Highlights

Reliability of pollution removal in one-stage CWs of HF type in different seasons during long-term operation was analyzed

One-stage CWs don't provide stable and reliable of pollution removal in different seasons

The lowest reliability of the pollutants removal (especially nitrogen and phosphorus) were usually obtained in winter and spring

One-stage CWs of HF type should not be recommended for wider use in temperate climate conditions.

Technological reliability of pollutant removal in different seasons in one-stage constructed wetland system with horizontal flow operating in the moderate climate

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ABSTRACT

The aim of this work was to determine the technological reliability of pollutions removal in different seasons in one-stage constructed wetland system with horizontal flow operating in the conditions of moderate climate. In the above-mentioned system, willow (*Salix Viminalis* L.) was planted and the average flow of domestic sewage were 1.2 m^3/d. The analyzed system is located in south-eastern Poland, where the climate is moderate transitional. The tests were carried out during the 14-year exploitation of the wastewater treatment plant (1997-2010). During this period, sewage samples were collected in 4 seasons (winter - February, spring - may, summer – August and autumn - November) to be analyzed. The average long-term air temperatures in these months were: -1.8; 13.8; 18.3 and 3.5 ^{o}C. Altogether 56 series of analyzes were carried out during the research and 112 samples of the sewage, both from the inflow and the outflow of the wastewater treatment plant, were collected. The measured parameters were: BOD_5, COD, total nitrogen, total phosphorus. On the grounds of the reliability analysis performed on the basis of the Weibull probability model, it was found that the reliability of pollutions removal in the tested constructed wetland system are higher in summer and autumn (August, November) than in winter and in spring (February, May). It was shown that exceedance of the admissible values of pollutant indicators in treated wastewater is dependent on the season (air temperature) and it occurred mainly in the winter period (February). It was proved that the tested CW does not provide effective elimination of biogenic indicators (nitrogen and phosphorus), as evidenced by small values of reliability. To increase the technological reliability of the tested treatment plant, it is proposed to expand the existing system and create a hybrid system consisting of two beds with vertical and horizontal flow and a special P-filter.

Keywords: Weibull reliability method, pollutions removal; wastewater treatment; one-stage constructed wetland, moderate climate

1. Introduction

In recent years in Poland and worldwide, household wastewater treatment plants are an integral part of a comprehensive wastewater treatment system in rural areas, where for economic reasons the construction of sewerage systems and collective sewage treatment plants is economically unjustified [1–6]. According to CSO data [7], there are currently around 217,000 household sewage treatment plants in Poland, among which the following systems are used: 1) a drainage pipe; 2) a sand filter; 3) a biological filter; 4) activated sludge; 5) constructed wetland, 6) hybrid system (activated sludge + biological filter) [5].

Among the aforementioned solutions, the most frequently used technological system consists of the initial settling tank and drainage pipe [8–10], mainly due to the low construction costs [11]. However, the application of this solution is the reason of much controversy in Poland [6, 12–14]. The multi-criteria analysis shows that the usage of systems with drainage pipe is inconsistent with the principles of sustainable development [5], because these systems collecting polluted water and let in untreated sewage into the environment and not ensure effective elimination of pollution [15]. They have a negative impact on the ecological status of the environment and contribute to the degradation of groundwater quality [14].

The exploitation of small wastewater treatment plants is significantly different from the one recommended to large facilities. First of all, small sewage treatment plants are exposed to very large irregularities in the amount and composition of incoming sewage. Therefore, the wastewater treatment technology used in household wastewater treatment plants should be chosen in such a way to ensure an adequate ecological effect, combined with low maintenance requirements and minimum exploitation costs. According to Mucha and Mikosz [16], taking the basic principles of sustainable development into account, the paramount criterion in the selection of the technology for a small sewage treatment plant should be the ecological criterion which means the efficiency of wastewater treatment (Figure 1).

Other criteria include:

- environmental criteria (impact on the natural environment and aesthetics),
- technical criteria (ease of use and maintenance and modernity of the solution),
- reliability criterion (reliability of operation),
- economic criteria (investment and operational costs).

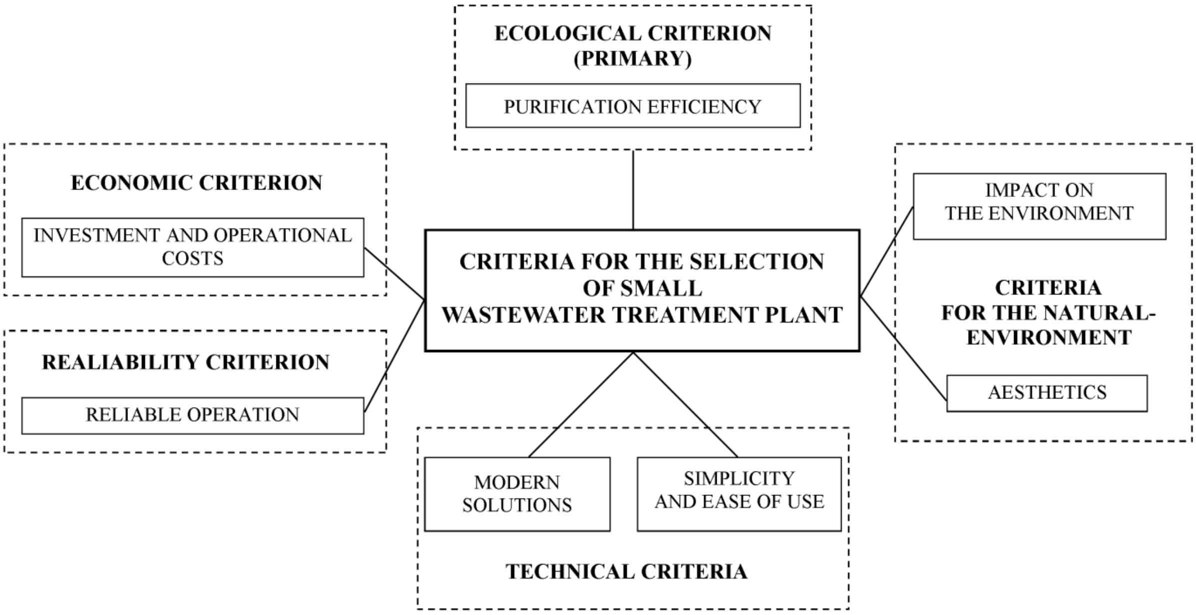

Fig. 1. Criteria of selection for small WWTPs according to sustainability principles [16]

In recent years, systems that meet most of the above-mentioned criteria are becoming more and more popular in Poland and around the world. These include technological systems with active sludge (mainly SBR - Sequential Biological Reactor), or with a biological bed (disc or sprayed), as well as hybrid systems- a combination of these two solutions [17–20]. Taking the ecological, and not only economical, aspect into consideration it is important that the technological system chosen by the user of a household sewage treatment plant should meet certain requirements included in legal regulations [21]. It should also be taken into account that there are many factors dependent and independent on the user, but affecting the efficiency of small wastewater treatment plants. One of the most important factors affecting the proper course of biological wastewater treatment processes is the temperature of air and sewage [22]. Therefore, in countries where climate conditions are characterized by significant variability of air temperature in different seasons, the used solutions should ensure high operational reliability and high effects of pollution removal in different seasons.

In recent years, for the treatment of small amounts of wastewater, more and more often constructed wetland systems (CWs) are used, which are easy to use and have an aesthetic appearance, and at the same time they ensure quite effective removal of pollutants. Jóźwiakowski et al. [15] proved that the usage of these systems is consistent with the principles of sustainable development. The literature suggests that CWs can purify various types of wastewater and are used in various climate conditions [23–25]. In Poland, such systems have been used in various technological configurations for about 30 years [26]. The research concerning CWs in recent years focus mainly on the processes and effects of pollution removal [24, 27–30], as well as determining the reliability of these systems [31–39] or the use of online systems to check the performance of the CW [40]. However, most of the existing papers usually describe the reliability of CWs at a given time, without taking into account changes in thermal conditions during the year. Therefore, the aim of this work is to determine the technological reliability of pollutions removal in one-stage constructed wetland system with horizontal flow in different seasons in the conditions of moderate climate.

2. Material and methods

2.1. Characteristics of the experimental facility

The analyzed treatment plant consists of an initial settling tank and a bed with a horizontal sewage flow with 1.2 m deep and with a surface area of 186 m^2. The bed was planted by willow (*Salix viminalis* L.) (Photo 1). The willow species *Salix viminalis* L. began to be used in CWs in the 1990's [41–42]. It has been shown too, that such systems with willow can be used not only for wastewater treatment, but also for production of biomass for energy purposes [43].

The construction of the analyzed wastewater treatment plant has been described earlier in the papers of Jóźwiakowski et al. [37–38]. The tested facility is located in south-eastern Poland in Jastków (51°18'N, 22°26'E). It is used to treat domestic wastewater coming from a building inhabited by 12 people, which has access to tap water, which is used to meet the basic needs of the residents (for bathing, washing-up, flushing the toilet and washing).

Considering the amount of inflow to the treatment plant, which during the experimental period was Q = 1,2 m^3/d, the analyzed object, according to legal acts in Poland, is included in the group of so-called household wastewater treatment plants [6, 44–45].

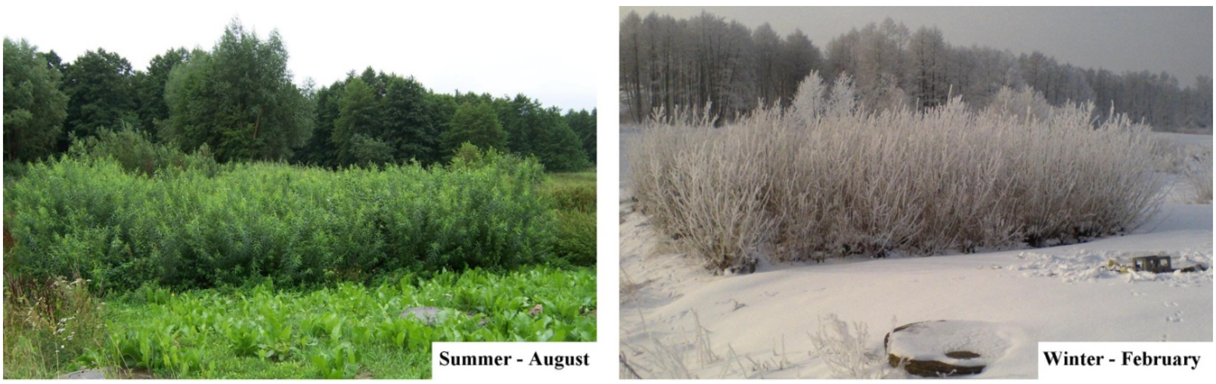

Photo. 1. One-stage constructed wetland in the summer and in the winter [46]

2.2. Climate conditions

The region, where treatment plant is located, has a temperate climate with visible influences of the continental climate. The climate in this area is formed by polar air masses (PP) which dominate in the year, especially the polar-marine air (PPM), which constitutes 60-66% of air masses per year and occurs mainly in summer and polar-continental air (PPk), which accounts for 24-31% of air masses per year and occurs mainly in February and during spring and autumn. The polar-sea air flows from the west, bringing moisture from the Atlantic sea. In winter, it causes thaw and warming with snow or rain, and cooling, cloudiness, rainfall and frequent thunderstorms in summer. The polar-continental air flows from Asia and Eastern Europe and is characterized by low humidity, in winter it brings fall in temperature and cloudless sky, and during summer, sunny, hot and dry weather [47]. High variability of weather during the year causes occurrence of 4 basic seasons (winter, spring, summer, autumn) with variable air temperatures.

The research on the operation of the wastewater treatment plant was carried out for 14 years (1997-2010). Sewage samples from the sewage treatment plant for analysis were collected in 4 seasons (winter - February, spring - May, summer - August, autumn - November).

2.3. Analytical methods

Bearing in mind the 14-year research period in each season (winter, spring, summer and autumn), analysis of 14 samples of sewage inflowing and outflowing from the treatment plant was performed. In total, 56 series of analyses were carried out during the tests and 112 sewage samples were collected, in which the values of organic pollutants were determined using indicators such as BOD_5 and COD as well as biogenic impurities: total nitrogen and total phosphorus.

BOD_5 was measured by the dilution method using a WTW Oxi 538 portable meter - after Siwiec et al. [48]. COD was determined using a PC Spectro spectrophotometer manufactured by AQUALYTIC, after oxidation of the samples at 148^{o}C in a WTW CR4200 thermo reactor. Total nitrogen was determined using a PC Spectro spectrophotometer manufactured by AQUALYTIC, after oxidation of the samples at 100°C in a WTW CR4200 thermo reactor. Total phosphorus was determined using a MPM 2010 spectrophotometer manufactured by WTW, after oxidation of the samples at 120°C in a WTW CR4200 thermo reactor. Sampling, sample transportation, processing and analysis have been done according to relative Polish Standards of Wastewater Examination which are compatible with APHA [49–50].

Acceptable (maximum) values for the 4 analyzed indicators, were adopted according to legal regulations binding in Poland [51]. According to these legal acts, the permissible values of pollutants in wastewater discharged from small wastewater treatment plants (from less than 2000 inhabitants) for the analyzed indicators are: BOD_5 – 40 mg/l; COD – 150 mg/l; total nitrogen – 30 mg/l; total phosphorus – 5 mg/l.

2.4. Statistical methods

On the basis of the obtained data, the technological reliability of the tested object was determined in various seasons during long-term operation. For this purpose, the Weibull method was used, which according to different authors [36–38, 52] is a useful general probability distribution that is still more often used to determine the technological operation reliability of wastewater treatment plants. The Weibull distribution can be used when the intensity of the exceedance of permissible values of pollution indicators is a variable with a monotonic course. The Weibull distribution is characterized by the probability density function (1) with the parameters b, c and θ:

$$f(x) = \frac{c}{b} \cdot \left(\frac{x-\theta}{b}\right)^{(c-1)} \cdot e^{-\left(\frac{x-\theta}{b}\right)^{c}} \quad (1)$$

Where:

x- variable defining the concentration of the pollutant index in treated wastewater,

b - scale parameter,

c - shape parameter,

θ - position parameter.

Assuming: $\theta < x$, $b > 0$, $c > 0$

The Weibull distribution parameters were estimated using the method characterized by the highest likelihood. The quality of matching the Weibull distribution to empirical data was carried out with the Hollander-Proschan test. The analysis of this part of the study results was carried out using the STATISTICA 8 program. The calculated parameters of scale, shape and position for particular indicators in treated wastewater are presented in the table 3.

The interpretation of the variation coefficient (Cv), in regard to the concentration of the analyzed indicators in sewage inflowing and outflowing from the treatment plant, was characterized according to the guidelines proposed by Mucha [53].

3. Results

3.1. Thermal conditions in the research period

In the discussed multi-year period (1997-2010), the median of temperature in individual months of the year, in the place where the treatment plant is located, ranged from -2.2°C – in January to 19.2°C – in July (Figure 2).

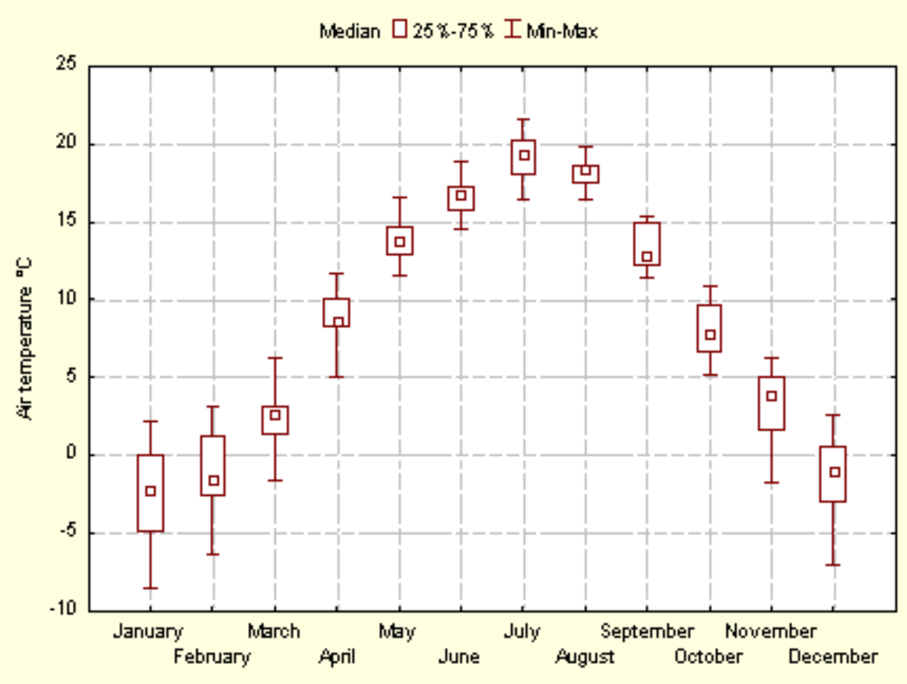

Fig. 2. Multi-year medians of atmospheric air temperature in different months of the discussed multi-year period 1997-2010 (based on the data from a meteorological station in Lublin – 12 km away from the location of the experimental object [54])

The long-term medians of air temperature in particular seasons (winter, spring, summer, autumn) were: -1.8; 13.8; 18.3 and 3.5°C, respectively. Therefore, the analysis of these data indicates that the most favorable thermal conditions for the course of basic pollution removal processes in the analyzed facilities prevailed in May and in August (when temperature was above 5°C).

3.2. Pollutant concentrations in inflowing wastewater

The values of pollutants in wastewater flowing into the treatment plant were similar to those noted in other domestic sewage [55–57]. The median for BOD_5 in the analyzed wastewater was 162.0 mg/l, with an arithmetic mean of 170.5 mg/l, while the median for COD was 339.0 mg/l, with an arithmetic mean of 339.4 mg/l. For biogenic indicators, i.e. total nitrogen and phosphorus, the overall median was 70.4 and 25.2 mg/l, respectively, with an arithmetic mean of 71.5 mg/l for total nitrogen and 24.8 mg/l for total phosphorus (Tab. 1).

Table 1. Pollutant concentrations in inflow wastewater [37–38]

Index	Statistics					
	Average [mg/l]	Median [mg/l]	Min. [mg/l]	Max. [mg/l]	Standard of deviation [mg/l]	Coefficient of variation [-]
BOD_5	170.5	162.0	62.0	441.0	69.7	0.41
COD	339.4	339.0	101.0	700.0	116.2	0.34
Total nitrogen	71.5	70.4	37.1	137.0	21.5	0.30
Total phosphorus	24.8	25.2	5.2	42.8	8.8	0.36

In the case of the analyzed organic and biogenic indicators, the average variation in their value in sewage flowing into the treatment plant was found, which was indicated by the calculated coefficients of variation. The lowest variation of values was stated for total nitrogen, whose coefficient of variation was W_z = 0.30, while the highest variation of results was observed for BOD_5 – the coefficient of variation was W_z = 0.41. Therefore, it can be concluded that in the analyzed treatment plant with a generally constant amount of incoming sewage, a permanent level of charges of organic and biogenic contaminants was noted, which should not affect the instability of the transformation processes of organic and biogenic compounds in the bed. Moreover, it was found that the seasons of year didn't impact for the concentrations of particular of organic and biogenic indicators in raw wastewater.

3.3. Pollutant concentrations in outflowing wastewater

Table 2 and Figures 3 and 4 present characteristic values of organic and biogenic contaminants in sewage flowing out of the wastewater treatment plant in particular seasons.

Table 2. Pollutant concentrations in outflowing wastewater in different seasons

Index	Period	Statistics					
		Average [mg/l]	Median [mg/l]	Min. [mg/l]	Max. [mg/l]	Standard of deviation [mg/l]	Coefficient of variation [-]
BOD_5	winter	23.1	23.1	7.1	56.0	13.1	0.57
	spring	31.8	22.5	10.7	105.8	25.0	0.79
	summer	22.0	23.1	7.0	36.1	8.7	0.39

	autumn	16.1	10.8	6.1	52.4	12.6	0.78
COD	winter	54.3	52.5	20.0	99.0	20.7	0.38
	spring	73.7	52.5	39.0	210.0	45.4	0.62
	summer	58.9	48.5	15.0	134.0	36.4	0.62
	autumn	48.8	39.0	9.0	105.0	32.5	0.67
Total nitrogen	winter	34.2	35.5	10.9	48.5	8.9	0.26
	spring	36.6	34.8	17.8	56.7	10.5	0.29
	summer	35.2	30.5	17.0	92.0	18.6	0.53
	autumn	25.7	28.0	9.0	39.0	9.4	0.36
Total phosphorus	winter	5.5	6.3	0.5	9.0	2.8	0.50
	spring	8.3	7.9	1.0	17.9	4.3	0.42
	summer	6.2	7.7	0.9	11.0	3.8	0.62
	autumn	4.3	4.5	0.1	10.0	2.8	0.66

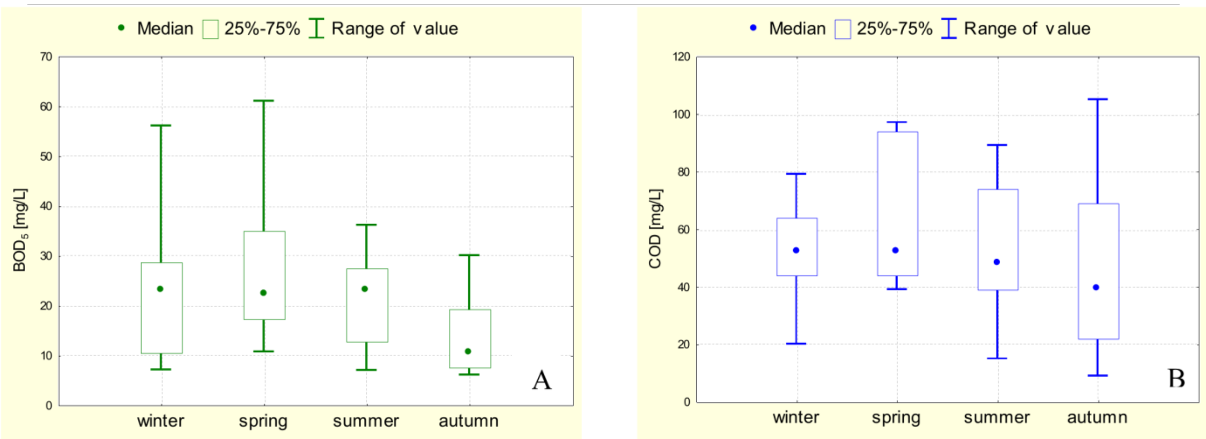

Fig. 3. Characteristic values of BOD_5 (A) and COD (B)
in treated wastewater in particular seasons

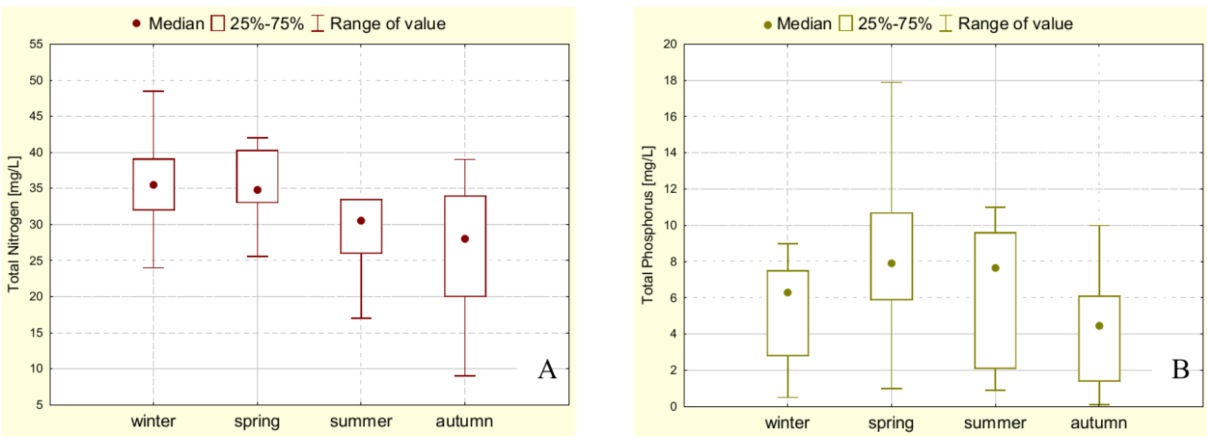

Fig. 4. Characteristic values of total nitrogen (A) and total phosphorus (B)
in treated wastewater in particular seasons

By analyzing the obtained results in detail, it was found that in the case of BOD_5 in the seasons such as winter, spring and summer, the median of this parameter oscillated in the range from 22.5 to 23.1 mg/l, while in autumn it was much lower and amounted to 10.8 mg/l (Fig. 3A). A similar relationship was observed in the case of COD, since the median from winter to summer ranged from 48.5 to 52.5 mg/l, while in autumn it was lower and was 39.0 mg/l (Fig. 3B).

By analyzing the concentrations of biogenic indicators, it was found that the median of total nitrogen and total phosphorus was the lowest in autumn. For total nitrogen, the median in autumn was 28.0 mg/l, while for the remaining 3 seasons the median value ranged from 30.5 to 35.5 mg/l (Figure 4A). For the second biogenic indicator, which is total phosphorus, the overall median during autumn was the lowest and amounted to 4.5 mg/l, while for other periods the median for total phosphorus varied from 6.3 to 7.9 mg/l (Fig. 4B).

Figures 3 and 4 show the median, quartile range 25% -75%, which specifies the length of the part of the variability range of particular indicators, in which there are 50% of the "middle" values and the range of irrelevant values for the indicators. The variability expressed by the coefficient of variation W_z for the analyzed parameters in treated wastewater was on a variable level during particular seasons of the year. For BOD_5 the coefficient of variation in summer was W_z = 0.39 and can be defined as the average diversity. In contrast, in winter it was W_z = 0.57, which indicates large variety. In the other two seasons, i.e. in spring and autumn, the BOD_5 values in treated wastewater were very diverse, as indicated by unevenness coefficients of W_z = 0.79 and 0.78, respectively.

The average variation of COD values was observed only during winter, because the coefficient of variation was W_z = 0.38. In the remaining three seasons, the COD values in treated wastewater were very diverse, since the coefficient of variability of W_z varied from 0.62 to 0.67. However, in the case of biogenic indicators, the average variation of total nitrogen concentration was observed in the following seasons: winter, spring and autumn, when the coefficient of variation of W_z varied from 0.26 to 0.36. In contrast, in summer the variability of the concentration of this parameter was very different and amounted to W_z = 0.53. The concentration of total phosphorus in all study periods showed a high level of variation in treated wastewater, as indicated by variation coefficients oscillating from W_z = 0.50 to 0.66.

Summing up the obtained results, it can be concluded that the processes of impurities removal in the CWs was unstable in different seasons, which is indicated by large or very large differences in the concentration of the analyzed organic and biogenic indicators in sewage flowing out of this bed.

3.4. The reliability of pollutions removal in different seasons

The main aim of this work is to determine reliability indices for the removal of organic and biogenic pollutants in individual seasons, using Weibull's reliability theory. For estimated distribution parameters, the hypothesis of accepting Weibull distribution for the approximation of empirical data was verified. As a result of the statistical analysis carried out concerning the test probability p, it was found that empirical data could be described by the Weibull distribution and taken as a zero hypothesis. The results of the distribution alignment with Hollander-Proschan test and the estimated scale, shape and position parameters are presented in Table 3.

Table 3. Results of the estimation of the Weibull distribution parameters together with the measures of goodness of fit to empirical data

Index	Period	Distribution parameters			Test Hollandera-Proschana	
		b	c	θ	Test value	p
BOD_5	winter	26.147	1.9408	5.1818	0.071593	0.94293
	spring	35.693	1.5123	9.5960	0.326170	0.74430
	summer	24.754	2.9608	-1.0000	-0.123561	0.90166
	autumn	18.074	1.5023	5.9495	0.297780	0.76969
COD	winter	60.884	2.9205	0.1818	0.118291	0.90584
	spring	83.712	1.8490	0.3869	0.293177	0.76939
	summer	66.625	1.8028	8.9091	0.223934	0.82281
	autumn	54.627	1.6069	5.5556	0.085200	0.93210
Total nitrogen	winter	37.227	4.9164	-2.0000	-0.297564	0.76604
	spring	40.360	3.8381	4.2626	0.198595	0.84258
	summer	33.756	3.6672	11.7370	0.257319	0.79683
	autumn	28.732	3.3025	-1.0000	-0.206697	0.83625
Total phosphorus	winter	6.1705	2.0767	-1.0000	-0.406984	0.68402
	spring	9.3381	2.0261	-2.0000	-0.232317	0.81676
	summer	6.8573	1.6109	0.6778	-0.201559	0.84026
	autumn	4.5657	1.3091	0.0000	-0.402418	0.68738

In the case of BOD_5, taking into account the occurrence of the maximum value, i. e. the limit value for this parameter of 40 mg/l, the calculated technological reliability for different seasons are: in winter - 90%, in spring - 70%, in summer - 100% and autumn - 97% (Fig. 5). On the basis of the data obtained, it can be concluded that there is a volatility of organic pollutant removal processes in particular seasons, which affects the variability of reliability index values and at the same time the effectiveness of reducing BOD_5 in the constructed wetland during the year. Bearing in mind that in each of the 4 seasons the number of days is about 90, it can be concluded that in winter the limit for BOD_5 can be exceeded in 9 days and in spring in 27 days. In summer the limit value for BOD_5 was not exceeded, whereas in autumn the limit value for this parameter may be exceeded in about 3 days. Therefore, in the case of BOD_5, the highest probability of occurrence of a value higher than the acceptable value is in spring (Fig. 5B), i. e. at a time when the vegetation period is just beginning in the region where the examined treatment plant is located. In summer and autumn, during the period of plant vegetation inhibition, the reliability of organic matter removal expressed by BOD_5 in the constructed wetland is at a very high level, and the risk of occurrence of a value higher than the acceptable value for this parameter is negligible (Fig. 5C, Fig. 5D).

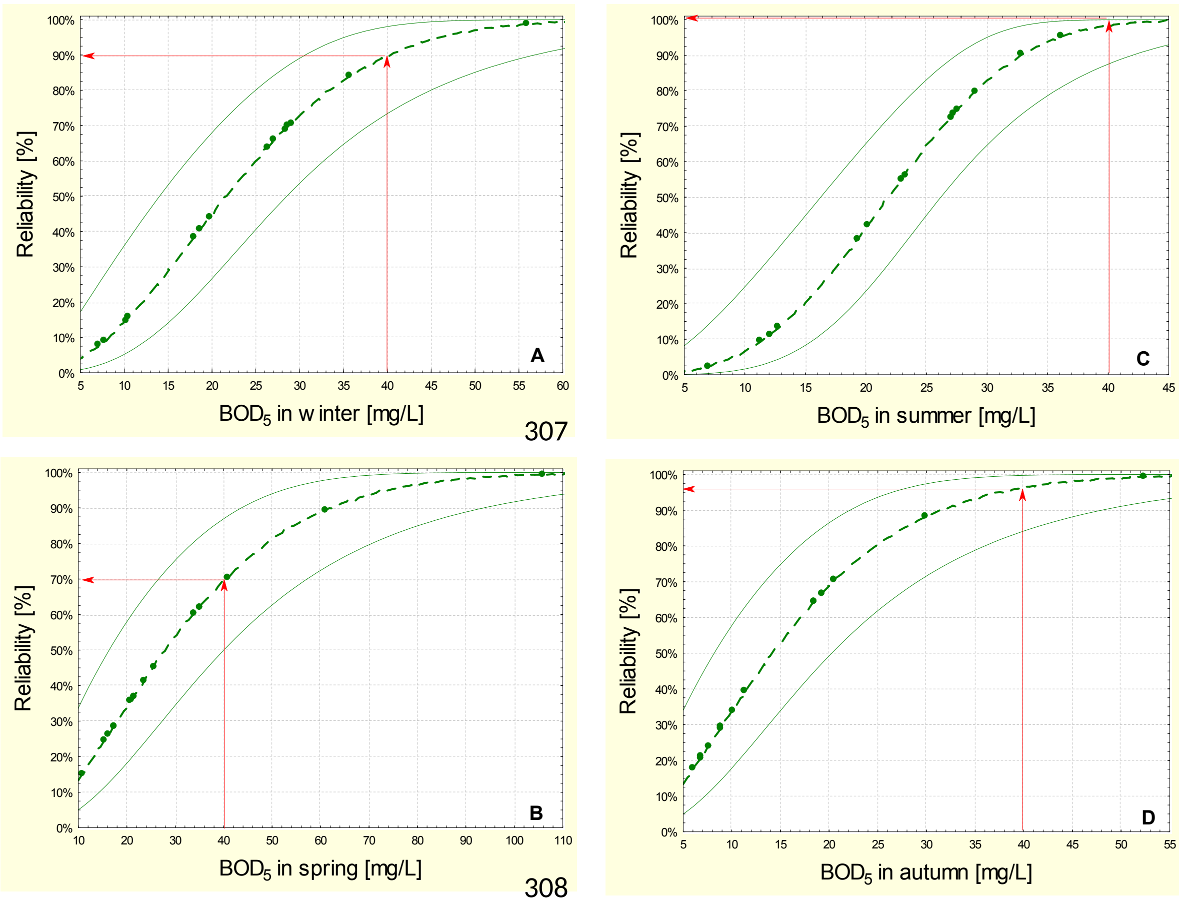

Fig. 5. Technological reliability for BOD_5 decrease in the wastewater treatment plant in different seasons (A - winter, B - spring, C - summer, D - autumn).

For COD, taking into account the occurrence of the maximum value, i. e. the limit value for this parameter of 150 mg/l, the calculated technological reliability index in spring was 94% (Fig. 6B). Therefore, it can be concluded that in this 90-day period it is possible to exceed the limit value specified for COD in about 7 days. In the remaining 3 seasons (summer, autumn, winter) the technological reliability indexes of the technological occurrence of the limit value specified for COD were 100% (Fig. 6A, Fig. 6C and Fig. 6D). It can therefore be concluded that the reliability indexes of COD decrease described by the Weibull model are at the highest level almost throughout the year. Only at the beginning of plant vegetation (spring), the reliability of the decrease in COD is at a lower level and during this period there is a likelihood that higher values of this parameter than the acceptable value will appear.

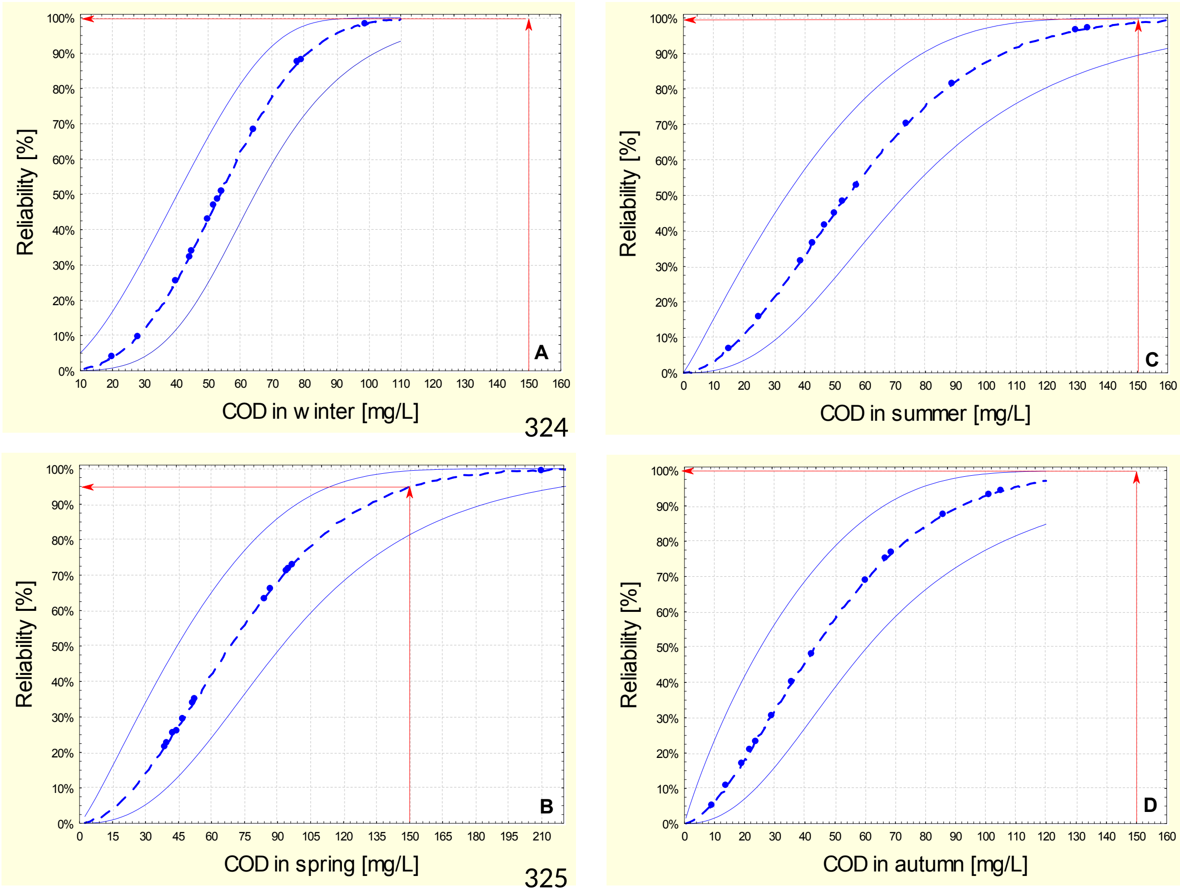

Fig. 6. Technological reliability for COD decrease in the wastewater treatment plant in different seasons (A - winter, B - spring, C - summer, D – autumn).

For total nitrogen, taking into account the occurrence of the maximum value, i. e. the limit value for this parameter of 30 mg/l, the calculated technological reliability indexes for different seasons are: in winter - 30%, in spring - 28%, in summer - 48% and in autumn - 68% (Fig. 7). It can therefore be concluded that in the wastewater treatment plant analysed in winter and spring, the absorption and conversion of nitrogen compounds do not occur at a sufficient intensity, which results in the fact that the concentrations of this parameter in treated wastewater are often higher than the limit value. A higher concentration of total nitrogen than the limit value was found in 11 out of 14 samples during the winter. The concentrations of total nitrogen during this period ranged from 2 to 8.5 mg/l above the limit value (Fig. 7A). In spring, 11 out of 14 samples were also found to have a higher concentration of total nitrogen than the limit value. These overruns ranged from 3 to 16.7 mg/l above the limit value (Fig. 7B). Conversely, in summer 7 out of 14 samples taken were found to have a higher concentration of total nitrogen than the limit value and exceedances ranged from 1 to 21 mg/l (Fig. 7C). In autumn however, 5 cases of exceeding the limit value for total nitrogen in waste water treated with 14 analyses were found. These overruns ranged from 1.4 to 9.0 mg/l above the limit value (Fig. 7D).

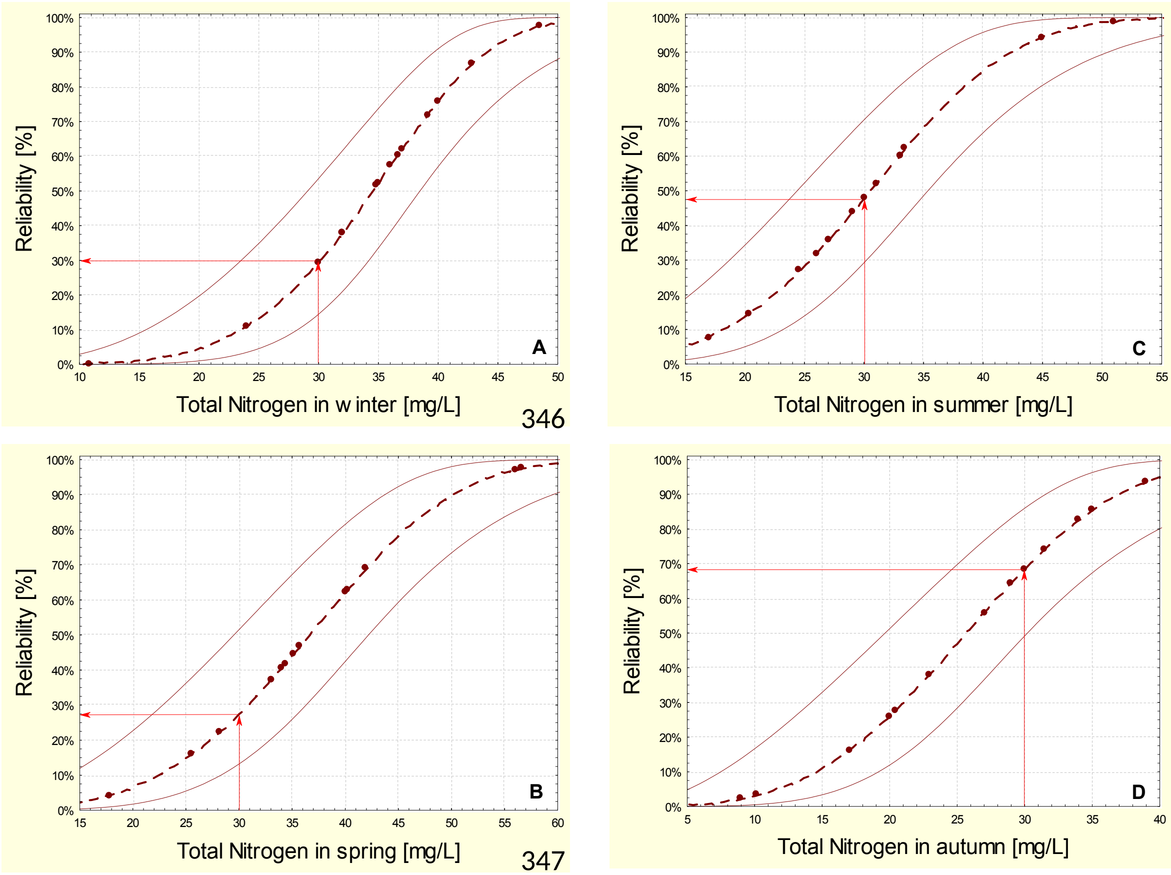

Fig. 7. Technological reliability for total nitrogen removal in the wastewater treatment plant in different seasons (A - winter, B - spring, C - summer, D – autumn).

The second of the analysed nutrient indices, i. e. total phosphorus, as in the case of the previous analysed parameters was unevenly removed in 4 analysed seasons of the year. For total phosphorus, taking into account the occurrence of the maximum value, i. e. the limit value for this parameter of 5 mg/l, the calculated technological reliability indexes for the different seasons are: in winter - 48%, in spring - 23%, in summer - 45% and in autumn - 68% (Fig. 8). In the winter period, 9 out of 14 samples taken were found to have a higher concentration of total phosphorus than the limit value. Total phosphorus concentrations during this period ranged from 0.7 to 4.0 mg/l above the limit value (Fig. 8A). In the spring, 12 out of 14 samples taken were found to have a higher concentration of total phosphorus than the limit value. These excesses ranged from 0.3 to 12.9 mg/l above the limit value (Fig. 8B). In summer, in 8 out of 14 samples, the total phosphorus concentration was higher than the limit value and the exceedances ranged from 1.8 to 6.0 mg/l (Fig. 8C). However, in autumn 6 cases of exceeding the limit value for total nitrogen in waste water treated with 14 analyses were found. These excesses ranged from 0.6 to 5.0 mg/l above the limit value (Fig. 8D).

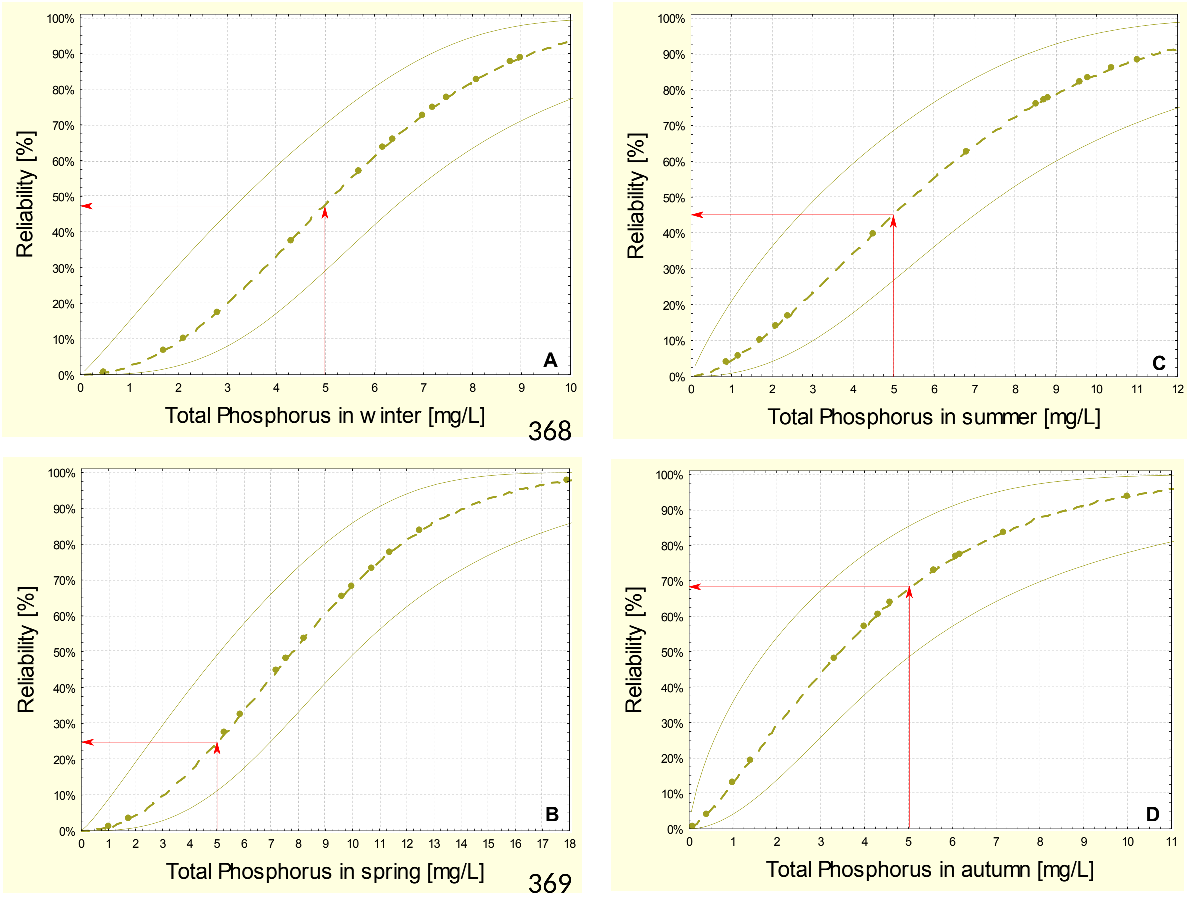

Fig. 8. Technological reliability for the total phosphorus removal in the wastewater treatment plant in different seasons (A - winter, B - spring, C - summer, D – autumn).

5. Discussion

Research shows that the technological reliability of the operation of a single-stage horizontal water treatment plant is unsatisfactory with respect to the removal of nutrient pollutants, i. e. total nitrogen and total phosphorus. On the other hand, the reliability of organic pollutant removal only met the expected requirements in the case of COD, whereas in the case of BOD_5 a seasonal decrease of its reliability was observed. The lowest reliability indexes of the removal of pollutants were usually obtained in winter and spring, which may prove the influence of low air temperatures on the efficiency of wastewater treatment and reliability of operation of a single-stage constructed wetland wastewater treatment plant. According to Gajewska and Obarska-Pempkowiak [58] the effectiveness of constructed wetland systems with vertical flow in the climatic conditions of Poland is about 40% less effective in the period outside vegetation than in the growing season. Therefore, the results and literature data obtained indicate that single-stage constructed wetland systems do not provide stable and reliable removal of contaminants in different seasons during many years of operation. Therefore, they should not be recommended for wider use in temperate climate conditions. According to literature, hybrid constructed wetland systems provide much greater reliability in the removal of organic and biogenic contaminants under Polish conditions [36, 39]. The research of Jucherski et al. [36] show that in the modified hybrid system, in which a filter with LECA® was used in front of the constructed wetland bed, the reliability of reducing BOD_5 and COD was about 100%, while the reliability of removing total nitrogen and PO_4-P was respectively 77 and 97%.

In order to optimize phosphorus removal reliability in constructed wetland systems, the possibility of using special P-filters filled with carbonate-silica is recommended [59–60]. However, the reliability of nitrogen removal can be increased by using a non-conventional method of wastewater oxygenation using hydrogen peroxide [61].

6. Conclusions

The technological reliability of the analysed one-stage, horizontal flow constructed wetland wastewater treatment plant during 14 years of operation were variable in particular seasons of the year. The lowest reliability indexes of the removal of pollutants were usually obtained in winter and spring, which may prove the influence of low air temperatures on the efficiency of wastewater treatment and reliability of operation of a single-stage constructed wetland wastewater treatment plant. The results show that one-stage constructed wetland systems do not provide stable and reliable removal of contaminants in different seasons during many years of operation. Therefore, they should not be recommended for wider use in temperate climate conditions. In order to increase the technological reliability of this type of treatment plant, it is proposed to expand it by creating hybrid systems consisting of two beds with vertical and horizontal flow and a special P-filter.

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