinations of two soil and plant beds (VF-HF CWs, HF-VF CWs, HF-FWS CWs, and FWS-HF CWs). There are also multi-stage CWs, which comprise more than three stages [9,18,19].

The most important element of any CW is the substrate, which not only provides a suitable medium for plants and microorganisms, but also enables proper sewage flow [9,18]. Moreover, substrate sorption may play a key role in the absorption of various pollutants, above all phosphorus [20]. A second important element, which should be taken into account when designing a CW, is the type of plant species to be used. More than 150 species of macrophytes were already applied in CWs, but only a small number of them are used on a large scale [9,21]. Selection of the plants for CWs should, therefore, be the focus of current research on the sustainable design of CWs [15]. Species growing in CWs should be tolerant of waterlogged anoxic and hyper-eutrophic conditions and capable of absorbing pollutants, in addition to being able to adapt to extreme climates [9].

The aim of the present work was to analyze the reliability and efficiency of pollutant removal (total suspended solids (TSS), biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD), total nitrogen, and total phosphorus) in a hybrid (two-stage) constructed wetland wastewater treatment plant with common reed, manna grass, and Virginia mallow.

2. Material and Methods

2.1. Characteristics of the Experimental Facility

The analyzed facility is located in Popkowice, Poland (50°99'81" N, 22°21'39" E) and has been operating since 2014. The treatment plant was designed at the request of the Urzędów Commune by the R-G Project company from Lublin in cooperation with the employees of the Department of Environmental Engineering and Geodesy of the University of Life Sciences in Lublin. The construction activities were carried out by the Municipal Services Office in Urzędów, which is also responsible for supervising the operation of the sewage treatment plant. The facility was designed to treat domestic sewage from a multi-functional building, a health center, two trading posts, and one household. The projected capacity of the treatment plant is 2.5 m$^3$/d, and its PE (population equivalent), determined on the basis of the BOD$_5$ load, is 21.

In the analyzed system, sewage flowing in from the serviced buildings is firstly treated mechanically in a three-chamber preliminary settling tank with an active capacity of 8.64 m$^3$. In the next stage, the sewage is separated into two streams and pressurized by a submersible pump into two vertical flow (VF) beds—IA and IB (Figures 1 and 2). The beds have a depth of 0.8 m and a surface area of 30 m$^2$ each. From the VF beds, sewage flows gravitationally into a horizontal flow (HF) bed with an area of 110 m$^2$ and a depth of 1.2 m [22]. At the outflow from the HF bed, a tilting pipe was installed, which allows the level of sewage in this bed to be raised during the summer (Figure 2).

To protect ground water from contamination, a 1-mm high-density polyethylene (HDPE) foil lining was used to seal the beds. The VF beds were filled with a layer of sand (1–2 mm) to a height of about 0.8 m and planted with common reed (Phragmites australis (Cav.) Trin. ex Steud) (VF-IA) and manna grass (Glyceria maxima (Hartm.) Holmb.) (VF-IB). The HF-type bed was filled to a height of 1.0 m with sand (1–2 mm), and covered with a 0.2-m-thick humus layer, which was obtained from
excavations during the construction of a wastewater treatment plant. The HF bed was planted with Virginia mallow (Sida hermaphrodita (L.) Rusby) [22].

At the time of the study, the average inflow of sewage fell within the projected range of values, although it should be noted that it was highly uneven over short periods of time, which resulted directly from the nature of the facilities serviced by the treatment plant. The VF beds received sewage periodically, after the subsurface pump was switched on in the pumping station (Figure 2). During the research period, each of the VF beds was fed four times a day with a single dose of sewage of about 0.3 m$^3$. The amount of mechanically treated sewage flowing into the VF-HF system was measured. The measurements were made using a flow meter installed in the discharge pipe between the preliminary settling tank and the vertical flow beds (VF-IA and VF-IB). Measurements on the gravity ducts (at the outflow from the VF and HF beds) were not carried out. The hydraulic load of the VF beds was approximately 0.042 m$^3$/m$^2$/d. The wastewater hydraulic retention time (HRT) for a fixed flow for VF beds was about 3 d. Thanks to the use of the tilting pipe downstream of the HF bed, the wastewater retention time in this bed was about 35.2 d in the summer and 17.6 d in the winter. Every year, above-ground parts of plants were removed from the beds after the winter period.

![Figure 1](image1.png)

**Figure 1.** Technological scheme of the tested vertical flow/horizontal flow (VF-HF) constructed wetland (CW) [22]. S1, S2, S3, and S4 are sampling points.

![Figure 2](image2.png)

**Figure 2.** Longitudinal profile of the tested VF-HF CW [22].

During the operation of the facility, no major operational problems or disturbances in sewage flow were observed. One problem that should be mentioned was a considerable weed infestation of the beds (mainly HF beds), which inhibited proper development of the target plants.

The receiver of purified sewage was the Urzędówka river, to which sewage was discharged by a 115-m-long drainage ditch [22].

### 2.2. Analytical Methods

The efficiency and reliability of pollutant removal in the wastewater treatment plant were assessed on the basis of the results of sewage tests conducted in the years 2014–2018. Sewage samples for analyses were taken seasonally in February, May, August, and November, at four points: S1—mechanically treated sewage from the pumping station, S2—sewage flowing out of the VF bed with common reed (VF-IA), S3—sewage flowing out of the VF bed with manna grass (VF-IB), S4—sewage flowing out of the HF bed with Virginia mallow (Figure 1). The frequency of wastewater sampling for the research resulted from the Polish regulations [23]. According to Polish law, in the case of small wastewater treatment plants (below 2000 PE), it is recommended to take four wastewater samples a year. Sampling and testing of sewage samples were performed beyond the periods of intense rainfall and spring thaw, which could significantly influence the obtained results. Sampling and transport of the samples were carried out in accordance with Polish standards PN-74/C-04620/00 [24] and PN-EN
The samples were used to determine dissolved oxygen, ammonium, nitrate and nitrite, total nitrogen, total phosphorus, total suspended solids content (TSS), and the levels of biochemical oxygen demand (BOD₅) and chemical oxygen demand (COD). The concentration of dissolved oxygen was determined using a Multi 340i meter (WTW, Weilheim, Germany). Nitrate and nitrite were determined using a LF 300 photometer (Slandi sp. z o.o., Michałowice, Poland), and ammonium nitrogen was measured using an PC Spectro spectrophotometer (AQUALYTIC, Dortmund, Germany). Total nitrogen was determined using the spectrophotometric method with the AQUALYTIC PC Spectro spectrophotometer, after oxidation of the samples at 100 °C for 1 h. Total phosphorus was determined using the photometric method with a WTW MPM 2010 photometer after oxidation of the samples at 120 °C for 0.5 h. BOD₅ was measured using the dilution method after vaccination with allylthiourea, based on the concentration of dissolved oxygen measured immediately after taking the samples and after five days of incubation. COD was determined using the photometric method with test-tube tests. COD measurements were taken using the WTW MPM 2010 photometer after oxidation of the samples at 148 °C for 2 h. TSS was determined using the gravimetric method with the use of paper filters with a basis weight of 84 g/m² and typical retention of 8–12 µm. Analyses were carried out in accordance with Polish standards [26–30].

In addition, the productivity of the plants from the beds was determined. Plant material for research was collected annually (starting from 2015) at the end of winter, in February or March. Samples of plants were collected by hand in three repetitions from plots with an area of 1 m² each. In the plant samples, the dry matter content was determined using the gravimetric method, after drying at 105 °C [31].

2.3. Meteorological Conditions

Meteorological conditions were characterized on the basis of monthly average temperatures and monthly precipitation values for the Radawiec station, located 26 km from Popkowice (Figure 3). The distribution of monthly average temperatures and monthly precipitation values in the individual years of the study was highly diversified. In the summer periods, high air temperatures and low total precipitation were observed, which potentially had a negative impact on the development of vegetation in the beds.

Figure 3. The average monthly temperatures (top) and monthly rainfall (bottom) for Radawiec near Lublin in the years 2014–2018 [32].
2.4. Statistical Analysis

On the basis of the results of the measurements, characteristic values of the selected pollution indicators in wastewater from different treatment stages were determined, including average, minimum, and maximum values, medians, standard deviations, and coefficients of variation. The average values of contamination indicators in sewage flowing into \((C_{in})\) and out of the beds \((C_{out})\) were used to calculate the average efficiency of removal of pollutants (BOD\(_5\), COD, TSS, total nitrogen, and total phosphorus) according to the following formula:

\[
\eta (\%) = 100 \left(1 - \frac{C_{out}}{C_{in}} \right) .
\]  (1)

Pollutant removal reliability values were assessed for the basic indicators of pollution (BOD\(_5\), COD, TSS, total nitrogen, and total phosphorus) using elements of Weibull’s reliability theory. The Weibull distribution is a useful, general probability distribution, applicable in reliability tests and in assessment of the risk of exceeding the permissible values of pollution indicators in treated wastewater [8,33–35]. It is characterized by the following probability density function:

\[
f (x) = \frac{c}{b} \left( \frac{x - \theta}{b} \right)^{c-1} e^{-\left( \frac{x - \theta}{b} \right)^c},
\]  (2)

where \(x\) is a variable describing the concentration of a pollution parameter in treated sewage, \(b\) is a scale parameter, \(c\) is a shape parameter, and \(\theta\) is a position parameter, assuming that \(\theta < x, b > 0, \) and \(c > 0.\)

The reliability analysis was carried out separately for each indicator, taking into account their values in treated wastewater discharged into the receiver \((n = 16)\). The analysis consisted of the estimation of the Weibull distribution parameters using the maximum-likelihood method and the verification of the null hypothesis that the analyzed variable could be described by the Weibull distribution. According to Dodson’s recommendations [36], for the number of samples exceeding 15, the null hypothesis was verified with the Hollander-Proshcan test at the significance level of 0.05.

Reliability was determined from the cumulative distribution function plotted in the graphs, taking into account the normative values of the indicators specified in the Regulation of the Ministry of Environment [23] for wastewater discharged from treatment plants of up to 2000 PE: BOD\(_5\)—40 mg O\(_2\)/L, COD—150 mg O\(_2\)/L, TSS—50 mg/L, total nitrogen—30 mg/L, and total phosphorus—5 mg/L. In the case of nitrogen and total phosphorus, the values defined for wastewater discharged into lakes and their tributaries, as well as directly into artificial water reservoirs located in flowing waters, were adopted as standard values [23]. The analysis was carried out using the Statistica 13 software (StatSoft Inc., Tulsa, OK, USA).

3. Results and Discussion

3.1. Composition of Treated Wastewater and the Efficiency of Pollutant Removal

In order to evaluate the effectiveness and reliability of the analyzed treatment plant, we used the results of tests of sewage samples collected from different treatment stages. Characteristic values of the analyzed parameters are given in Table 1.

The concentrations of organic pollutant, expressed as BOD\(_5\) and COD, and the concentrations of TSS, as well as total nitrogen and total phosphorus, in mechanically treated wastewater were close to the average values reported in the literature [37–39]. The mean concentration of the analyzed pollutants were 284 mg/L for BOD\(_5\), 588 mg/L for COD, 143 mg/L for TSS, 84.9 mg/L for total nitrogen (TN), and 13.6 mg/L for total phosphorus (TP) (Table 1). The content of ammonium nitrogen in sewage flowing out of the pumping station to the constructed wetland system was at an average level of 76 mg/L; the remaining forms of nitrogen were found in trace amounts: nitrate—0.99 mg/L,
and nitrite—0.11 mg/L. The values of standard deviations and coefficients of variation, as well as the proportions of minimum and maximum values, indicate a substantial variation in the results within the individual groups (indicators). The diversity of pollutant loads in wastewater may be related to the conditions of mechanical treatment in the settling tank and the specificity of the facilities served by the treatment plant. In particular, one venue’s activity was associated with the occasional organization of large receptions. This facility periodically discharged large quantities of sewage with high concentrations of pollutants at longer time intervals.

Table 1. Basic statistics for the indicator values in the treated wastewater (n = 16). $C_v$—coefficient of variation; $\text{BOD}_5$—biochemical oxygen demand; COD—chemical oxygen demand; TSS—total suspended solids; TN—total nitrogen; TP—total phosphorus.

| Parameters                  | Statistics Indicators |
|-----------------------------|-----------------------|
|                             | Average  | Median | Min  | Max  | SD    | $C_v$  |
| Dissolved oxygen (mg O$_2$/L) | S1       | 1.05   | 0.83 | 0.09 | 4.28  | 1.01  | 96.09 |
|                             | S2       | 4.69   | 4.93 | 1.32 | 7.16  | 1.86  | 39.68 |
|                             | S3       | 5.10   | 4.95 | 0.81 | 9.94  | 2.57  | 50.41 |
|                             | S4       | 5.42   | 5.17 | 2.45 | 9.94  | 1.83  | 33.84 |
| $\text{BOD}_5$ (mg O$_2$/L) | S1       | 284.0  | 283.3| 52.0 | 637.0 | 157.60| 55.49 |
|                             | S2       | 18.2   | 6.4  | 1.4  | 55.2  | 19.27 | 105.79 |
|                             | S3       | 10.2   | 5.2  | 0.2  | 45.0  | 11.57 | 113.14|
|                             | S4       | 2.9    | 2.4  | 0.2  | 8.0   | 2.29  | 78.79 |
| COD (mg O$_2$/L)            | S1       | 588.4  | 550.0| 210.0| 1366.0| 290.33| 49.34 |
|                             | S2       | 35.5   | 28.5 | 9.0  | 97.0  | 25.18 | 70.92 |
|                             | S3       | 32.8   | 20.0 | 4.0  | 160.0 | 39.06 | 119.04|
|                             | S4       | 11.8   | 11.5 | 1.0  | 26.0  | 7.97  | 67.45 |
| TSS (mg/L)                  | S1       | 143.4  | 116.7| 20.0 | 528.0 | 126.20| 88.00 |
|                             | S2       | 40.9   | 32.2 | 9.1  | 188.0 | 41.34 | 101.06|
|                             | S3       | 22.4   | 19.1 | 6.4  | 89.3  | 19.15 | 85.36 |
|                             | S4       | 11.3   | 10.3 | 3.7  | 46.7  | 10.04 | 88.80 |
| TN (mg/L)                   | S1       | 84.9   | 83.0 | 38.0 | 135.0 | 29.83 | 35.15 |
|                             | S2       | 52.9   | 48.0 | 16.0 | 108.0 | 25.19 | 47.64 |
|                             | S3       | 39.9   | 45.0 | 8.5  | 76.0  | 19.15 | 52.20 |
|                             | S4       | 11.5   | 8.3  | 0.9  | 28.0  | 9.36  | 81.72 |
| Ammonium nitrogen (mg/L)    | S1       | 76.0   | 72.5 | 29.0 | 118.0 | 29.04 | 38.21 |
|                             | S2       | 6.45   | 4.58 | 0.22 | 22.20 | 6.81  | 105.63 |
|                             | S3       | 6.96   | 5.40 | 0.21 | 21.80 | 6.76  | 97.11 |
|                             | S4       | 2.79   | 1.07 | 0.03 | 12.10 | 3.61  | 129.50|
| Nitrate nitrogen (mg/L)     | S1       | 0.99   | 0.32 | 0.03 | 11.05 | 2.69  | 271.18|
|                             | S2       | 18.55  | 15.76| 0.197| 46.83 | 16.48 | 88.81 |
|                             | S3       | 12.09  | 7.94 | 0.01 | 33.88 | 11.00 | 91.03 |
|                             | S4       | 1.84   | 1.14 | 0.06 | 9.75  | 2.48  | 134.87|
| Nitrite nitrogen (mg/L)     | S1       | 0.11   | 0.09 | 0.02 | 0.27  | 0.08  | 72.29 |
|                             | S2       | 0.29   | 0.15 | 0.01 | 1.22  | 0.34  | 117.49|
|                             | S3       | 0.18   | 0.13 | 0.01 | 0.93  | 0.24  | 131.08|
|                             | S4       | 0.18   | 0.03 | 0.01 | 1.91  | 0.47  | 265.16|
| TP (mg/L)                   | S1       | 13.6   | 12.5 | 4.7  | 38.0  | 7.40  | 54.33 |
|                             | S2       | 5.30   | 5.33 | 0.63 | 10.20 | 2.72  | 51.20 |
|                             | S3       | 4.33   | 4.44 | 0.40 | 11.40 | 2.50  | 57.79 |
|                             | S4       | 0.53   | 0.29 | 0.06 | 2.90  | 0.71  | 134.72|

Note: S1—inflow to vertical flow (VF) IA and IB beds; S2—outflow from VF-IA bed; S3—outflow from VF-IB bed; S4—outflow from horizontal flow (HF) bed.
The ratio between average COD and BOD$_5$ values in raw sewage was 2.1, which was relatively high in comparison to that recommended for raw sewage in the literature [40]. This finding indicates that the wastewater flowing into the investigated CW system contained a low proportion of decomposable organic matter and was not very susceptible to biochemical degradation. Unfavorable values were also found for BOD$_5$:TN and BOD$_5$:TP ratios, which were 3.3 and 20.9, respectively (Table 2), which may have had a significant impact on the supply of carbon compounds and the course of the processes of nitrogen and phosphorus removal at the stage of biological treatment.

| Relationship | Recommended Value [40] | Values in the Analyzed Object |
|--------------|------------------------|------------------------------|
| COD:BOD$_5$  | $\leq 2.2$             | 2.1                          |
| BOD$_5$:TN   | $\geq 4.0$             | 3.3                          |
| BOD$_5$:TP   | $\geq 25$              | 20.9                         |

The average BOD$_5$ value in sewage discharged from the VF-IA bed was 18.2 mg O$_2$/L, while the COD value was 35.5 mg O$_2$/L, and the average concentration of total suspended solids was 40.9 mg/L. The average levels of the analyzed indicators at this stage of purification were lower than the limit values set out in the Regulation of the Ministry of Environment for sewage treatment plants with a PE below 2000 [23]; however, it should be pointed out that the variability of these concentrations in this particular series of tests was substantial. The concentration of total nitrogen during purification in the bed with common reed decreased, on average, by 32.0 mg/L to the level of 52.9 mg/L. The average content of ammonium nitrogen, which predominated the sewage flowing into the bed from the preliminary settling tank, decreased to 6.45 mg/L, while the concentration of nitrate increased. The average concentration of total phosphorus downstream of the VF-IA bed was 5.30 mg/L.

After treatment in the bed with manna grass, the average BOD$_5$ and COD values for the effluent were 10.2 mg/L and 32.8 mg/L, respectively. They were lower than the corresponding values found in the bed with common reed. The content of total suspended solids reached an average value of 22.4 mg/L at this treatment stage. The concentrations of nitrogen and phosphorus compounds at the outflow from the VF-IB bed were also lower than those recorded at the same stage in the VF-IA bed. The concentration of total phosphorus was on average 4.33 mg/L, and that of total nitrogen was 39.9 mg/L. The concentration of nitrate was reduced, while the content of ammonium was similar. Sewage flowing out of the HF bed was characterized by a low content of organic contaminants. The mean values of BOD$_5$, COD, and TSS were 2.9 mg/L, 11.8 mg/L, and 11.3 mg/L, respectively (Table 1), which are clearly below the normative values set for these indicators in the Regulation of the Ministry of Environment [23]. The average concentration of total nitrogen at the outflow from the HF bed was 11.5 mg/L, and that of total phosphorus was 0.53 mg/L (Table 1). The concentration of pollutants in the effluent discharged from the HF bed was much more diversified than that in sewage flowing out of the preliminary settling tank and from VF beds. With the low concentration of pollutants in the sewage at this stage of treatment, environmental factors, such as precipitation, air temperature, and processes of plant material degradation, may have had a much higher impact on the results.

The effectiveness of the entire VF-HF system in terms of organic pollutants removal was 99% for BOD$_5$, 98% for COD, and 92.1% for TSS (Table 3). These results are comparable to or higher than those recorded for other hybrid CWs operating in similar climate conditions [13,14,41]. In the studied system, the majority of the organic pollutants discharged from the preliminary settling tank were removed at the first purification stage in VF beds, which is consistent with the results of other authors [12,42–45]. The average rates of BOD$_5$ reduction in the VF-IA and VF-IB beds were 93.6% and 96.4%, respectively. Obarska-Pempkowiak et al. [42], Gajewska et al. [45], and Vymazal [43] reported efficiencies of up to 98% for VF beds. Organic contaminants, expressed as COD, were removed with almost identical efficiencies in both VF beds, on average about 94% (Table 3). This is a high efficiency against the background of results reported in the literature, which indicate maximum efficiencies in the range of...
87–94% [12,13,44,46]. Organic pollution loads were further reduced in the HF bed. The average rate of BOD$_5$ reduction was still high at nearly 88%, whereas COD removal efficiency was clearly lower at about 50%.

Table 3. The efficiency of pollutant removal in the investigated system ($n = 16$).

| Parameters | Efficiency (%) |
|------------|----------------|
|            | VF-IA | VF-IB | HF   | VF-HF |
| BOD$_5$    | 93.6  | 96.4  | 87.9 | 99.0  |
| COD        | 94.0  | 94.4  | 50.4 | 98.0  |
| TSS        | 71.5  | 84.4  | 62.2 | 92.1  |
| TN         | 37.7  | 53.0  | 73.0 | 86.5  |
| TP         | 61.0  | 68.2  | 86.9 | 96.1  |

There was no significant seasonal variation in TSS removal. Regardless of the time of year, the average efficiency of TSS elimination was quite stable across all stages of the treatment process (Figure 4). A similar observation was made with reference to BOD$_5$. Organic pollutants, expressed as COD, were most effectively removed in VF beds, regardless of the season of the year. Seasonal differences were found in the HF bed, where the highest removal efficiencies were obtained in February and May, and the lowest in November (Figure 4). With a long HRT, a slow decomposition of organic solids accumulated may occur in the filling spaces, including plant roots. Headley et al. [47] suggested a similar possibility in their research.

The present results show that the tested system provided favorable conditions for the mineralization of organic compounds, including adequate oxygen availability, which is a key factor in this process [16,48]. This could have been influenced by the periodic supply of VF beds with large amounts of wastewater. Gervin and Brix [49] and Jia et al. [50] showed that such a method of feeding a treatment plant allows sewage to be oxygenated before it is introduced to the biological purification stage, and increases the diffusion of atmospheric oxygen to the beds due to the occurrence of alternating wet and dry periods. In addition, effective removal of organic contaminants, especially in VF beds, can be associated with the activity of the plants used. Common reed and manna grass have the ability to effectively transport oxygen to the roots, thereby determining the development of various groups of microorganisms in the rhizosphere [51–53]. The present results show that manna grass has better properties in this case, and the treated sewage flowing out of the VF-IB bed was characterized by a higher oxygen content (Table 1). Furthermore, in this bed, the efficiency of organic contaminants removal was slightly higher than in the VF-IA bed (Table 3). In the bed with Virginia mallow, in spite of the horizontal flow of sewage, the dissolved oxygen content, as well as the effectiveness of organic pollutants removal, especially expressed as BOD$_5$, remained high (Table 3). In the light of the research carried out by Klimont and Bulińska-Radomska [54], this effect may be associated with the forming of a well-developed root system by Virginia mallow, and thus, the formation of a crumbly ground structure that facilitates oxygen penetration into deeper layers of the bed and the sewage saturation zone.

![Figure 4. Cont.](image-url)
The factors described above also determine the removal of nitrogen and phosphorus compounds. In this case, in addition to good sewage aeration, it is essential to have underoxidized zones, providing reduction conditions and availability of organic carbon sources that are necessary for microbiological reactions [16,55].

The average efficiency of the analyzed facility, when it comes to total nitrogen removal, was 86.5%, with less than 50% of the load carried from the preliminary removal process.

Figure 4. Average removal efficiency of pollutants in different months of the research. II—February; V—May; VIII—August; XI—November.
The factors described above also determine the removal of nitrogen and phosphorus compounds. In this case, in addition to good sewage aeration, it is essential to have underoxidized zones, providing reduction conditions and availability of organic carbon sources that are necessary for microbiological reactions [16,55]. The average efficiency of the analyzed facility, when it comes to total nitrogen removal, was 86.5%, with less than 50% of the load carried from the preliminary settling tank being removed in the VF beds. During purification in the HF bed, the average concentration of total nitrogen in the sewage decreased by 73% (Table 3). The facility provided good conditions for oxidation and sorption of ammonium nitrogen, the content of which decreased, on average, by more than 96%. Purification in VF type beds was of utmost importance for the elimination of this form of nitrogen as its concentration in the effluent from these beds decreased, on average, by more than 90% compared to the initial value. At the same time, low concentrations of total nitrogen and its aerobic forms at the outflow from the sewage treatment plant indicated that heterotrophic reduction of nitrates had a smooth course. The factor stimulating this process was the high supply of organic compounds [56,57]; however, Zhao et al. [58] pointed out that there were exceptions to this rule. This led to the conclusion that the BOD₅:N ratios allowing optimal denitrification coefficients are, to a large extent, dependent on the individual features of the constructed wetland system, including the configuration of the beds, the plant species used, the accumulation and decay of plant material in the bed or the type of sewage, and the structure of the nitrogen compounds [16]. When it comes to the analyzed treatment plant, no clear relationship was found between the BOD₅:N ratios at the inflow to the VF-HF system in the individual measurement series, and the corresponding effectiveness of total nitrogen removal from sewage and its concentration at the outflow.

It was observed that the efficiency of nitrogen removal in the particular components of the analyzed system, especially in the HF-type beds, was slightly higher in the autumn–winter period (February and November) than in the spring–summer period (May and August) (Figure 4). This contradicts the conclusion drawn in numerous studies that the efficiency of removal of nitrogen compounds increased at higher temperatures [16,58]. Bulc [59] found a clear lack of difference in nitrogen removal during the summer and winter periods, which was connected, among others, with the dominance of physical processes over microbiological removal. One of them is the sorption of ammonium nitrogen by media components. Adsorbed ammonium nitrogen can be nitrified by the attached biofilms [16].

Literature reports indicate that a large role in the removal of nitrogen and phosphorus compounds from sewage is played by the plants growing in beds [6,16,60,61]. According to Jucherski and Walczowski [53], common reed and manna grass applied in VF beds are characterized by good evapotranspiration parameters and have the ability to accumulate nitrogen and phosphorus from wastewater, which promotes the growth of plant biomass. Results obtained by other authors and our own observations do not seem to confirm this theory. In the case of common reed, the average dry matter (DM) productivity in 2015 was 0.49 kg DM/m², and increased each year to reach 0.67 kg DM/m² in 2017 (Figure 5). In the case of manna grass, the tendency was reversed: the highest average productivity of dry matter was noted in 2015 as 0.39 kg DM/m², and the lowest in 2017 as 0.21 kg DM/m². In both cases, these values were relatively low and indicated a rather poor biological condition of the plants used, which could have partly resulted from unfavorable weather conditions. Staniszewski et al. [62] and Wesołowski and Brysiewicz [63] also found that manna grass was characterized by a lower nitrogen accumulation capacity; thus, it is difficult to explain the higher rate of removal of this element in the VF-IB bed in terms of plant activity. An even lower productivity was found in the case of Virginia mallow (Figure 5). In this situation, it seems likely that the uptake by plants, both in VF and HF beds, plays a less important role in nitrogen elimination from wastewater, which was also pointed out by Wu et al. [6,61]. The microbiological removal and sorption properties of the substrate could have a large impact on the elimination of nitrogen compounds.
According to the studies of Wesołowski and Brysiewicz [63], the capacity of manna grass to accumulate phosphorus is greater than in the case of common reed; however, the content of this component in the dry mass of plants is small. Additionally, bearing in mind the low productivity of the plants, especially manna grass and Virginia mallow, it is difficult to attribute to them a significant role in the removal of phosphorus from wastewater. The sorption properties of the sand used to fill the beds could have had a large impact on phosphorus elimination. Many researchers pointed out the importance of this material in phosphorus sorption processes in soil and plant beds, especially in the first years of operation of treatment plants [8,64,65]. According to Xu et al. [66], the phosphorus sorption capacity of sands can reach up to 0.3 g/kg. The test results provided by these authors also indicate that during long-term exploitation of the beds, the sorption capacity of sands decreases, which also results in a decrease in phosphorus removal efficiency [8,64,65]. The domination of phosphorus sorption by the hole-filling mechanism may also explain the higher efficiency of removing this component during the post-vegetative period (November and February) (Figure 4).

3.2. Reliability of Pollutants Removal

The average efficiency of total phosphorus removal in the tested VF-HF CW was 96.1%. Studies of other hybrid CWs showed phosphorus removal efficiencies in the range of 70–89% [41,44]. Additionally, 61% and 68.2% of the load inflowing with sewage was removed in the VF-IA and VF-IB beds, respectively, whereas in the HF bed, the average concentration of phosphorus decreased by nearly 87%. According to the studies of Wesołowski and Brysiewicz [63], the capacity of manna grass to accumulate phosphorus is greater than in the case of common reed; however, the content of this component in the dry mass of plants is small. Additionally, bearing in mind the low productivity of the plants, especially manna grass and Virginia mallow, it is difficult to attribute to them a significant role in the removal of phosphorus from wastewater. The sorption properties of the sand used to fill the beds could have had a large impact on phosphorus elimination. Many researchers pointed out the importance of this material in phosphorus sorption processes in soil and plant beds, especially in the first years of operation of treatment plants [8,64,65]. According to Xu et al. [66], the phosphorus sorption capacity of sands can reach up to 0.3 g/kg. The test results provided by these authors also indicate that during long-term exploitation of the beds, the sorption capacity of sands decreases, which also results in a decrease in phosphorus removal efficiency [8,64,65]. The domination of phosphorus sorption by the hole-filling mechanism may also explain the higher efficiency of removing this component during the post-vegetative period (November and February) (Figure 4).

3.2. Reliability of Pollutants Removal

The reliability of the wastewater treatment plant was determined using the Weibull method. In the first step, the parameters of the distribution were estimated and the null hypothesis that empirical data could be described by the Weibull distribution was verified. The datasets consisted of the concentration values of the main pollutants (BOD$_5$, COD, TSS, total nitrogen, and total phosphorus) in the wastewater discharged from the VF–HF CW to the receiver. The null hypothesis was accepted. The results of the Hollander-Prochansan goodness-of-fit test, along with the estimated parameters, are presented in Table 4.

![Figure 5. Plant biomass production at the tested VF-HF CW.](image-url)
Table 4. Parameters of the Weibull distribution and the Hollander-Proschan goodness-of-fit test.

| Parameter | Location | Shape | Scale | Stat | p |
|-----------|----------|-------|-------|------|---|
| BOD<sub>5</sub> | 0.0409 | 1.2736 | 3.1000 | 0.0172 | 0.9863 |
| COD | −0.2000 | 1.5536 | 13.0000 | −0.1397 | 0.8889 |
| TSS | 3.5909 | 1.4033 | 12.0000 | 0.2348 | 0.8144 |
| TN | 0.5667 | 1.1600 | 12.0000 | −0.0481 | 0.9616 |
| TP | 0.0530 | 0.9496 | 0.5100 | 0.2972 | 0.7663 |

Note: Stat—value of the test statistic, p—significance level of the test; when p ≤ 0.05, the distribution of data is not a Weibull distribution.

The goodness of fit of the obtained distributions was high, in the range of 76–98%, at a significance level of α = 0.05.

The technological reliability of the sewage treatment plant was determined on the basis of the cumulative distribution function, taking into account the limit concentration of the pollutants specified in the Regulation of the Ministry of Environment for sewage treatment plants below 2000 PE [23] (Figure 6).

The reliability of organic pollutants removal, expressed by indicators such as BOD<sub>5</sub>, COD, and TSS was 100% (Figure 6). This meant there was a 100% probability that the values of the abovementioned parameters in the treated wastewater would be lower than the maximum limit levels set in Polish law (BOD<sub>5</sub>—40 mg O<sub>2</sub>/L, COD—150 mg O<sub>2</sub>/L, and TSS—50 mg/L), which was synonymous with a failure-free operation of the facility. On this basis, it can be stated that, with respect to the discussed indicators, the facility would successfully pass performance tests throughout the year.

Figure 6. Cont.
Figure 6. Weibull cumulative distribution functions and the technological reliabilities determined for each pollution parameter. The dashed red line represents the reliability function, and the dashed black line represents the probability that a parameter will reach the limit value in the effluent.

The probability that the concentration of total nitrogen in treated wastewater will not exceed the normative value, determined for wastewater discharged to standing waters from treatment plants of less than 2000 PE (30 mg/L), was 94%. According to the guidelines proposed by Andraka and Dzienis [67], the minimum reliability level for this size of wastewater treatment plants should be 97.27%.
The reliability of total phosphorus removal from wastewater was 100%. This meant that the concentration of total phosphorus in the treated wastewater would be below the normal value (5 mg/L) for the entire year, and the sewage treatment plant would successfully pass performance tests.

The results show that the investigated facility, which was a hybrid VF-HF system with common reed, manna grass, and Virginia mallow, provided high removal efficiencies for organic, nitrogen, and phosphorus compounds. As a result, the values of pollution parameters obtained at the outflow from the treatment plant were many times lower than admissible, which was also reflected in high levels of technological reliability. Hybrid systems were shown, among others, by Jucherski et al. [35] and Jóźwiakowski [68] to be highly reliable in reducing the levels of BOD$_5$ and COD. In addition, in the studies of Jucherski et al. [35], the reliabilities of total nitrogen and total phosphorus removal in hybrid constructed wetland systems were 76.8% and 95.2%, respectively. To compare, in sewage treatment plants using conventional treatment methods (activated sludge, trickling filter, or hybrid reactor), the reliability of organic pollutants removal was in the range of 60–88% for BOD$_5$ and 89–96% for COD [7,33,69,70]. When nitrogen and phosphorus removal was considered, the technological reliability of such sewage treatment plants generally did not exceed 50%, often reaching values below 20% [7,70].

The values of pollution parameters obtained at the outflow from the treatment plant were clearly lower than the limit values set in Polish law as safe for the environment, i.e., values which do not cause any negative changes in the receiver. The direct impact of the sewage treatment plant on the quality of water in the receiver was not studied, but it can be assumed that it was negligible. The average flow of water (SSQ) at the measuring point at the Urzędówka-Skorczyce Bridge, located downstream of the point of discharge of treated wastewater from the treatment plant, was about 0.457 m$^3$/s [71]. The designed wastewater treatment capacity was only 2.5 m$^3$/d, or about 0.00003 m$^3$/s, which represented 0.006% of the average flow of river water. In fact, this share is much smaller due to the fact that sewage discharged from the treatment plant is infiltrated and evaporates during the flow through a periodically dry grass-grown drainage ditch.

4. Conclusions

The average effectiveness of the analyzed facility in terms of organic pollutants removal, expressed as BOD$_5$ and COD, was 99% and 98%, respectively, and the TSS removal efficiency was 92.5%. The purification process in the VF beds had a decisive role in the elimination of organic pollutants and suspended solids from sewage. The efficiency of total nitrogen removal from wastewater was 86.5%, and that of total phosphorus removal was 96.1%.

The average concentrations of all the analyzed pollutants in the sewage discharged to the receiver were clearly lower than the limit values set out in the Regulation of the Ministry of Environment.

The reliability of BOD$_5$, COD, total suspended solids, and total phosphorus removal was 100%, which meant that the facility guaranteed legally required levels of pollution indicators in the effluent throughout the year, and was, thus, certain to successfully pass inspection. The reliability of total nitrogen removal was 94%.

The efficiency and technological reliability of the hybrid constructed wetland system with common reed, manna grass, and Virginia mallow were similar to those of other CW systems described in the literature, and were clearly higher than those found in conventional treatment plants.

Reliability assessment of household sewage treatment plants allows determining which technological solutions are optimal from the point of view of environmental protection, and which of them should be an important element of planning the sanitary infrastructure in rural areas.

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References
1. Obarska-Pempkowiak, H.; Kolecka, K.; Gajewska, M.; Wojciechowska, E.; Ostoji, A. Sustainable wastewater management on the example of rural areas. Rocznik Ochrona Środowiska 2015, 17, 585–602. (In Polish)
2. Pawełek, J.; Bugajski, P. The development of household wastewater treatment plants in Poland—Advantages and disadvantages. Acta Scientiarum Polonorum Formatio Circumiectus 2017, 16, 3–14. (In Polish) [CrossRef]
3. Mikosz, J.; Mucha, Z. Validation of Design Assumptions for Small Wastewater Treatment Plant Modernization in Line with New Interpretation of Legal Requirements. Ochr. Srod. 2014, 36, 45–49. (In Polish)
4. Jóźwiakowski, K.; Mucha, Z.; Generowicz, A.; Baran, S.; Bielińska, J.; Wójcik, W. The use of multi-criteria analysis for selection of technology for a household WWTP compatible with sustainable development. Arch. Environ. Prot. 2015, 3, 76–82. [CrossRef]
5. GUS. Municipal Infrastructure in 2016; Główny Urzad Statystyczny: Warszawa, Poland, 2017. (In Polish)
6. Wu, H.; Zhang, J.; Li, C.; Fan, J.; Zou, Y. Mass balance study on phosphorus removal in constructed wetland microcosms treating polluted river water. CLEAN Soil Air Water 2013, 41, 844–850. [CrossRef]
7. Marzec, M. Reliability of removal of selected pollutants in different technological solutions of household wastewater treatment plants. J. Water Land Dev. 2017, 35, 141–148. [CrossRef]
8. Jóźwiakowski, K.; Bugajski, P.; Kurek, K.; Fátima Nunes de Carvalho, M.; Adelaide, M.; Almeida, A.; Siwiec, T.; Borowski, G.; Czekala, W.; Dach, J.; et al. The efficiency and technological reliability of biogenic compounds removal during long-term operation of a one-stage subsurface horizontal flow constructed wetland. Sep. Purif. Technol. 2018, 202, 216–226. [CrossRef]
9. Wu, H.; Zhang, J.; Ngo, H.H.; Guo, W.; Hu, Z.; Liang, S.; Fan, J.; Liu, H. A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation. Bioresour. Technol. 2015, 175, 594–601. [CrossRef] [PubMed]
10. Rai, U.N.; Tripathi, R.D.; Singh, N.K.; Upadhyay, A.K.; Dwivedi, S.; Shukla, M.K.; Mallick, S.; Singh, S.N.; Nautiyal, C.S. Constructed wetland as an ecotechnological tool for pollution treatment for conservation of Ganga river. Bioresour. Technol. 2013, 148, 535–541. [CrossRef] [PubMed]
11. Seo, D.C.; DeLaune, R.D.; Park, W.Y.; Lim, J.S.; Seo, J.Y.; Lee, D.J.; Cho, J.S.; Heo, J.S. Evaluation of a hybrid constructed wetland for treating domestic sewage from individual housing units surrounding agricultural villages in South Korea. J. Environ. Monit. 2009, 11, 134–144. [CrossRef] [PubMed]
12. Masi, F.; Martinuzzi, N. Constructed wetlands for the Mediterranean countries: Hybrid systems for water reuse and sustainable sanitation. Desalination 2007, 215, 44–55. [CrossRef]
13. Gajewska, M.; Obarska-Pempkowiak, H. 20 years of experience of hybrid constructed wetlands exploitation in Poland. Rocznik Ochrony Środowiska 2009, 11, 875–888. (In Polish)
14. Vymazal, J.; Kröpfelová, L. Removal of organics in constructed wetlands with horizontal sub-surface flow: A review of the field experience. Sci. Total Environ. 2009, 407, 3911–3922. [CrossRef] [PubMed]
15. Vymazal, J. Plants used in constructed wetlands with horizontal subsurface flow: A review. Hydrobiologia 2011, 674, 133–156. [CrossRef]
16. Saeed, T.; Sun, G. A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: Dependency on environmental parameters, operating conditions and supporting media. J. Environ. Manag. 2012, 112, 429–448. [CrossRef] [PubMed]
17. Mojiri, A.; Tajuddin, R.M.; Ahmad, Z.; Ziyang, L.; Aziz, H.A.; Amin, N.M. Chromium(VI) and cadmium removal from aqueous solutions using the BAZLSC/cockle shell constructed wetland system: Optimization with RSM. Int. J. Environ. Sci. Technol. 2018, 15, 1949–1956. [CrossRef]
18. Kadlec, R.H.; Wallace, S.D. Treatment Wetlands, 2nd ed.; CRC Press/Taylor & Francis Group: Boca Raton, FL, USA, 2009; ISBN 9781420012514.
19. Vymazal, J. The use of hybrid constructed wetlands for wastewater treatment with special attention to nitrogen removal: A review of a recent development. Water Res. 2013, 47, 4795–4811. [CrossRef] [PubMed]
20. Ju, X.; Wu, S.; Huang, X.; Zhang, Y.; Dong, R. How the novel integration of electrolysis in tidal flow constructed wetlands intensifies nutrient removal and odor control. *Bioresour. Technol.* 2014, 169, 605–613. [CrossRef] [PubMed]

21. Vymazal, J. Emergent plants used in free water surface constructed wetlands: A review. *Ecol. Eng.* 2013, 61, 582–592. [CrossRef]

22. Jóźwiakowski, K.; Goral, R.; Perehubka, A.; Jakubowski, S.; Marzec, M.; Pytka, A.; Gizisńska, M.; Kowalczyk-Julso, A.; Szpakowski, G.; Musyka, L.; et al. *The Construction Project of Hybrid Household Wastewater Treatment Plant in Popkowice (Urzdów Commune)*; Manuscript, Department of Environmental Engineering and Geodesy, University of Life Sciences in Lublin, R-G Projekt: Lublin, Poland, 2013. (In Polish)

23. Regulation of the Minister of Environment of November 18, 2014 laying down conditions for the introduction of sewage into water or soil and substances particularly harmful to the aquatic environments (No 2014 Item 1800). Available online: [http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20140001800/O/D20141800.pdf](http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20140001800/O/D20141800.pdf) (accessed on 5 July 2018). (In Polish)

24. *Water and Sewage—Sampling—General Provision and Scope of the Standard*; Polski Komitet Normalizacji, Miar i Jakości: Warszawa, Poland, 1975. (In Polish)

25. *Water Quality—Sampling—Guidance on Sampling Techniques*; Polski Komitet Normalizacyjny: Warszawa, Poland, 1999. (In Polish)

26. *Water Quality—Determination of Biochemical Oxygen Demand after n Days (BOD)—Part 1: Dilution and Vaccination Method with the Addition of Allythiourea*; Polski Komitet Normalizacyjny: Warszawa, Poland, 2002. (In Polish)

27. *Water Quality—Determination of the Chemical Oxygen Demand Index (ST-COD)—Small-Scale Sealed-Tube Method*; Polski Komitet Normalizacyjny: Warszawa, Poland, 2005. (In Polish)

28. *Water Quality—Determination of Phosphorus—Ammonium Molybdate Spectrometric Method*; Polski Komitet Normalizacyjny: Warszawa, Poland, 2006. (In Polish)

29. *Determination of Total Nitrogen by a Test Spectrometric Method*; Wydawnictwa Normalizacyjne: Warszawa, Poland, 2013. (In Polish)

30. *Water Quality—Determination of Suspended Solids—Method by Filtration through Filters*; Polski Komitet Normalizacyjny: Warszawa, Poland, 2007. (In Polish)

31. *Solid Biofuels—Determination of Moisture Content—Oven Dry Method—Part 3: Moisture in General Analysis Sample*; Polski Komitet Normalizacyjny: Warszawa, Poland, 2017. (In Polish)

32. Institute of Meteorology and Water Management. Average Monthly Air Temperatures Monthly Rainfall for the Station in Radawiec near Lublin. 2018. Available online: [https://dane.imgw.pl/data/dane_pomiarowo_obserwacyjne/](https://dane.imgw.pl/data/dane_pomiarowo_obserwacyjne/) (accessed on 5 August 2018). (In Polish)

33. Bugajski, P.; Walega, A.; Kaczor, G. Application of the Weibull reliability analysis of household sewage treatment plant. *Gaz Woda i Technika Sanitarna* 2012, 2, 56–58. (In Polish)

34. Bugajski, P. Analysis of reliability of the treatment plant Bioblok PS-50 using the method of Weibull. *Infrastruct. Ecol. Rural Areas* 2014, 2, 667–677.

35. Jucherski, A.; Nastawny, M.; Walczowski, A.; Jóźwiakowski, K.; Gajewska, M. Assessment of the technological reliability of a hybrid constructed wetland for wastewater treatment in a mountain eco-tourist farm in Poland. *Wat. Sci. Technol.* 2017, 75, 2649–2658. [CrossRef] [PubMed]

36. Dodson, B. *Weibull Analysis*; ASQV Quality Press: Milwaukee, WI, USA, 1994; ISBN 087389295X/978-0873892957.

37. Bugajski, P.; Bergel, T. Values of selected concentrations of pollutants in domestic sewage exiting the countryside. *Gaz Woda i Technika Sanitarna* 2008, 9, 28–29. (In Polish)

38. Gajewska, M.; Obarska-Pempkowiak, H. Efficiency of pollutant removal by five multistage constructed wetlands in a temperate climate. *Environ. Prot. Eng.* 2011, 37, 27–36.

39. Jóźwiakowski, K.; Bugajski, P.; Mucha, Z.; Wójcik, W.; Jucherski, A.; Nastawny, M.; Siwiec, T.; Gajewska, M.; Mazur, A.; Obroslák, R. Reliability and efficiency of pollution removal during long-term operation of a one-stage constructed wetland system with horizontal flow. *Sep. Purif. Technol.* 2017, 187, 60–66. [CrossRef]

40. Heidrich, Z.; Kalenik, M.; Podedworna, J; Stańko, G. *Rural Sanitation*; Wyd. Seidel-Przywecki: Warszawa, Poland, 2008; ISBN 978-83-60956-04-5. (In Polish)

41. Krzanowski, S.; Jucherski, A.; Walega, A. Influence of season on technological of reliability of multi-degrees plant-ground adjacent of sewage treatment. *Infrastruct. Ecol. Rural Areas* 2005, 1, 37–55. (In Polish)
42. Obarska-Pempkowiak, H.; Gajewska, M.; Wojciechowska, E. Constructed Wetlands to Water and Wastewater Treatment; Wydawnictwo Naukowe PWN: Warszawa, Poland, 2010; pp. 35–40. (In Polish)

43. Vymazal, J. Constructed Wetlands for Wastewater Treatment. Water 2010, 2, 530–549. [CrossRef]

44. Sharma, P.K.; Inoue, T.; Kato, K.; Ietsugu, H.; Tomita, K.; Nagasawa, T. Potential of hybrid constructed wetland system in treating milking parlor wastewater under cold climatic conditions in northern Hokkaido, Japan. In Proceedings of the 12th International Conference on Wetland Systems for Water Pollution Control, Venice, Italy, 4–8 October 2010; pp. 929–938.

45. Gajewska, M.; Obarska-Pempkowiak, H.; Kopeć, Ł. Operation of small wastewater treatment facilities in a scattered settlement. Rocznik Ochrona Środowiska 2011, 13, 207–225.

46. Haberl, R.; Perll, R.; Mayer, H. Constructed wetlands in Europe. Wat. Sci. Technol. 1995, 32, 305–315. [CrossRef]

47. Headley, T.R.; Herity, E.; Davison, L. Treatment at different depths and vertical mixing within a 1-m deep horizontal subsurface flow wetland. Ecol. Eng. 2005, 25, 567–582. [CrossRef]

48. Ong, S.A.; Uchiyama, K.; Inadama, D.; Ishida, Y.; Yamagiwa, K. Performance evaluation of laboratory scale up-flow constructed wetlands with different designs and emergent plants. Bioresour. Technol. 2015, 101, 7239–7244. [CrossRef] [PubMed]

49. Gervin, L.; Brix, H. Removal of nutrients from combined sewer overflows and lake water in a vertical-flow constructed wetland system. Wat. Sci. Technol. 2001, 44, 171–176. [CrossRef]

50. Jia, W.; Zhang, J.; Wu, J.; Xie, H.; Zhang, B. Effect of intermittent operation on contaminant removal and plant growth in vertical flow constructed wetlands: A microcosm experiment. Desalination 2010, 262, 202–208. [CrossRef]

51. Stottmeister, U.; Wießner, A.; Kuschk, P.; Kappelmeyer, U.; Kästner, M.; Müller, R.A.; Moormann, H. Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechnol. Adv. 2003, 22, 93–117. [CrossRef] [PubMed]

52. Zhang, L.; Zhang, L.; Liu, Y.; Shen, Y.; Liu, H.; Xiong, Y. Effect of limited artificial aeration on constructed wetland treatment of domestic wastewater. Desalination 2010, 250, 915–920. [CrossRef]

53. Jucherski, A.; Walczowski, A. Influence of selected macrophytes on sewage treatment effectiveness in the slope soil-vegetation filtration beds. Probl. Agric. Eng. 2012, 1, 115–124. (In Polish)

54. Klimont, K.; Bulińska-Radomska, Z. The possibility of using Virginia mallow plant (Sida Hermaphrodita L.) All. to reclamation of post-borehole Sulphur exploitation terrains. Probl. Agric. Eng. 2013, 1, 125–132. (In Polish)

55. Vymazal, J. Removal of nutrients in various types of constructed wetlands. Sci. Total. Environ. 2007, 380, 48–65. [CrossRef] [PubMed]

56. Rustige, H.; Nolde, E. Nitrogen elimination from landfill leachates using an extra carbon source in subsurface flow constructed wetlands. Wat. Sci. Technol. 2007, 56, 25–133. [CrossRef]

57. Songliu, L.; Hongying, H.; Yingxue, S.; Jia, Y. Effect of carbon source on the denitrification in constructed wetlands. J. Environ. Sci. 2009, 21, 1036–1043.

58. Zhao, Y.J.; Hui, Z.H.; Chao, X.; Nie, E.; Li, H.J.; He, J.; Zheng, Z. Efficiency of two-stage combinations of subsurface vertical down-flow and up-flow constructed wetland systems for treating variation in influent C/N ratios of domestic wastewater. Ecol. Eng. 2011, 37, 1546–1554. [CrossRef]

59. Bulc, T.G. Long term performance of a constructed wetland for landfill leachate treatment. Ecol. Eng. 2006, 26, 365–374. [CrossRef]

60. Greenway, M.; Woolley, A. Changes in plant biomass and nutrient removal over 3 years in a constructed wetland, Cairns, Australia. Water Sci. Technol. 2001, 44, 303–310. [CrossRef] [PubMed]

61. Wu, H.; Zhang, J.; Wei, R.; Liang, S.; Li, C.; Xie, H. Nitrogen transformations and balance in constructed wetlands for slightly polluted river water treatment using different macrophyces. Environ. Sci. Pollut. Res. 2013, 20, 443–451. [CrossRef] [PubMed]

62. Staniszewski, R.; Szoszkiewicz, J.; Tomoń, M. The Role of Selected Plants in Limitation of Freshwater Trophy with Emphasis on Salvinia natans (L.) All. Pol. J. Environ. Stud. 2004, 13 (Suppl. 1), 67–69.

63. Wesolowski, P.; Brysiwicz, A. The ability to onshore rushes in mid-field ponds to accumulate macro and micronutrients. Water-Environ.-Rural Areas 2014, 14, 111–119.

64. Vymazal, J. Removal of phosphorus in constructed wetlands with horizontal sub-surface flow in the Czech Republic. Water Air Soil Pollut. 2004, 14, 657–670. [CrossRef]
65. Saeed, T.; Sun, G. A lab-scale study of constructed wetlands with sugarcane bagasse and sand media for the treatment of textile wastewater. *Bioresour. Technol.* 2013, 128, 438–447. [CrossRef] [PubMed]

66. Xu, D.; Xu, J.; Wu, J.; Muhammad, A. Studies on the phosphorus sorption capacity of substrates used in constructed wetland systems. *Chemosphere* 2006, 63, 344–352. [CrossRef] [PubMed]

67. Andraka, D.; Dzienis, L. Required reliability level of wastewater treatment plants according to European and Polish regulations. *Zeszyty Naukowe Politechniki Białostockiej. Ser. Inżynieria Środowiska* 2003, 16, 24–28. (In Polish)

68. Jóźwiakowski, K. Studies on the efficiency of sewage treatment in chosen constructed wetland systems. *Infrastruct. Ecol. Rural Areas* 2012, 1, 232. (In Polish)

69. Wałęga, A.; Miernik, W.; Kozień, T. The efficiency of a domestic sewage treatment plant type RetroFAST. *Przem. Chem.* 2008, 87, 210–212. (In Polish)

70. Bugajski, P.; Almeida Araujo, M.A.; Kurek, K. Reliability of sewage treatment plants processing sewage from school buildings located in non-urban areas. *Infrastruct. Ecol. Rural Areas* 2016, VI/3, 1547–1557. (In Polish)

71. Zielirski, M. An Expert Study of Water-Related and Legal Aspects of Discharge of Treated Wastewater from a Domestic Wastewater Treatment Plant into the River Urzędnik at 12+662 km; Biuro Projektowe “SKALA”: Włodawa, Poland, 2011. (In Polish)

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