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Effect of initial treatment of surface water at an artificial infiltration intake

Joanna Jeż-Walkowiak*, Aleksandra Makała, Beata Mądrecka-Witkowska, Michał Michałkiewicz, Natalia Kolwicz

Poznan University of Technology, Institute of Environmental Engineering and Building Installations, Berdychowo 4, 60-965 Poznań, Poland, emails: joanna.jez-walkowiak@put.poznan.pl (J. Jeż-Walkowiak), aleksandra.makala@doctorate.put.poznan.pl (A. Makała), beata.madrecka@put.poznan.pl (B. Mądrecka-Witkowska), michal.michalkiewicz@put.poznan.pl (M. Michałkiewicz), natalia.kolwicz@put.poznan.pl (N. Kolwicz)

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ABSTRACT

The goal of the research was to determine the effects of artificial infiltration as an initial water treatment process at the river water intake. The effects were determined with respect to removal of chemical admixtures as well as lowering microbiological parameters. The impact of the seasons and operating conditions of the intake on the achievement of stabilized infiltration effects was investigated. The research was carried out on a water intake for a town with a population of 500,000 in Central Poland. The field research installation was used for the tests. The metering wells (piezometers) were drilled along the water flow path from the pond to the collecting well. The effects of infiltration were assessed in terms of the changes of the physical, chemical and microbiological parameters of infiltration water, compared to river water. The test results confirmed that the infiltration process improves the physicochemical and microbiological parameters of water. The water after the infiltration process exhibits similar characteristics to groundwater. The infiltration effects are affected by the phase of the pond operation cycle. This was visible in the case of organic compounds, the removal of which were the lowest at the beginning of pond operating cycle.

Keywords: Surface water treatment; Infiltration process; Filtration; Adsorption; Biodegradation; Bacteria; Chlorophyll-a; Organics

1. Introduction

An increase of water deficiency and pollution can be observed at a global scale. Groundwater is the most valuable source for the production of drinking water. In order to increase the groundwater resources, which may be depleted, the surface water infiltration process is carried out on the intakes. Infiltration is based on forcing the flow of the surface water into the ground as a result of the intake of the water feeding the aquifer through deep wells. Artificial groundwater replenishment is justified and effective in the areas with favourable geological and hydraulic conditions [1–3].

The surface water which feeds the infiltration intakes contains the inorganic and organic compounds of natural origin in suspended and soluble forms. In most cases, the surface water in rivers is contaminated with sewage, chemicals, drugs, hormones, bacteria, viruses, fertilizers, plant protection agents and their breakdown products [4,5]. Artificial infiltration of surface waters improves numerous physicochemical and microbiological parameters of water [6–10]. The improvement of the water quality in the infiltration process occurs as a result of the filtration, sedimentation, adsorption, biodegradation, and ion exchange processes [2,11]. The infiltration process changes the quality

* Corresponding author.

of surface water to that of groundwater with an elevated concentration of iron and manganese [2,3].

The infiltration process is commonly used in every region of the world. The effect of initial pretreatment at the intake mainly is influenced by the raw water quality. The infiltration intakes are supplied by the lake waters for example in Finland, [12,13] and by river waters for example in Germany (Zurich, Dusseldorf and Berlin) [2], Poland (Warszawa, Legnica, Poznań, Bydgoszcz), Brazil [14], India and USA [15].

It is important to situate the infiltration intake in favorable hydrogeological conditions [2]. The ground should be permiable to an appropriate degree and create the opportunity for effective filtration.

The other factor which influences the infiltration water quality is the balance of raw groundwater and surface water supplying the intake. The balance depends on the location of the intake and the aquifer. The retention time of water in the ground is a very important factor which affects the pre-treatment efficiency.

The operation conditions and design approaches depend on the water authority. In European infiltration intakes, the ground retention time lasts from weeks to even months giving the opportunity to eliminate the dissolved organic carbon, while in the USA the retention is usually much shorter and effects are focused on the removal of pathogens [2].

The efficiencies in the order of several dozen percent contribute to measurable benefits in terms of the treatment costs of water treatment stations. A well designed infiltration intake situated at an appropriate hydrological site may provide high quality water that needs much simpler treatment [16].

For the efficiency of the treatment system, it is important that the effects of infiltration carried out on the intake are kept at a stable level in order to maintain the required treatment effects on the water treatment plant. The effect of the infiltration might be affected by several operational conditions such as sudden deterioration of the supply water quality, increased water demand and the operating phase of infiltration ponds.

The operation of infiltration ponds consists of four stages:

- the initial stage of pond operation (after periodic cleaning of the ponds), which includes a gradual improvement of the infiltration water quality,
- the stage of operation with constant treatment efficiency,
- the final stage of operation, in which the infiltration efficiency decreases,
- the stage of cleaning the bottom of the pond.

It is important to estimate the impact of operation conditions for the certain infiltration intake to evaluate the risk of lowering the elimination efficiency of organics and microbial. The efficiency of the infiltration process decreases over time, because detritus, organic and inorganic matter accumulate at the bottom of the infiltration ponds. When the filtration rate is too low, the upper filtration layer must be removed. The process of cleaning the bottom of the infiltration pond determines the pond operation cycle analogously to the cycle of the rapid filters.

The total organic carbon (TOC) parameter is used in many studies to evaluate the efficiency of organics removal in infiltration process. The average efficiency of reducing the TOC value achieved in the infiltration process reaches values up to 70% [12–16]. The effectiveness of reducing TOC in the infiltration process on selected infiltration intakes in the world is presented in Table 1. The values in the table show that the infiltration intakes are characterized by a significant removal efficiency of organic compounds. The efficiencies in the order of several dozen percent contribute to measurable benefits for the treatment costs of water treatment stations.

The study presents the results of water testing from two operation periods of the test pond: immediately before cleaning the bottom of the pond from accumulated sediments (stage I of research) and after cleaning it from bottom sediments (stage II of research). The long stage II period allowed elucidating the effects of infiltration and to determine the variability of infiltration water quality depending on the pond exploitation period, seasons and intake efficiency.

The purpose of the research was to determine the effects of artificial infiltration performed at the river water intake as well as to evaluate the factors affecting this performance, such as raw water quality changes during the year and stage of infiltration pond operation. The effects were determined with respect to removal of chemical admixtures as well as lowering microbiological parameters.

The experiment was designed in accordance with the research methodology of the infiltration process [7] in

Table 1
TOC removal effectiveness at selected infiltration intakes

Infiltration intake, location	Raw water TOC, (mg/L)	Average TOC removal efficiency, (%)	Literature
Hietasalo, Finland	12.1	20	[12]
Lake Vihnusjärvi, Finland	10	55	[13]
Vesijärvi	4.8	29	[13]
Louisville, USA	–	60	[17]
Krajkowo–Mosina, Poland (vertical and horizontal wells)	14.25	22.5–25.7	[7]
USA	–	35–67	[15,18]
Lagoa do Peri, Santa Catarina, Brazil	6.0	28	[14]

order to determine changes in the quality parameters of the infiltrating water during its flow through the ground.

2. Material and methods

2.1. Study area, research installation and measuring points

The research was carried out on a water intake for a town with a population of 500,000 in Central Poland. The infiltration intake is supplied by Warta River at the 247–251 km of the river course. Warta is the third longest river in Poland, the second fully within its borders; and the main, right tributary of the Oder River. Warta Dolna (68.2 km, from Santok to the mouth of the Oder) is an element of the International Waterway E70, established in 1996 in the AGN (European Agreement on Main Inland Waterways of International Importance).

From the hydrogeological point of view, Debina intake is located within quaternary uncovered groundwater reservoir. It covers part of the floodplain terrace of the left-bank Warta River valley. The ground of the reservoir is made of Upper Miocene clays. The quaternary aquifer consists of two age series – the younger from Holocene and the older from Pleistocene. In total, they do not exceed 20 m in thickness. Holocene sediments reach 4–8 m deep on average. They are strongly diversified. They are dominated by fine-grained and dusty sands, but intercalations of silt, peat and alluvion can also be countered. Holocene sediments are the base of infiltration ponds. Pleistocene sediments occur in the bottom part of the reservoir and are more homogeneous. They consist of medium-grained and coarse-grained sands with an admixture of gravel or only gravel with pebbles. Finer deposits are rarely observed. The most favourable infiltration conditions are in the south of the reservoir in the region of Luboń – a bed in sands of considerable thickness. Less favourable conditions occur along the Starołęcka edge – left-bank infiltration limited by tertiary clays. The worst infiltration conditions occur along the III siphon wells – large amount of organic sediments.

The balance of raw water directed from Debina intake to the water treatment system is as follows: artificial infiltration – approx. 70%, riverbank infiltration – approx. 20%, groundwater – 10% [19].

The river water is taken from the bay current intake and pumped to infiltration ponds without pre-treatment. Infiltration water is taken up by a system of siphon wells located 60–90 m from the edge of the infiltration ponds. The infiltration water is then treated at the water treatment plant through the aeration, rapid filtration and disinfection processes.

The experimental installation is located on the way between the bank of the infiltration pond (one of 27 operated ponds at the intake) and one of the intake wells included in the water collecting system – levar II. The levar II collects water from 92 wells with average capacity of 1,200 m^3/h.

The retention time of water in the ground of field experimental installation was determined on the basis of temperature measurements in the pond, piezometers and collecting wells. The retention time of water during infiltration corresponds to the travel time of a wave of water of the same temperature [1]. The retention time for the field installation is equal to 70 d. The retention time for the entire intake is approx. 4–8 weeks [20].

Water-bearing formations in the infiltration intake are characterized by very good permeability. The ground is an excellent filter bed for acquiring groundwater from natural and artificial water from infiltration ponds. The temperature of the water, which ranges from 0.5°C to 24°C, affects the filtration speed. The coefficients of filtration and hydraulic conductivity of the aquifer may vary. The maximum filtration rate is 18.32 m^3/h and the minimum is 3.2 m^3/h.

An on-site research installation which consisted of 3 piezometers drilled along the water flow path from the pond to one of the siphon wells was built (Fig. 1). The line drawn by piezometers is perpendicular to the edge of the pond and the line of siphon wells. The metering wells (piezometers) are 5.5, 7.5 and 9.5 m deep and have diameter of 10 cm. The collecting well is 15.50 m deep. The infiltration pond is 600 m long and approximately 20 m wide at the bottom. The water flow at the intake and in the research installation together with measuring points is presented in Fig. 1. The cross-section of the infiltration path is presented in Fig. 2. The conducted geological research shows that in the subsurface layer of the ground up to a depth of approx. 2.5 m below the ground level there are fine sands. Below there are non-composites, including medium-grained and coarse-grained sands with an admixture of gravel. In the lowest tested cross-section, 8 m below the ground level the presence of gravel with pebbles was found.

The measuring points for water testing included: the Warta River (R), beginning of the pond (PB), middle of the pond (PM), end of the pond (PE), piezometers (PP-1, PP-2, PP-3) and the infiltration well (W). The distance of the measuring points from the edge of the infiltration pond is given in Table 2.

2.2. Stages and scope of the research

The studies were conducted from the 17th of January 2018 to the 23rd of September 2019. The experiments were divided into two stages: initial and main research. The initial tests were conducted from January 2018 to July 2018. They included the analysis of the water collected from five measuring stations: from the Warta River (R), from three infiltration pond positions (beginning of the pond – PB,

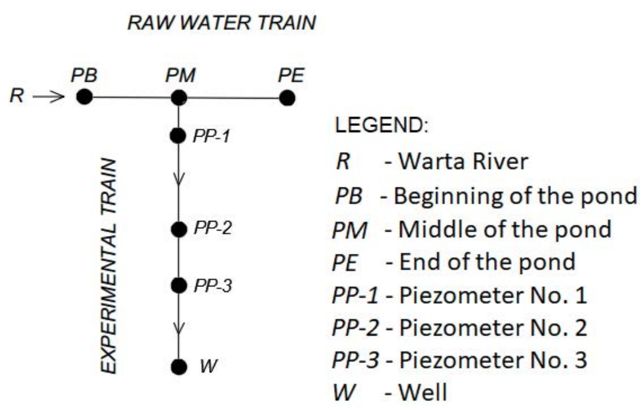

Fig. 1. Water flow scheme on the intake with measuring points.

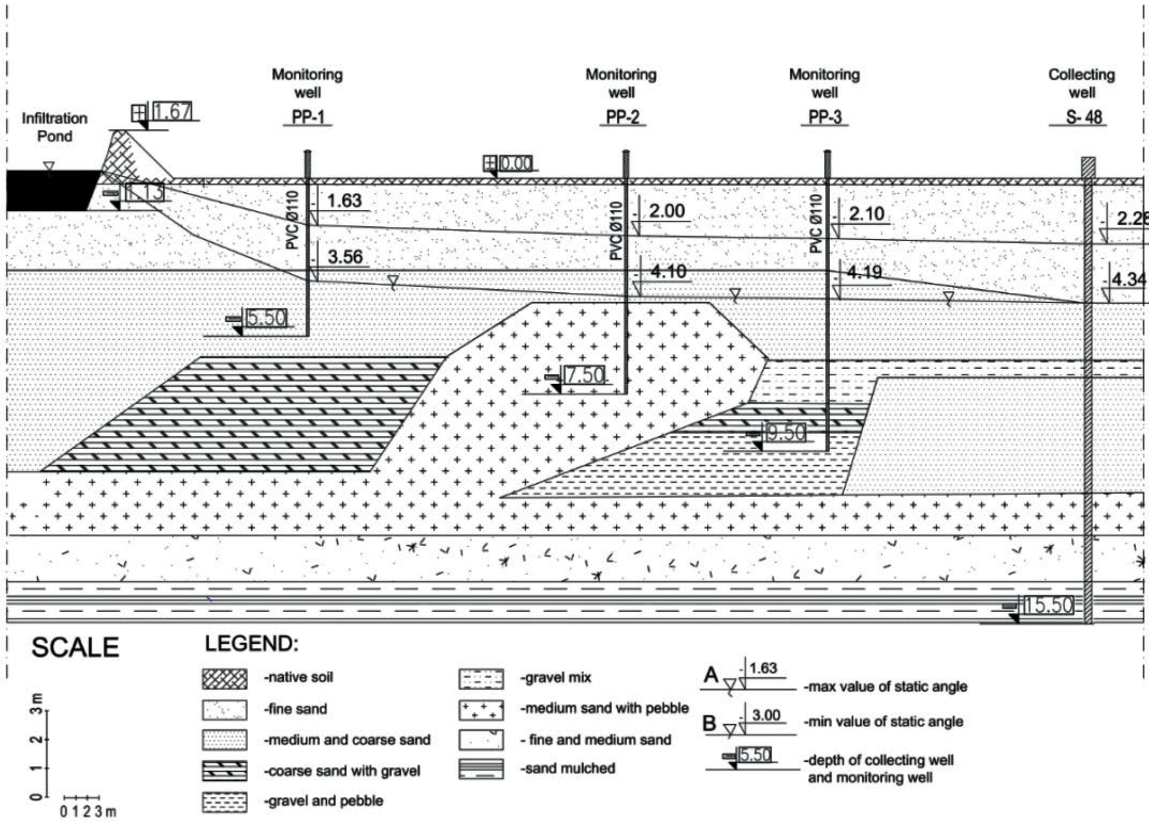

Fig. 2. Cross-section of the infiltration path (Cierniak et al. [1]).

Table 2
Distance of measuring points from the bank of the infiltration pond

Sampling points	Distance from pond's bank, (m)
PP-1	18.00
PP-2	45.50
PP-3	62.90
Well – W	85.90

middle of the pond – PM, end of the pond– PE) and wells (W station). Initial examinations were carried out during the final period of the pond work cycle before the cleaning process in July 2018. Six research series were carried out during the preliminary period. The samples were collected by every month.

The experiments during the second stage were extended in relation to the preliminary tests by the analyses of the water collected from the piezometers located on the path of infiltration water flow from the pond through the ground to the well (measuring stations PP-1, PP-2, PP-3). The second stage began with a new cycle of the pond operation after its cyclic cleaning. Thirteen research series were carried out during the second main period of research from October 2018 to September 2019. The samples were collected every month. In the second stage, the water analyses were performed for all 8 measuring points.

The effects of artificial infiltration were assessed in terms of the changes of river and infiltration water quality parameters, such as: turbidity, colour, total suspension, nitrogen and phosphorus, iron, organic compounds measured as TOC, chemical oxygen demand (COD-Mn), microbiological parameters (abundance of coliform, *Escherichia coli*, enterococci, mesophilic and psychrophilic bacteria) and Chlorophyll-a.

2.3. Sampling methods

The sampling of water for the bacteriological tests from the Warta River and infiltration ponds was carried out from the subsurface layer (approx. 30–50 cm under the water surface).

The infiltration ponds are shallow and their depth is equal to approx. 1.2–1.5 m. In order to avoid cloudiness of the water by moving the bottom sediment by the bathometer and at the same time not to collect water from the surface, samples were collected from the subsurface layer, from a depth of approx. 30–80 cm. Samples taken from several depths of such a layer would not represent the variability of the parameters tested. Therefore, 5 L water samples were collected in order to average the water quality. In case of the river, water samples were taken from a similar depth, as there are pump inlets there, forcing the water to the infiltration ponds.

The water collection from piezometers and from the well was carried out by means of a pump and a hose (sterile).

Collection of water from PP-1, PP-2 and PP-3 for analysis was carried out after pumping out two volumes of water from the piezometer.

2.4. Field analyses

The retention time of infiltrated water in the ground was evaluated by temperature measurements. The temperature of water was measured in the infiltration pond, in piezometers and in collecting well about two meters below the water level, every 2–4 weeks.

2.5. Laboratory analyses

The physicochemical analyses of pH-value, temperature, conductivity, dissolved oxygen, COD-$KMnO_4$, nitrogen (ammonium, nitrate, nitrite), phosphorus (total, orthophosphate), iron, colour and turbidity, total suspended solids (TSS) were carried out according to Standard Methods [21]. The TOC analyses were carried out using the Multi N/C® 3100, Analytik Jena, Germany. Total suspended solids were determined after filtration through Whatman GF/F glass fibre filters and desiccation at 105°C. Chlorophyll-a was determined spectrophotometrically after filtration through Whatman GF/F glass fibre filters and extraction in 90% acetone. The calculation of its concentration was carried out using Lorenzen's formula [22].

The microbiological sanitary analysis of water included the determination of the total number of mesophilic bacteria in a 1 mL water sample (culture at 36°C ± 2°C for 48 h), psychrophilic bacteria in a 1 mL water sample (culture at 20°C ± 2°C for 72 h), coliform bacteria in a 100 mL water sample (culture at 36°C ± 2°C for 24–48 h), *Escherichia coli* in a 100 mL water sample (culture at 44°C for 24–48 h) and faecal enterococci (*Enterococcus*) in a 100 mL water sample (culture at 36°C ± 2°C for 24–48 h). The mesophilic and psychrophilic bacteria were studied by means of pour plate technique using nutrient agar, the coliform and *Escherichia coli* bacteria by means of membrane filtration using Endo FM Agar, while faecal enterococci were determined based on membrane filtration and Slanetz and Bartley Medium *Enterococcus* Agar [23–25]. Due to the different degree of microbial water contamination, dilutions of water samples were used during the tests, and the final result was calculated in the case of mesophilic and psychrophilic bacteria as CFU/1 mL (CFU – colony forming unit), while in case other microbiological parameters, CFU/100 mL was used.

TSS and Chlorophyll-a in the groundwater samples at the initial stage of the tests were close to zero therefore, at a further stage of research, the analysis of these parameters were limited to the surface water samples only.

All field and laboratory analyses were performed in triplicates.

3. Results

3.1. Preliminary research

Selected results of physicochemical analyses of water from the Warta River and the infiltration pond from the first stage of research are summarized in Table 3.

In the winter period of preliminary tests, the measured parameters (COD, ammonia, nitrites, nitrates, turbidity, colour, total phosphorus, orthophosphates and TSS) were relatively stable in river water (R), at the beginning (PB) and at the end (PE) of the pond. COD, turbidity, colour and orthophosphates in the R-PB-PE flow path fluctuated during the summer because biodegradation processes and better sedimentation occur at higher temperatures.

In the initial period of research, from January to June 2018, variable values of Chlorophyll-a and TSS were measured at measuring points. In winter, the Chlorophyll-a values were very low – below 7 μg/L, while in the spring, along with the development of phytoplankton organisms, they began to increase. In the Warta River in April and June its concentration was high and reached >50 μg/L. High values of this parameter indicated the eutrophication of the Warta River according to the criteria proposed by Dodds et al. [26] and sampling points located in the pond based on the Carlson's Trophic State Index for Chlorophyll-a – TSI(CHL) (mean values >50) [27,28].

During preliminary tests, the water samples for microbiological determinations were collected in the Warta River (R) as well as at the beginning (PB) and at the end (PE) of the infiltration pond. The total number of mesophilic and psychrophilic bacteria in a 1 mL water sample as well as coliform, *Escherichia coli* and enterococci bacteria in a 100 mL water sample were analysed. The test results are summarized in Table 4.

During the complete research period, significant fluctuations in the number of all microorganisms were noted. In all water samples, a higher number of the psychrophilic compared to the mesophilic bacteria was usually noted, while the presence of coliforms, *Escherichia coli* and enterococci indicated faecal water contamination.

3.2. Second stage of research

On the basis of the measurement of the temperature changes at measuring points in the period from October 2018 to July 2019, the residence time of water in the ground was determined at 70 d [1]. The water quality parameters of 8 measuring points, including river, beginning, middle and end of the pond as well as metering wells are presented in the following charts. In the infiltration process, the amount of easily oxidizable organic compounds is reduced, which is measured by the reduction of COD-Mn. The COD-Mn of water during infiltration decreased from 6.3–12.84 mg O_2/L (river) to 4.10–5.86 mg O_2/L (well). The average COD-Mn values calculated for individual seasons were presented in Fig. 3. The change of the TOC value in river water, in the pond and along the infiltration route to the tested well was presented in Fig. 4. The concentrations of TOC was much higher in the Warta River (3.55–10.06 mg C/L) than in the well (0.00–4.92 mg C/L).

The following figures show the change of colour (Fig. 5) and turbidity (Fig. 6) in raw and infiltrating water.

The colour of the water (Fig. 5) decreased in the flow path from the river to the well to the value 8–16 mg Pt/L.

The infiltration results in a high removal of turbidity (Fig. 6). The lowest turbidity values of 0.09–0.34 NTU were recorded in the PP-3 piezometer. The total iron concentration

Table 3
Values of selected physicochemical parameters of water in the Warta River (R) as well as at the beginning (PB) and the end (PE) of the infiltration pond during the initial study period

Station	Date						Average ± standard deviation
	17.1.18	8.2.18	28.3.18	24.5.18	25.6.18	9.7.18	
			Turbidity (NTU)				
R	15	2	2	6	15	10	8.3 ± 6.0
PB	ns	2	2	10	9	ns	5.8 ± 4.3
PE	16	2	2	2	90	ns	22.4 ± 38.3
			Colour (mg Pt/L)				
R	40	35	40	50	40	40	40.8 ± 4.9
PB	ns	35	40	50	40	ns	41.3 ± 6.3
PE	45	30	45	35	40	ns	39.0 ± 6.5
			Chemical oxygen demand (COD-Mn) (mg O_2/L)				
R	7.8	4.6	8.9	11.9	10.5	ns	8.7 ± 2.8
PB	ns	4.4	9.4	10.3	10.2	ns	8.6 ± 2.8
PE	8.1	4.7	9.7	7.9	8.5	ns	7.8 ± 1.9
			Ammonium nitrogen (mg NH_4/L)				
R	0.48	0.46	0.38	0.31	0.00	0.00	0.27 ± 0.2
PB	ns	0.49	0.40	0.36	0.00	ns	0.31 ± 0.2
PE	0.02	0.44	0.39	0.31	0.00	ns	0.23 ± 0.2
			Nitrites (mg NO_2/L)				
R	0.18	0.13	0.16	0.23	0.07	0.05	0.14 ± 0.07
PB	ns	0.13	0.17	0.12	0.07	ns	0.12 ± 0.04
PE	0.13	0.12	0.18	0.36	0.11	ns	0.18 ± 0.10
			Nitrates (mg NO_3/L)				
R	0.05	0.03	0.03	0.06	0.04	0.05	0.04 ± 0.01
PB	ns	0.07	0.01	0.04	0.04	ns	0.04 ± 0.02
PE	0.08	0.06	0.02	0.03	0.05	ns	0.05 ± 0.02
			Orthophosphates (mg P/L)				
R	0.0130	0.0053	0.0102	0.0253	0.0088	0.0203	0.0138 ± 0.008
PB	ns	0.0048	0.0124	0.0182	0.0062	ns	0.0104 ± 0.006
PE	0.0160	0.0037	0.0120	0.0106	0.0044	ns	0.0093 ± 0.005
			Organic phosphorus (mg P/L)				
R	0.0730	0.0267	0.0818	0.6947	0.0462	0.0827	0.1675 ± 0.259
PB	ns	0.0282	0.0456	0.0708	0.0468	ns	0.0479 ± 0.018
PE	0.0420	0.0223	0.0770	0.7294	0.0866	ns	0.1915 ± 0.302
			Total phosphorus (mg P/L)				
R	0.0860	0.0320	0.0920	0.7200	0.0550	0.1030	0.1813 ± 0.265
PB	ns	0.0330	0.0580	0.0890	0.0530	ns	0.0583 ± 0.023
PE	0.0580	0.0260	0.0890	0.7400	0.0910	ns	0.2008 ± 0.303
			TSS (mg/L)				
R	4.9	3.2	6.6	25.8	12.4	29.4	13.7 ± 11.2
PB	ns	4.4	7.0	25.6	14.6	17.4	13.8 ± 8.5
PE	5.6	2.2	6.9	17.0	2.4	40.8	12.5 ± 14.9
			Chlorophyll-a (μg/L)				
R	2.49	2.25	20.58	53.51	26.20	69.28	29.05 ± 27.3
PB	ns	3.61	15.72	55.38	17.59	46.19	27.70 ± 22.0
PE	4.74	6.42	44.91	23.95	4.12	78.69	27.14 ± 29.8

ns – not studied

Table 4
Results of preliminary microbiological tests of water in the Warta River (R), at the beginning (PB) and end (PE) of the infiltration pond

Station	Date								
	17.1.18	8.2.18	28.3.18	24.5.18	25.6.18	9.7.18	Min.	Max.	Average ± SD
	Mesophilic bacteria (CFU/1 mL)								
R	650	2,600	480	1,770	13,200	1,650	480	13,200	3,392 ± 4,868
PB	ns	1,500	750	8,500	2,850	11,600	750	11,600	5,040 ± 4,763
PE	440	300	170	775	1,260	1,500	170	1,500	741 ± 540
	Psychrophilic bacteria (CFU/1 mL)								
R	4,700	6,100	6,600	4,300	15,100	13,200	4,300	15,100	8,333 ± 4,625
PB	ns	6,400	5,100	11,500	4,400	11,400	4,400	11,400	7,760 ± 3,444
PE	4,500	5,200	1,350	450	2,400	2,050	450	5,200	2,658 ± 1,837
	Coliform (CFU/100 mL)								
R	2,020	3,400	3,500	5,000	57,500	ns	2,020	57,500	14,284 ± 24,181
PB	ns	3,500	1,875	5,250	43,200	ns	1,875	43,200	13,456 ± 19,877
PE	800	152	2,125	1,200	14,400	ns	152	14,400	3,735 ± 6,004
	Escherichia coli (CFU/100 mL)								
R	360	240	1,750	85	22,000	ns	85	22,000	4,887 ± 9,590
PB	ns	84	150	80	18,000	ns	80	18,000	4,579 ± 8,948
PE	34	5	175	6	6,200	ns	5	6,200	1,284 ± 2,749
	Enterococci (CFU/100 mL)								
R	200	280	590	100	440	ns	100	590	322 ± 195
PB	ns	120	190	140	420	ns	120	420	218 ± 138
PE	75	28	12	4	280	ns	4	280	80 ± 115

ns – not studied

in the water collected from all measuring points is presented in Fig. 7. The iron present in surface water is removed in the ground up to the last PP-3 piezometer. Iron is washed out of the deep soil near the well.

The following charts show the changes in the concentration of various forms of nitrogen (Fig. 8) and phosphorus (Fig. 9) in raw and infiltrating water.

The highest concentrations of ammonium nitrogen occurred in winter and spring (up to 0.95 mg NH_4/L), in turn, the lowest – in autumn (0.11 mg NH_4/L). Higher concentrations of nitrates (NO_3) occurred in spring and summer (up to 1.66 mg NO_3/L), whereas they were very low in autumn and winter at a level of 0.01–0.03 mg NO_3/L. The highest nitrite nitrogen concentrations occurred in winter and spring (up to 0.54 mg NO_2/L), while the lowest were determined in summer (0.01–0.23 mg NO_2/L).

The average total phosphorus remained in the range of 0.02–0.39 mg P/L. As the infiltration proceeded, the concentration of orthophosphates increased, while the concentration of total phosphorus fluctuated slightly. The concentration of TSS in the second stage of the study usually was the lowest at the end of the pond (Fig. 10).

From October to February, low Chlorophyll-a values (usually <10 μg/L) were observed in the river and in the pond (Fig. 11). In turn, from March to September there was a continuous increase in Chlorophyll-a concentration in the Warta River. The values exceeding 30 μg/L recorded in spring and summer indicated the eutrophication of the Warta River waters according to the criteria proposed by Dodds et al. [26]. In turn, mean year TSI(CHL) (trophic state index) calculated for the pond indicated its eutrophication in the measuring station – PB (TSI(CHL) > 50) and mesotrophy in other stations (TSI(CHL)) – the obtained values were between 40 and 50) [27,28]. This indicated a reduction of water trophy with the flow of water along the pond. At the PM and PE stations, much lower Chlorophyll-a values in comparison to the PB station were usually measured. The sample collected in early July was an exception, in the case of which the Chlorophyll-a concentration was very low in the pond at each site. During this time, intensive zooplankton development was observed in the pond – mainly of *Cladocera*, which are consumers of phytoplankton organisms.

The microbiological analysis of water included the same determinations that were carried out during the initial tests. The obtained results regarding mesophilic and psychrophilic bacteria, coliforms, *Escherichia coli* and enterococci were summarized in Figs. 12–16.

The abundance of mesophilic bacteria in the Warta River and in the pond (Fig. 12) fluctuated significantly and ranged from 20 (14.05. PM) to 37,800 (15.01. PB) CFU/1 mL. More often, higher numbers were found in the river water

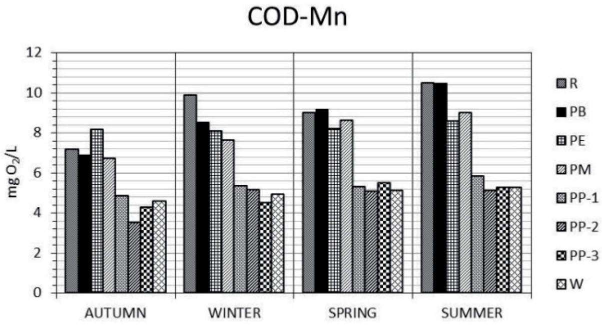

Fig. 3. COD-Mn in water at the infiltration intake.

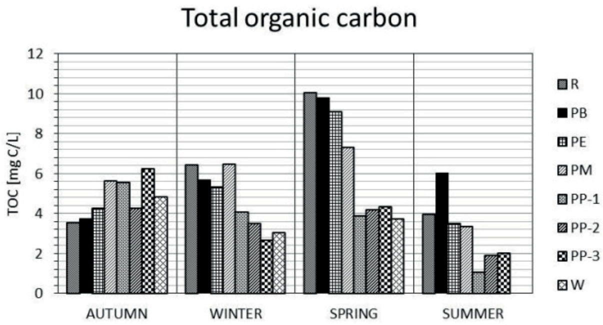

Fig. 4. TOC in water at the infiltration intake.

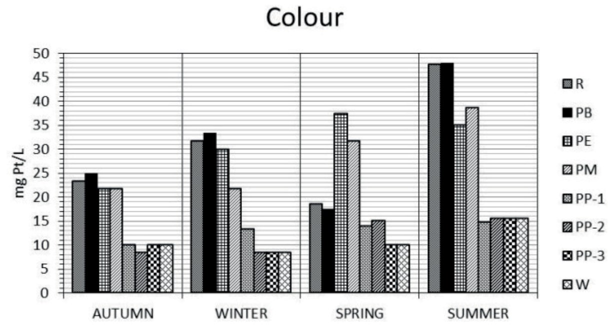

Fig. 5. Colour in water at the infiltration intake.

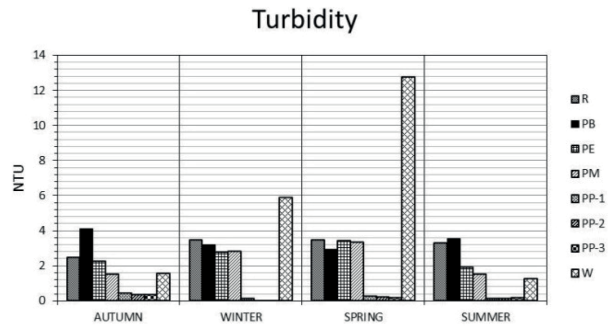

Fig. 6. Turbidity in water at the infiltration intake.

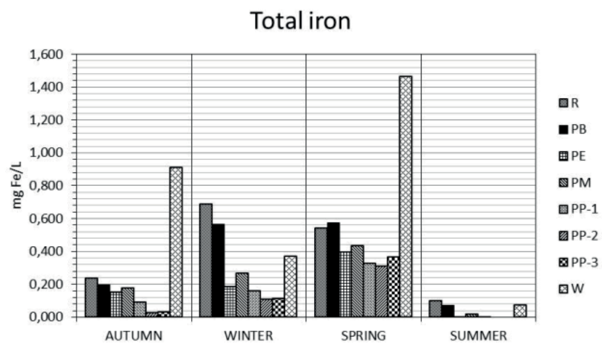

Fig. 7. Total iron in water at the infiltration intake.

(R) or at the beginning of the pond (PB), while the lowest values were measured at the end of the pond (PE) or in the middle (PM). A similar relationship concerned the psychrophilic bacteria (Fig. 13); however, their numbers were usually higher compared to the mesophilic bacteria. Coliform bacteria, *Escherichia coli* and enterococci (Figs. 14–16), which indicate the faecal contamination of water, were also more commonly found in the river water (R) or at the beginning of the pond (PB). Their numbers also fluctuated significantly during the individual research periods.

The average values and standard deviations for chemical and microbiological water quality parameters are presented in Tables 5 and 6.

4. Discussion

The use of infiltration ponds at the water intake allows the retention of surface water in the event of a sudden deterioration in the quality of feed water or an ecological disaster. The infiltration intake provides retention for a period of approx. a month in the event of the need to stop the flow of river water to infiltration ponds, for example, in the event of an ecological disaster [19,20]. The residence time of water in the infiltration ponds can result in the stabilizing and averaging of water quality parameters in relation to the usually high variability of the surface water quality parameters [29]. High variability of surface water may occur, for example, after intense atmospheric precipitation, and include an increase of nitrogen, phosphorus and suspension concentrations due to the surface runoff from agricultural areas [9,10,30]. Long-term observations of water quality at the intake confirm the averaging effect of the ponds [20]. Such averaging of physicochemical parameters was not observed during our research.

However, a change in the physicochemical parameters of water were observed during its retention in the pond and flow from the beginning of the pond to its end in both the initial and the second research period. During the winter period of the initial study (January–March), low air and water temperatures resulted in the termination of the biodegradation processes and the development of microorganisms in the pond [2,31,32]. Similarly, the rate of biodegradation processes in spring were very low.

The second stage of research began after the bottom sediments were removed from the ponds. During this period, the hydraulic load of the pond is lower and filtration is

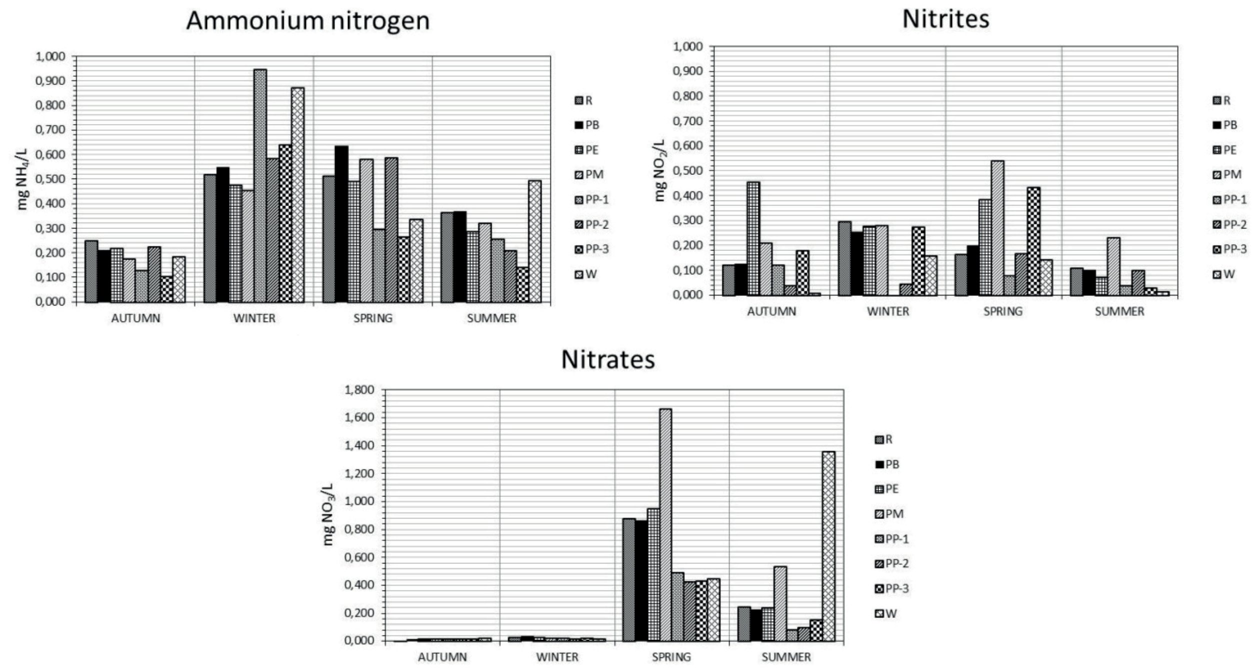

Fig. 8. Nitrogen in water at the infiltration intake.

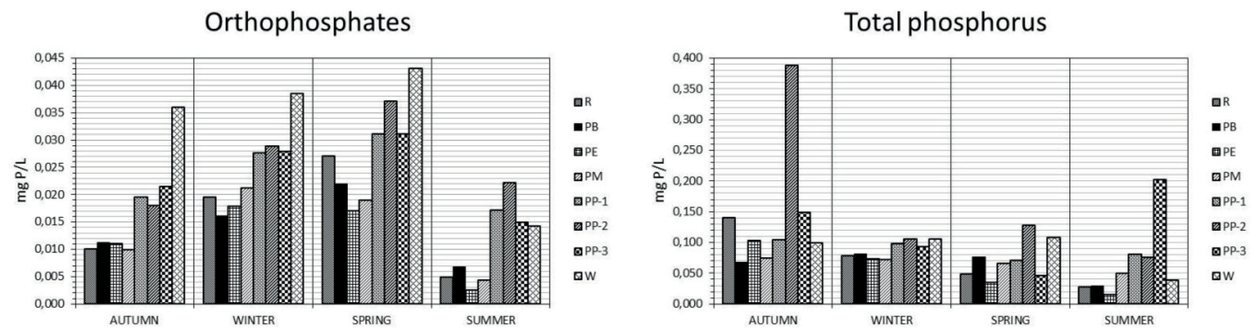

Fig. 9. Phosphorus in water at the infiltration intake.

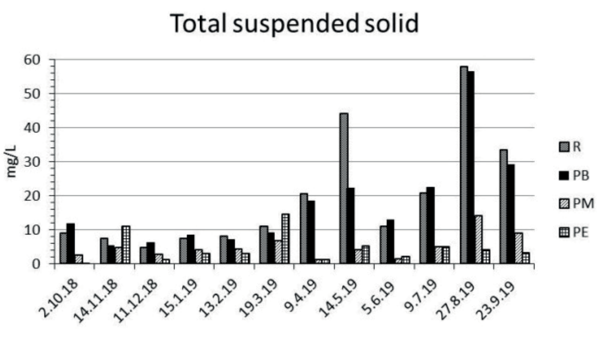

Fig. 10. Total suspended solids in water at the infiltration intake.

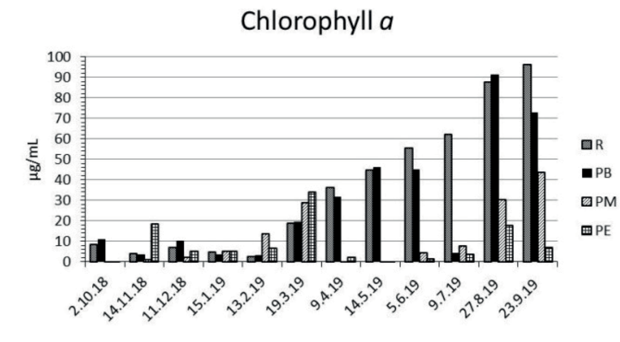

Fig. 11. Chlorophyll-a in water at the infiltration intake.

carried out at a higher rate, until the sediment layer semi mineral-biological filter membrane is formed at the bottom. Most of the heterogeneous contaminants carried in river water are retained in the sediment layer [20]. The quality of the infiltrating water is also changed as a result of adsorption and filtration in the bottom layer of the filtration membrane [2,20,29,33]. The aeration zone under the bottom of the pond also plays an important role in water

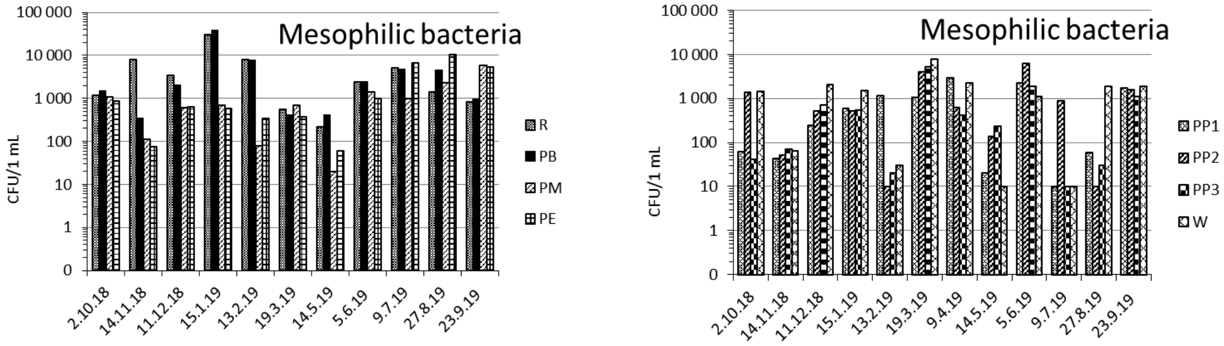

Fig. 12. Mesophilic bacteria (CFU/1 mL) in water at the infiltration intake.

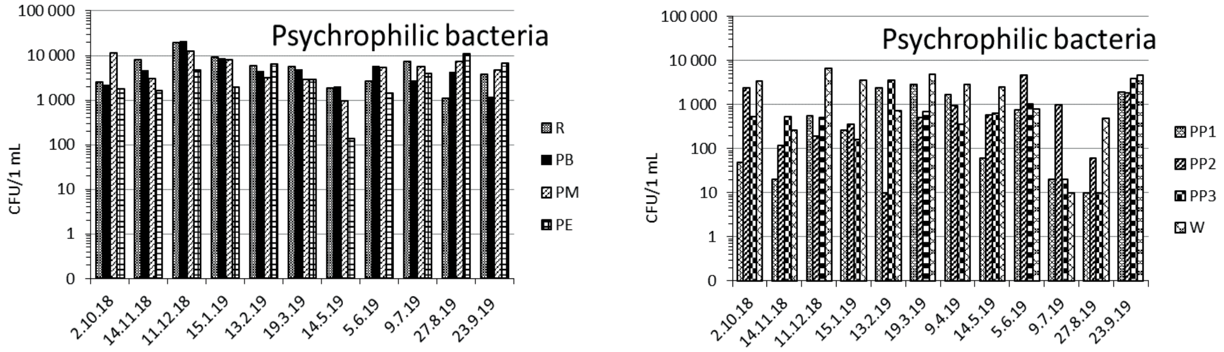

Fig. 13. Psychrophilic bacteria (CFU/1 mL) in water at the infiltration intake.

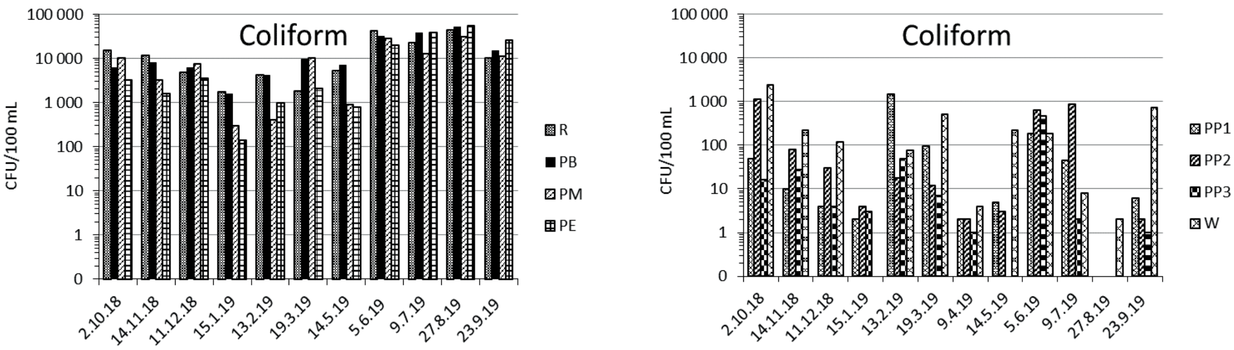

Fig. 14. Coliform bacteria (CFU/100 mL) in water at the infiltration intake.

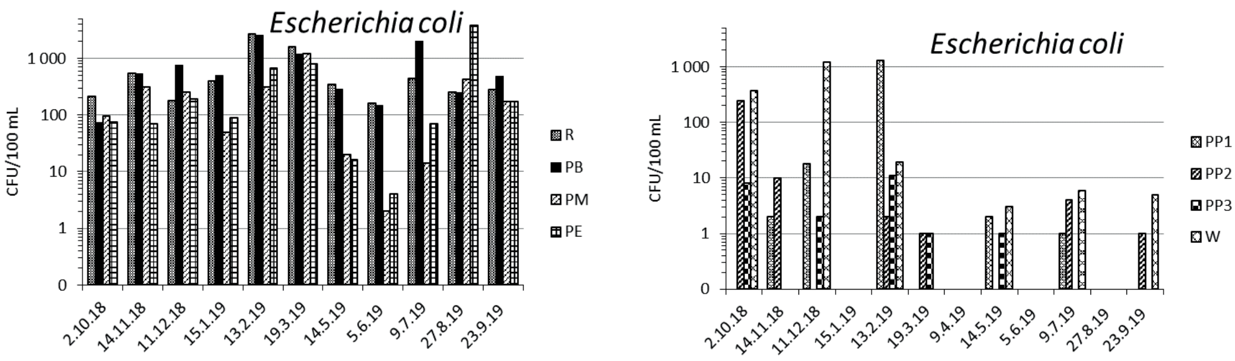

Fig. 15. *Escherichia coli* (CFU/100 mL) in water at the infiltration intake.

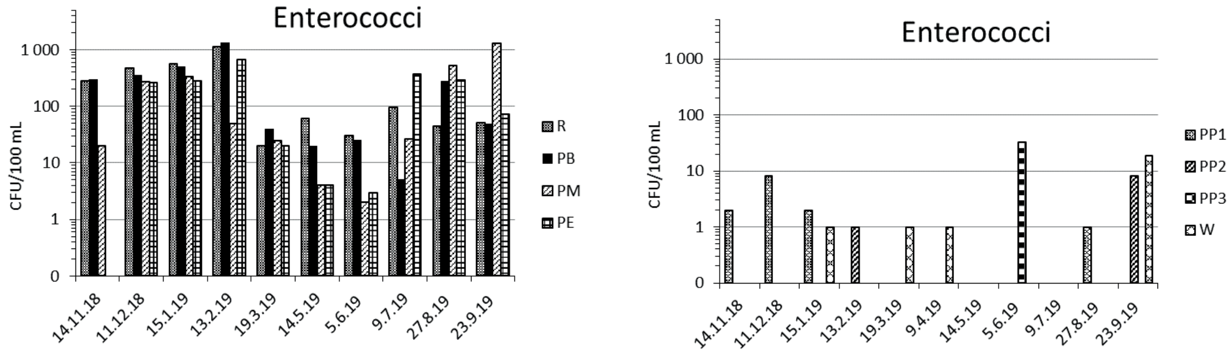

Fig. 16. Enterococci (CFU/100 mL) in water at the infiltration intake.

treatment. The bacteria and fungi present in this zone mineralize organic compounds.

During the initial period of pond operation after cleaning, the treatment effects are reduced and increase over time until the processes stabilize [2,20]. This phenomenon was observed during this study (Figs. 3 and 4). Comparable effects of organic compounds removal were also reported in the literature [29,32,34]. Biodegradation in infiltration ponds includes the dissolved organic carbon oxygen processes and denitrification.

The water colour in the well decreased throughout the entire study period to 8–16 mg Pt/L. It can be concluded that the effects of colour removal were favoured by the summer water temperature and the biodegradation processes of humic substances during this season [35]. In turn, a similar colour removal effect at low temperatures was achieved as a result of soil adsorption [36,37]. It can be considered that the remaining colour of the water in the well is a natural hydrogeological background of mixed infiltrating and underground water. The colour does not pose a direct threat to health, but indicates the presence of humic compounds in water, which are precursors of Trihalomethanes [38,39].

The passage of water through soil results in a high degree of turbidity removal from infiltrating water [36,40]. In the case of the water collected from the well, the increased turbidity appears with iron, the concentration of which increases in the well water. This increase in iron in the well (the depth of the well is notably greater than that of the analysed piezometers) may result from an inflow of groundwater richer in iron or as a result of leaching of iron(III) compounds from the soil in the vicinity of the well, which is a common situation in many infiltration wells [41]. The phenomenon may occur due to an increase of corrosivity of water, leading to iron compound dissolution [42,43]. According to the hydrological estimate, approx. 10% of the water taken in the intake is groundwater with different chemical characteristics than surface waters. The concentration of iron and manganese in groundwater is higher than in the water flowing into the well through the ground. Passage to PP-3 virtually deprives infiltration water of iron. The area where the wells are dug has been exploited by the intake for approx. 100 y. The ground around the well is clogged with, *inter alia*, iron compounds.

The presence of iron compounds in dissolved, colloidal and suspended forms in water taken from the well affects the values of parameters such as: turbidity and colour, but it does not affect the results of microbiological parameters and the presence of organic compounds or nutrients. Despite the fluctuations of turbidity of the water collected from the well, the well should also be included in the interpretation of changes in the quality of infiltrating water because the presence of iron oxides in the ground increases the adsorption effects in relation to pure quartz sand, influencing further pre-treatment of infiltrating water [44].

During periods of higher pond water temperatures, an increase of nitrification process intensity and an increase in the concentration of nitrate nitrogen is observed [45]. These biological changes are influenced by several biological factors such as nitrification in the pond, denitrification in soil, denitrification at the bottom sediment [11,46], which result in the increase or decrease in the concentration of particular forms of nitrogen.

The decrease in the concentration of the TSS suspensions observed in the second stage of research along the flow path from the river to the end of the pond was most likely a result of the water flow through the reservoir and sedimentation of the particles.

The Warta River water pumped into the pond is eutrophic, as confirmed by earlier studies [47,48]. These studies also established mass development of algae in the Warta River – mainly diatoms and cyanobacteria in summer. Some phytoplankton taxa abundant in river waters can adapt to the pond conditions and cause water blooms. This was noticeable at the end of the pond operation period, during initial tests.

Low Chlorophyll-a values which occurred in the second study period and in the winter season were the result of the deteriorated conditions for photosynthesis and phytoplankton development (low temperature and low isolation, ice cover on the pond), which is a typical change observed in the surface waters in the temperate zone. The decrease of the Chlorophyll-a concentration along the pond at the beginning of new pond operation cycle may indicate that phytoplankton has undergone significant changes. Its biomass was reduced, probably due to the natural death of phytoplankton (as in the case of bacteria) and its sedimentation assisted by infiltration. The change of the flowing water of the Warta River into infiltration pond water could result in the elimination of some taxa which were not able to move vertically in the water column and remain at the

Table 5
Average values and standard deviations for chemical water quality parameters

	Average ± SD									
	COD-Mn	TOC	Colour	Turbidity	Total iron	Ammonium	Nitrates	Nitrites	Orthophosphates	Total phosphorus
R	9.12 ± 1.45	6.00 ± 3.00	30.31 ± 12.83	3.15 ± 0.48	0.39 ± 0.27	0.41 ± 0.13	0.29 ± 0.41	0.17 ± 0.08	0.015 ± 0.010	0.075 ± 0.050
PB	8.78 ± 1.50	6.31 ± 2.53	30.96 ± 13.07	3.45 ± 0.51	0.35 ± 0.26	0.44 ± 0.19	0.28 ± 0.40	0.17 ± 0.07	0.014 ± 0.006	0.064 ± 0.024
PE	8.25 ± 0.22	5.55 ± 2.48	31.04 ± 6.98	2.57 ± 0.66	0.19 ± 0.16	0.37 ± 0.14	0.31 ± 0.44	0.29 ± 0.17	0.012 ± 0.007	0.059 ± 0.042
PM	7.98 ± 1.03	5.69 ± 1.70	28.44 ± 8.33	2.29 ± 0.92	0.23 ± 0.17	0.38 ± 0.17	0.56 ± 0.78	0.31 ± 0.15	0.014 ± 0.008	0.066 ± 0.011
PP-1	5.32 ± 0.40	3.63 ± 1.88	13.02 ± 2.10	0.23 ± 0.15	0.15 ± 0.14	0.41 ± 0.37	0.15 ± 0.23	0.06 ± 0.05	0.024 ± 0.006	0.090 ± 0.018
PP-2	4.70 ± 0.80	3.46 ± 1.09	11.79 ± 4.00	0.18 ± 0.11	0.17 ± 0.19	0.40 ± 0.21	0.14 ± 0.20	0.09 ± 0.06	0.026 ± 0.008	0.172 ± 0.145
PP-3	4.87 ± 0.59	3.83 ± 1.89	10.96 ± 3.13	0.19 ± 0.11	0.12 ± 0.17	0.29 ± 0.24	0.15 ± 0.19	0.23 ± 0.17	0.024 ± 0.007	0.126 ± 0.066
W	4.95 ± 0.30	2.90 ± 2.07	10.96 ± 3.13	5.37 ± 5.39	0.67 ± 0.63	0.47 ± 0.30	0.46 ± 0.63	0.08 ± 0.081	0.033 ± 0.013	0.087 ± 0.033

surface. Consumers could also play an important role in the formation of the phytoplankton community in the pond, mainly zooplankton. The environmental conditions in the pond are more favourable for the zooplankton growth than in the river what can result in significant reduction of the phytoplankton biomass [49,50].

The slow flow of water through the pond resulted in a significant improvement of the water quality in terms of the microbiological parameters at the final section of the pond, as the vast majority of microorganisms died. In some cases, the decrease of the number of microorganisms in the pond was relatively low, but it should be noted that the pond is exposed to the external environment (including surface runoff from soil after precipitation, access by waterfowl and other animals living in the vicinity of the pond), which may have caused secondary water contamination and an increase in the number of some microorganisms.

In the surface water and groundwater the number of bacteria can be very different and vary notably. In the case of heavily contaminated surface waters, it may even exceed 1×10^7 CFU/mL [51]. The coliform bacteria, *Escherichia coli* and enterococci (Figs. 14–16) were more commonly found in the river (R) or at the beginning of the pond (PB). It can be assumed that the faeces of the animals living near the intake area (birds, mammals) are additional source of all studied microorganisms in the pond. At the same time, it should be noticed that the water from the Warta River is continuously pumped into the pond; hence, the level of the pond contamination is influenced by the quality of river water supplied to the pond within a few days prior the water samples collection.

The bacterial diversity and composition in rivers are influenced by water temperature, day length, pH, nutrients and water retention time [52]. In contrast, the water in piezometers and in a well (Figs. 12–16) is usually much better in terms of microbiological parameters than that found in the river and in the pond. The best effects of water purification from microbial contaminants were noted for enterococci. Faecal streptococci were present in the smallest concentrations (ranging from 0 to 32 CFU/100 mL) in both piezometers and wells.

According to Maran et al. [53] degradation and contamination of groundwater are related to the depth and the type of wells. The high temperature of some samples promotes the development of microorganisms and changes their organoleptic characteristics, such as taste, odour and colour. Increased turbidity may be caused by suspended particles, by the very nature of the rocks or by improper pipe maintenance, which is a problem for the consumers using wells.

The studies of Michałkiewicz et al. [54] indicated that the inflows of point and area contaminants have a significant impact on the quality of water in the Warta River. The bacteriological sanitary analysis of water indicated an intensive inflow of faecal sewage, and concentrations of Chlorophyll-a, dry matter of seston and the presence of *Cyanobacteria* in the phytoplankton indicated that eutrophication of the river has occurred. Małecka and Donderski [55] examined the Brda River, in a section of the city of Bydgoszcz, and reported that the highest abundance of microorganisms in the water was measured in June and August, and the lowest in November and March. Among

Table 6
Average values and standard deviations for microbiological water quality parameters

	Average ± SD				
	Mesophilic bacteria	Psychrophilic bacteria	Coliform	*Escherichia coli*	Enterococci
R	5,513 ± 8,569	6,107 ± 5,082	14,917 ± 15,162	647 ± 791	278 ± 365
PB	5,726 ± 10,885	5,534 ± 5,364	16,090 ± 16,188	803 ± 814	289 ± 402
PE	2,376 ± 3,432	3,857 ± 3,168	13,747 ± 18,654	547 ± 1,130	198 ± 222
PM	1,248 ± 1,637	5,892 ± 3,646	10,577 ± 10,596	260 ± 344	257 ± 409
PP-1	845 ± 991	886 ± 1,052	159 ± 426	108 ± 367	1 ± 2
PP-2	1,333 ± 1,907	1,043 ± 1,327	232 ± 403	22 ± 69	1 ± 2
PP-3	867 ± 1,506	988 ± 1,308	49 ± 135	2 ± 4	3 ± 10
W	1,662 ± 2,087	2,552 ± 2,131	367 ± 662	134 ± 352	2 ± 6

bacteria, there were three times more psychrophilic bacteria compared to the mesophilic bacteria (TVC 37°C). The quantitative ratios of mesophilic and psychrophilic bacteria were similar to our research in the Warta River, while the dates of the highest and lowest numbers were slightly different.

The autochthonous (natural) and allochthonous (foreign) microflora flows into the pond along with the river water. Natural microflora is involved in the processes of water self-purification (both in the water column and at the bottom of the pond), because it includes both autotrophic and heterotrophic microorganisms, which in surface waters carry out, for example, the decomposition of numerous organic substances. On the other hand, the allochthonous microorganisms originating from, for example, surface runoff, air and domestic sewage, contaminate the water and are represented mainly by bacteria found in the digestive tract of humans and animals. These microorganisms do not reproduce in water and die over time. For this reason, psychrophilic, mesophilic and indicator bacteria were investigated in water, indicating faecal contamination of the water. The infiltration is a preliminary treatment step. The achievement of essential effects is the task of the water treatment plant. Final disinfection carried out at the water treatment plant effectively inactivates microorganisms and allows to achieve chemical stability of the water introduced into the network [20].

5. Conclusions

5.1. Effects in the pond

During the flow of water through the infiltration pond, a gradual decrease in the bacterial numbers was found in many cases due to natural cell death. Surface runoff from the areas surrounding the pond and the droppings of animals (birds and mammals) living on the intake area may be an additional source of bacteria in the pond. Therefore, in some cases, the number of individual bacteria in the pond was higher compared to the Warta River. The amount of phytoplankton measured by the concentration of Chlorophyll-a is also reduced. Seasons, and therefore temperature, affect the intensity of the biodegradation processes, which improves the quality of water in the pond during the flow of water from the beginning of the pond to its end.

5.2. Effects in the ground passage

The analysis of microbiological parameters in the infiltrating water indicated that the highest reduction of enterococci and *Escherichia coli* was observed. The lowest reduction was observed in the mesophilic and psychrophilic bacteria, because the psychrophilic bacteria can be a natural microflora found in water and in the ground. During the flow of water through the soil, the colour decreases to a level of approx. 10 mg Pt/L. Infiltration results in a high degree of turbidity removal. The amount of organic compounds is reduced in the infiltration process, which is measured by the reduction of COD-Mn and the concentration of TOC.

6. Summary

The developed and applied methodology (using a field research installation) of tracking the water stream in the ground during infiltration process, combined with chemical and biological analysis, makes it possible to evaluate the effects of the infiltration process as a preliminary stage of surface water treatment in the intake.

The quality of the infiltration water was enhanced in terms of the microbiological contamination and the colour, turbidity as well as the content of organic compounds were decreased. The total suspended solids and phytoplankton measured by Chlorophyll-a concentration were eliminated.

Determining the reliability of surface water pre-treatment for drinking water production based on the artificial infiltration system requires long time tests that take into account the seasonal changes in surface water quality, the change in the effects of the biodegradation process (the process that determines the treatment effects), as well as the operation phase of infiltration ponds. This is particularly visible in the case of TOC removal, COD-Mn and colour, as the removal effects were the lowest in the second study period, in autumn, after cleaning the pond bottom from sediments. As the pond operating conditions were established, the effects of removal of organic compounds were significantly improved and stable.

The infiltration intake, even in suboptimal conditions (winter, the first phase of the pond operation), ensures high treatment effects in terms of microbiological (algae and bacteria) and organics removal. Research has shown that indicator organisms, such as *Escherichia coli* and enterococci, were effectively removed during infiltration. During the secondary stage of research even mesophilic and psychrophilic bacteria were removed to a high extent. The microbial activity measured by the number of colony forming units declines along the pond-well path.

It is important to analyse the changes in iron concentration in the infiltration water during the assessment of the quality of effects of preliminary surface water treatment in the intake. In the examined intake, the iron contained in the surface water is removed from it by the flow path from the pond to the PP-3. It is most likely iron bound in complexes with organic compounds. Removal of this form of iron is important for a treatment technology based solely on aeration and rapid filtration at the water treatment plant. The iron that appears in the water collected from the well can flow into it with groundwater or it can be dissolved from the sediments of iron compounds collected in the ground around the well. This iron is in the form of mineral compounds, easily removable in reagent-free processes, typical for groundwater treatment (aeration followed by rapid filtration). The phenomenon of dissolution (redox and pH changes in the flow path) of iron and manganese is an interesting issue that will be the subject of further research and analysis.

In summary, it should be stated that the infiltration process is a highly effective method of pre-treatment of surface waters and is in line with the principle of sustainable development. The effects achieved during infiltration allow simplifying further treatment processes, often resulting in a system of non-reactant groundwater treatment. The use of infiltration minimizes the use of chemical reagents (e.g., coagulants and flocculants) and thus leads to a significant reduction of the sludge produced in the course of the water treatment processes.

Acknowledgments

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