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Abstract: The effect of river–lake systems on the surface water self-purification process is a significant and not fully recognised scientific issue. The conditions prevailing in the hyporheic zone of these ecosystems are of great importance in the process of component exchange between water and sediments. The aim of this study was to investigate the influence of the type of sediments located at the bottom of the riverbed being part of a river–lake system on microbial activity in the hyporheic zone. An ex situ experiment was used to study the microbiological activity and the transformation of components in the collected river sediments. It was found that the specific properties of sediments varied depending on their location in the riverbed between the lakes comprising the system and that the prevailing meteorological conditions can also have an effect on microbial activity in the hyporheic zone, e.g., aerobic conditions. These conditions determined the intensity of component conversion in the sediments due to microbial metabolism. A closer understanding of the processes occurring in the hyporheic zone may allow the processes of water self-purification within river–lake systems to be supported in the future, which will contribute to the improvement of surface water quality.

Keywords: hyporheic zone; river-lake system; microbial activity; biogeochemical cycle

1. Introduction

Previous studies of the hyporheic zone functioning in the literature mainly concern riverbeds [1,2]. In rivers, there are changes in the flow rate, which affect the conditions prevailing at the bottom. These conditions change primarily at the location where the water flow slows down, e.g., due to water retention in reservoirs. Therefore, the capacity of bottom-dwelling microorganisms to metabolise components varies depending on the location, i.e., it is different upstream of the reservoir, near the outlet to the reservoir, or even downstream from the reservoir. In lowland areas, the presence of river-lake systems is an integral part of the landscape. In drainage basins of the main lowland rivers, streams connect alternately with lakes, consequently feeding the transboundary waters of seas, for example. Ensuring water quality in the upper part of these systems enables a reduction in the pollution of their receiving waters. The bottom sediments of river-lake systems can play a special role in metabolic conversions in surface waters. The conditions prevailing at the boundary between two systems (river and lake) may also have an effect on microbial activity and, consequently, on the biogeochemical cycle, thus enabling the assimilation of components in the hyporheic zone. Therefore, any efforts to identify the processes occurring at the bottom which support water self-purification processes are important [3].

Bottom sediments are the site of the accumulation of different chemical elements in quantities that may exceed their content in lake water. Under certain conditions, they can re-pollute the water depths [3,4]. Water velocity in a river has an enormous impact on the



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). shape of the bottom and the type of sediments due to the strength and relationship of the so-called fluvial processes, i.e., erosion, transport, and accumulation [3].

The biogeochemical cycle in water reservoirs is determined by the activity of microorganisms at the bottom. In turn, the variability of the conditions prevailing at the bottom affects the component conversion rate and, consequently, the microbial activity. Therefore, the ability of flowing waters to self-purify is due to the presence of biofilm on the sediment surface, which is capable of metabolising dissolved compounds. These processes are restricted by the duration of contact between water and the biofilm and by the renewal of sediments through the transport and accumulation of dragged rock debris [5]. Due to the intense water movement in the riverbed, processes such as component conversions occur mainly in surface sediments [1]. In contrast, when the water flow slows down, e.g., near the watercourse mouth, the contact time between water and sediment is longer [5], which enables water infiltration into the sediment. This can be determined, e.g., by the type of sediments and their structure. The presence of larger particles improves water oxygenation due to the larger spaces between sediment particles. This enables interstitial water to flow freely deep into the sediment [6,7]. Peter et al. [8] defined the hyporheic zone as a natural bioreactor that is capable of "attenuating" chemical pollutants. Research conducted to date shows that this zone is a modulator of most metabolic processes and serves as a habitat for a variety of aquatic organisms. A longer duration of water remaining in the hyporheic zone promotes the removal of pollutants. In river–lake systems, there is a diversity in water flow depending on the location in the riverbed or at the lake bottom. At the same time, the water flow slows down near the outlet to the lake, thus extending the duration of the inflowing waters with this zone. The benthic layers of slightly deeper lakes may play virtually no part in the horizontal flow [8].

According to Fudyma et al. [9], the hyporheic zone, in which groundwater mixes with surface water, is characterised by a high content of dissolved organic matter and high microbial activity. Lewandowski et al. [10] distinguish the following functions of the hyporheic zone: nutrient exchange, conversion of trace organic compounds, stimulation of nutrient cycling, filtration of fine particles, a refuge for aquatic organisms, and a biodiversity reservoir.

While flowing in the riverbed, water collides with the bottom, thus inducing a change in the pressure field at the sediment–water phase interface. This subsequently propels the flow of interstitial water from areas of relatively high pressure to areas of lower pressure. The flow in the benthic zone takes place alternately above and under the sediment, along with the horizontal downstream flow [11].

The nature of the catchment basin, including climatic variability or land use, may have an indirect effect on the functioning of organisms in the hyporheic zone [9]. According to the views presented in the literature [12–15], the following develop in bottom sediment: anaerobic putrefactive microflora, e.g., hydrogen sulphide-releasing, SO_4^{2-} reducing, denitrifying— NO_3^- reducing, methanogenic (methane-releasing), and hydrogen-oxidising bacteria; anaerobic cellulolytic bacteria, e.g., hemicellulose-degrading Clostridium; and aerobic cellulolytic bacteria, e.g., Sporocytophaga, Cytophaga, Pseudomonas, and Achromobacter.

The metabolism of substances involves carbon transformations and oxygen consumption in the process of organism respiration and primary production. It is usually estimated by means of an oxygen balance dependent on metabolic processes, the transfer between river water and the atmosphere, and between river water and groundwater [16]. Dissolved oxygen is responsible for many processes taking place at the bottom of aquatic ecosystems. Little is known about the dynamics of dissolved oxygen variability in transient flow regimes [17]. Microorganisms use up oxygen, and they use other components as an electron acceptor once oxygen is depleted.

The use of tracer methods for analysing microbial activity has become a rather new issue in the literature. Tracer methods are basic techniques used for water transport analysis in hydrological research on surface water and groundwater [18]. According to González-Pinzón et al. [16], the use of tracers, i.e., resazurin and resorufin, has proven to be

a good integrator of the processes of dissolved substance transport as well as metabolism. Resazurin and its reaction product, resorufin, are increasingly being used as reactive indicators of the quantitative determination of metabolic activity and exchange in the hyporheic zone. Research conducted to date indicates that these tracers undergo sorption in the sediment core [11]. Haggerty et al. [18] referred to resazurin as an "intelligent" tracer, i.e., one that provides additional information on the environment, either directly or through the measurement of its concentration or of its concentration in combination with another compound. It is used inter alia in research into the integration between dissolved substance transport and metabolic activity at the water–sediment phase interface in freshwaters.

The conversion of these tracers involves the irreversible reduction of resazurin to resorufin in the metabolic processes of cellular organisms in sediments. The rate of this conversion is more rapid in hyporheic sediments because they are intensively colonised [11]. Resazurin is weakly fluorescent but more sensitive to redox processes. On the other hand, resorufin is intensely fluorescent, even under mildly reducing conditions, most often in the presence of microorganisms [18]. Resazurin and resorufin compounds in natural water are stable for several weeks, and the acceleration of their photochemical degradation is induced by the presence of intense light [18].

Therefore, the aim of this study was to assess the effect of the morphometric conditions of riverbeds and the type of fluvial deposits related to them on microbial activity and the cycle of component conversions in the hyporheic zone of the sediments found at the bottom of a river in a river–lake system.

2. Materials and Methods

The current study assumed the performance of an experiment under controlled conditions using a variety of sediment types derived from the bottom of the bed of the main river feeding the reservoir being part of the river–lake system. To achieve the aims of the research, the study design included an analysis of the effect of temperature and aerobic conditions on microbial activity and the carbon cycle in the tested sediments. The relationship between this activity and the sediment properties arising from their location within the river–lake system was also analysed.

In view of the difficulty of carrying out the assumed study by an in situ method, the study used polyvinyl chloride chambers filled with the tested sediments, in which the processes occurring at different depths of the sediments were analysed.

The study design assumed the following:

- recording the oxygen consumption rate, temperature, and total carbon content in the sediment column;
- recording the concentrations and conversion rates of tracers, i.e., resazurin, resorufin, and fluorescein;
- an analysis of the physicochemical properties of the collected sediments.

2.1. Study Area

This study focused on a river–lake system comprising the Symsarna River and four lakes located along its route. The Symsarna River (a third-order tributary of the Pregolya River) is situated in the Olsztyn Lakeland and has its origin in Lake Luterskie. It flows through lakes Ławki, Blanki, and Symsar (Figure 1), and then flows into the Łyna River, which, in turn, via the Pregolya River located in the Kaliningrad Oblast of the Russian Federation, discharges waters into the Baltic Sea. The area or the studied river's catchment basin was formed during the last glacial period and is mainly covered with agricultural land (Figure 2). To date, the river was only studied in its outlet section, i.e., beginning downstream of Lake Symsar and ending at the outlet to the Łyna River. The conducted study showed moderate ecological status and good chemical status [19].



Figure 1. Longitudinal profile of the Symsarna River.



Figure 2. Location of sampling points.

2.2. Sampling Sites and Regime

The study assumed the collection of bottom sediments from the bottom of the river under study. Five samples were collected at a time from the bottom of riverbeds located upstream and downstream of the reservoirs (Figure 2). The location of the measurement points was determined by the location in the river section and the nature of the area, as well as the absence of water objects. Sample collection was repeated four times. The samples were collected using columns with a diameter of 6 cm and a length of 100 cm. In each repetition, each column was filled with sediments to a volume of 900 cm³, which were characterised by the same structure. The thickness of the core collected was approximately 50 cm. Each sediment sample was collected using a separate column that was subsequently

used in the experiment. A dark-coloured polyvinyl chloride was used, which reduced the possible undesirable reactions of tracers used in the experiment under the influence of sunlight and, at the same time, provided near-natural conditions. At the same time, during field operations, representative samples of bottom sediments were collected to analyse their physicochemical properties, even before the experiment was commenced.

After collection, pipes with samples of undisturbed sediment were transported to the laboratory of the Department of Water Resources and Climatology of the University of Warmia and Mazury in Olsztyn, where they were subjected to further testing. The cores were then placed in an external laboratory (outdoors, in an open space). To each sediment column, groundwater was collected from the outlet located in the catchment area of the river under study (the water was characterised by a low microorganism content) and was introduced using a peristaltic pump with a specified flow rate of $0.25 \text{ mL} \cdot \text{min}^{-1}$, along with a resazurin and fluorescein solution with a concentration of 0.1 and 0.01 mg dm^{-3} , respectively. The water was stored at a temperature such as that of the sediment columns and was not filtered. With the measurement of the oxygen content and the temperature on a daily basis, the intensity of water flow through the columns was determined by the hydraulic conductivity of the sediments themselves and the flow was not forced. The water was then drained using a pipe located at the bottom of the column. In each vertical column filled with sediment, samplers ended with a tap were located every 10 cm of the depth. During the experiment, the taps enabled the intake of interstitial water (Figure 3). Interstitial water samples were collected from each depth, i.e., benthic water, water from a depth of 10, 20, 30, 40, and 50 cm. The measurements were taken for eight days, every other day. The duration of this period was determined on the basis of the results of a trial experiment, which indicated that, after this time, the inflowing water was filtered through the entire sediment column, and the tracers were not further converted.



Figure 3. Diagram of the columns used in the experiment.

Immediately after collection, the following were measured every day: the temperature and oxygen concentration in interstitial water flowing into the columns as well as in the air, using an optical oxygen meter and temperature sensor (a probe by Pyroscience GmbH, Aachen, Germany) and the pH and electrolytic conductivity. Moreover, changes in the concentrations of resazurin and resorufin as a product of its conversion were recorded using a GGUN-FL30 linear fluorometer (Allbilia Sárl, Neuchâtel, Switzerland). The water samples were then passed through a glass filter with a pore diameter of 0.7 μ m. The water samples were subjected to an analysis of total carbon contents using Shimadzu TOC-VPN analysers (Shimadzu Corporation, Kyoto, Japan) at the Department of Chemistry of the University of Warmia and Mazury in Olsztyn. The measurement method involved heating a sample under UV light to convert the dissolved carbon contained in the sample into carbon dioxide. Carbon dioxide travelled with a carrier gas (O₂—99.999%; Linde Gas) through a dryer to the NDIR measurement cell. The analysis measured the area of the carbon dioxide peak signal. The analysis measured the area of the carbon dioxide peak signal. The area of the peak obtained was used to calculate the concentration of total carbon on the basis of the calibration curve. The calibration curve was prepared using phthalate standards manufactured by the Shimadzu company.

In the air-dried sediments, the following were analysed:

- organic matter by the gravimetric method, by means of drying at 105 °C and roasting at 550 °C;
- the granulometric composition using sieves with mesh sizes of Ø 0.35, Ø 0.30, Ø 0.25, Ø 0.15, Ø 0.12, Ø 0.088, Ø 0.075, and Ø 0.06 mm. On this basis, the proportions of individual fractions, i.e., medium sand (Ø 0.25–0.35 mm), fine sand (Ø 0.102–0.015 mm), very fine sand (Ø 0.088–0.06 mm), and particulate/clay (Ø < 0.06 mm) were determined in the sediments.

2.3. Analytical Procedure

Statistically significant differences in the physical and chemical properties of bottom sediments (depending on their location within the river–lake system, the depth of sediment deposition, and the day of the experiment) were tested using a nonparametric analysis of variance (ANOVA), i.e., a Kruskal–Wallis test followed by Dunn's test, as a post hoc procedure. Moreover, the correlation between individual properties as well as between these properties and the fractions of individual sediments was assessed using Spearman's rank correlation analysis. Due to the implementation of multiple tests, Bonferroni correction was applied, consisting of reducing the α value by dividing it by the number of tests performed [20].

For individual procedures, the Statistica 13 PL program was used (StatSoft Polska 2014, Kraków, Poland). The effect of environmental conditions on the properties of individual sediments was studied using a multivariate statistical analysis, i.e., a redundancy analysis (RDA). The following environmental factors were taken into account: (A) location of sediments within the river–lake systems, (B) sediment deposition depth, (C) day of the experiment. The data analysis was carried out using the Canoco 4.5 software package (Microcomputer Power, Ithaca, NY, USA) [21].

3. Results

3.1. Impact of Location on Interstitial Water and Bottom Sediment Properties

The bottom sediment of the studied system comprising the Symsarna River and four lakes located along its route contained mainly medium sand particles, from $47.09 \pm 7.71\%$ in the riverbed upstream of the Lake Ławki to $86.46 \pm 2.91\%$ upstream of Lake Blanki (Table S1). The oxygen content in interstitial water of the sediments under study ranged from 6.69 ± 0.84 mg·dm⁻³ in the initial section of the river (downstream of Lake Luterskie) to 7.56 ± 0.30 mg·dm⁻³ upstream of Lake Blanki, while the temperature of the water under study ranged from 23.12 to 23.99 °C. The results of the Kruskal–Wallis test and the post hoc test showed a highly statistically significant difference between the total carbon content and saturation of water and the location of sediments (p = 0.003 and 0.001, respectively). Interstitial water upstream of Lake Ławki, which exhibited one of the lower oxygen concentrations, contained the highest carbon concentrations (119.91 ± 20.00 mg·dm⁻³). On the other hand, sediments with the highest oxygen concentration contained the lowest carbon concentrations (63.70 ± 18.72 mg·dm⁻³, Table S1, Figure 4).



Figure 4. Distribution values of individual indicators of interstitial water of sediments collected at individual locations of the river–lake system in relation to the bottom sediment deposition depth and day of the experiment.

3.2. Impact of Depth on Interstitial Water Properties

Indicators such as oxygen, fluorescein, and resazurin were characterised by the highest concentrations in the surface layer of water in the sediment column and amounted to 7.68 mg \cdot dm⁻³, 108.24 ppb, and 115.69 ppb, respectively. The Kruskal–Wallis test results showed highly statistically significant differences (p = 0.000 for each) in the concentrations of these components, depending on the depth of sediment deposition. In interstitial water in the deepest layer of the sediment column, the concentrations of these components were lower by 6.53%, 34.17%, and over six times, respectively, than that of those in surface layers (Table S2). In turn, as regards the resorufin concentration, the test also showed statistically significant differences in individual layers (p = 0.000), but with an inverse trend. With the increasing depth, the concentrations of this component increased almost twofold already in the second layer (10–20 cm in depth), where they were the highest, and at a depth of 20–30 cm, they amounted to 33.23 ± 15.62 ppb and 30.50 ± 10.81 ppb, respectively (Figure 4). This indicates microbial activity in deeper sediment layers that are not reached by sunlight. At that depth, the organisms use up resazurin to convert it into resorufin. The highest concentrations were observed within this particular layer and at a depth of 20–30 cm and were 33.23 ± 15.62 ppb and 30.50 ± 10.81 ppb, respectively. A similar relationship was observed for the total carbon concentration, with the highest concentrations observed within the 30–40 cm depth layer (77.76 \pm 7.34 mg·dm⁻³).

3.3. Impact of the Day of the Experiment on Interstitial Water Properties

On subsequent days of the experiment, the oxygen concentration decreased in the sediments under study by almost 4%, with the differences being highly statistically significant at p = 0.000. A similar relationship was noted for the carbon concentration, which, on the last day of the experiment, was lower by 42.07% than that on the first day. From the second day, the resazurin concentration decreased (by 7.7%), while the resorufin concentration increased, with the differences on individual days being highly statistically significant at p = 0.000. Dunn's test results showed significant differences on the first and second day (Table S3).

3.4. Relationship between Individual Properties of Interstitial Water

On the basis of the results of Spearman's nonparametric rank correlation test, we determined the concentrations of tracers, i.e., fluorescein and resorufin (r = -0.163 and 0.302), by the inflow water temperature that was correlated with the air temperature (r = 1.000, Figure 5) and with inflow water saturation (r = 0.572 and 0.309). Moreover, the resazurin content in interstitial water was determined by its oxygenation of interstitial water (r = 0.239, Table 1), which was correlated with the meteorological conditions.



Figure 5. Diagram of RDA to identify the impact of environmental factors on the parameters of bottom sediments.

Table 1. The results of Spearman's nonparametric rank correlation test (physical properties of the feed water and air, and physicochemical properties of interstitial waters).

Inflow water saturation	Temperature of interstitial water	Inflow watertemperature	AirTemperature	Fluorosceine	Rru	Raz	Conductivity	Total carbon	Indicator:
0.203	0.042	0.067	0.403	0.338	0.015	0.239	0.219	0.135	Saturation of interstitial water
Х	0.045	0.173	0.059	0.572	0.309	0.172	_ 0.064	0.029	Inflow water saturation
	Х	0.696	0.809	_ 0.089	0.106	_ 0.168	_ 0.115	_ 0.145	Temperature of interstitial water
		X	1.00	0.163	0.302	_ 0.101	0.091	_ 0.080	Inflow water temperature
			х	_ 0.281	0.325	_ 0.047	_ 0.338	_ 0.080	Air Temperature
				х	0.259	0.409	_ 0.085	_ 0.037	Fluorosceine
					х	0.058	0.149	0.119	Rru
						Х	0.028	_ 0.018	Raz
							X	0.061	Conductivity

Results highlighted in red—statistically significant results after taking into account the Bonferroni correction.

Furthermore, as in the case of resorufin, the layers immediately under the surface, at 10–20 cm, were characterised by carbon concentrations being lower by 56.4% as compared to those at other depths (Figure 4). Moreover, the concentrations of this component were the highest on the first day and then decreased by 33.1% on subsequent days of the experiment.

4. Discussion

This study confirmed the assumed research hypothesis that the different types of bottom sediments (often dependent on morphometric conditions of riverbeds and their location along the river route and the prevailing meteorological conditions) have an effect on microbial activity and the component cycle in the hyporheic zone. Rivers that are part of a river-lake system serve both retention and transport roles, which may significantly modify the organic and mineral composition of the sediments within the cascade system [22,23]. An example of the system comprising the Symsarna River and four lakes located along its route confirmed that the location of sediments in the bed of a river in a river–lake system determined their significant diversity in terms of the physicochemical conditions, including the granulometric composition. Moreover, the lakes in a river-lake system and the bed of the river in the vicinity of these lakes may differ from each other in both the morphology as well as the development of the shoreline, which indeed may have a significant effect on the composition of sediments deposited at the bottom. The river sediments of the river-lake system under study were mainly dominated by medium sand. The river's current transports particles of dragged material deposited at the bottom and near the riverbank, whose sediment eroded the outlet to the lake [24]. This is due to the decreasing velocity of the water flowing into the reservoir. The slower the current, the more intensely the dragged material (which can form deltas in the river mouth section) is accumulated. In the lower course of the river, the flow is so low that gravel and sand, as well as silt, accumulate at the bottom [24]. Kaufman et al. [17] pointed out that even small changes in the flow affected the dynamic nature of streams and rivers. Therefore, in order to ensure the free flow of a river, the material must be temporarily deposited in sediments [24]. Research conducted to date confirms that successive lakes being part of the system can be receivers of pollutants transported with river waters or can supply waters with dissolved substances accumulated at the bottom [23]. On the basis of the granulometric composition under analysis, we estimated that the material dragged from the initial section of the river with river waters was lighter and sedimented before it reached the second reservoir of the system (an increase in fine sand content by 65.0%), which was due to the presence of a water-damming hydroelectric plant along the river flow route. As the downstream velocity of river water increases, an increase in the content of medium sand larger particles (by 83.6%), which were deposited at the river bottom, was observed upstream of the next lake (Lake Blanki). Kuriata-Potasznik et al. [23] demonstrated that river current promoted the accumulation of larger fractions next to the outlet due to a drop in the water flow rate on this section, thus preventing them from being transported further.

The distribution of particles in the sediments of the last lake (Symsar) confirms the view of Kuriata-Potasznik et al. [23] that the last reservoirs of the system can act as a centre for the accumulation of material, including pollutants, while reducing the material being transported out of the catchment basin. Due to sediment resuspension, the water movement collects particles with a small diameter more easily [25], and the process itself is primarily determined by the specific weight of sediment particles. The results obtained show that in the riverbed downstream of Lake Symsar, a reduction in the content of larger particles by 16.2% in relation to the starting point of the system, and an increase in the fine sand content by 88.9% was observed. This may suggest that heavier particles were deposited at the lake bottom. Szalińska et al. [26] observed that the content of larger particles in the sediments of the Detroit River before the inflow to Lakes Huron and St. Clair (situated in the upper course of the river) were 25% higher than that in sediments originating from lower river sections. The balance of material in the system is very important, as it helps understand the pollutant transport process. These processes are determined by metabolic conversions and the activity of microorganisms capable of metabolising the components.

Moreover, Fudyma et al. [9] pointed out that the composition of both surface water and interstitial water, depending on their location in the riverbed, contributed to a change in microbial activity.

Mineral particles can form complexes with, e.g., heavy metals, thus affecting the content of these pollutants in the studied aquatic ecosystems [23]. Moreover, the presence of larger particles as well as plants at the bottom loosens the structure of the substratum through the roots of these plants, which contributes to an increase in the filtration coefficient [6,7]. Larger spaces between the particles have a positive effect on the oxygenation of interstitial water. The conducted study confirms this relationship: in the Symsarna riverbed, upstream of the Lake Symsar, the average oxygenation of interstitial water was 10.3% higher than that at other intake points, and since the content of medium sand particles was, on average, 28.8% higher than that at other locations. Moreover, the translocation of benthic macrofauna within the sediment has an effect on the rate of organic matter production and carbon accumulation. At the same time, it affects the oxygenation of the sediment, as a stream of dissolved oxygen penetrates deep into the sediment and disturbs anaerobic processes. Metabolism in hyporheic zones may affect the flow of oxygen and carbon in sediments through primary production and microbial respiration. Oxygen balance is used to estimate metabolic processes [16]. The available literature lacks studies on the dynamics of dissolved oxygen in transient flow regime zones. Lewandowski et al. [10] point out that extending the duration of contact with the conditions prevailing in this zone can result in the retention or conversions of components. However, Kaufman et al. [17] observed drops in oxygen concentration in deeper layers, resulting from the filtration of fine particles in the hyporheic zone. The capillary spaces are then decreased. The conducted study also confirmed the dependence of thermal-oxygen conditions prevailing at the bottom in interstitial water on meteorological conditions. Moreover, local climate change can be a very important environmental factor, as it has an indirect effect on microbial activity [6]. Local climate change is more difficult to observe than global change [6]. The hyporheic zone is characterised by relatively constant conditions resulting from its being deposited deeply at the bottom, which does not mean that the conditions prevailing in it will not change in the long term. Intense horizontal water movement [6] in the river-lake system, precipitation-determined changes in the groundwater and surface water levels, and the availability of sunlight resulting from both the pollution and the intensity of insolation in the season have an effect on the availability of water and oxygen, as well as the temperature in the hyporheic zone [27]. In the study presented, the concentrations of tracers, i.e., fluorescein and resorufin, were determined by the interstitial water temperature that was correlated with the air temperature. The resazurin content in interstitial water was determined by its oxygenation and indirectly by the meteorological conditions.

According to González-Pinzón et al. [16], oxygen consumption in the hyporheic zone is equivalent to carbon transformations due to metabolic processes. Dissolved organic carbon regulates biotic processes, which, in turn, regulates the oxygen concentration [28]. In this study, the oxygen content in interstitial water was inversely proportional to the carbon content, which may indicate metabolic processes occurring in sediments. Moreover, research shows that carbon concentrations may be determined by the location of sediments within the river-lake system. Interstitial waters in sediments located in the initial sections of the river were characterised by lower oxygen concentrations (by over 5% as compared to the others) and higher total carbon levels (by 65.3%). This could have been determined by the flow rate and thus by the water movement within the hyporheic zone. Moreover, according to Trimmer et al. [28], the flow rate can increase the transport of carbon, but its accumulation at the river mouth zone is determined by the reduction in the flow rate and the changes in water temperature, the season, precipitation, and water oxygenation. Dissolved organic carbon in an aquatic ecosystem originates from two sources: from autochthonous production or from allochthonous sources [29]. In turn, carbon originating from lakes can be transported to rivers when the water level is lower and the year is dry [30]. According to Wen et. al. [31], in river–lake systems, the lake waters are characterised by

higher carbon concentrations than river waters and depend on the catchment area slope and the organic matter content in the soil found in the catchment area [31]. A study by Burrows et al. [27] showed that the carbon transformation rate in the hyporheic zone is determined by the conditions prevailing in it. According to the authors, the hyporheic zone is characterised by almost constant environmental conditions that are responsible for sustaining high indicators of many biogeochemical processes, as compared to the surrounding environment.

The conducted research showed that with increasing depth, the concentrations of resorufin increased almost twofold just below the surface and increased with depth. Deeper organisms use up resazurin to convert it into resorufin. Moreover, water temperature affected the temperature of interstitial waters, which, in turn, determined the tracer conversions. A study by Lemke et al. [11] used the phenomenon of tracer sorption within sediments. Sediment sorption may determine the component movement rate and, thus, the rate of their conversions. In the conducted study, the levels of certain tracers, i.e., resazurin, were up to six times lower in the interstitial water of deep sediments than their levels in the near-surface water. Therefore, Peralta-Maraver et al. [5] noted that the biomass productivity and content decreased with the greater sediment depth. As regards the resorufin concentration, the relationship is reversed, which demonstrates that more intensive metabolic processes occur within these sediments [11]. Gonzalez-Pinzon et al. [16] showed that higher metabolic rates (i.e., those measured according to the intensity of resazurin conversion into resorufin) were characteristic of aquatic ecosystems with slower water flows in the hyporheic zone.

5. Conclusions

This publication shows that the specific properties of sediments found in a river–lake system have an effect on microbial activity in the hyporheic zone. This is an extremely important issue since it is in the hyporheic zone that the main processes of component assimilation occur if the appropriate conditions are provided. The current study demonstrated that the type of bottom sediments in river–lake systems was determined by the morphometric characteristics of the riverbed and the location within the system. Moreover, it was found that the properties of sediments and the prevailing meteorological conditions could affect microbial activity in the hyporheic zone. The aerobic conditions had an effect on the intensity of component transformation in the sediments due to microbial metabolism. The study also confirmed the dependence of thermal-oxygen conditions prevailing in interstitial water on meteorological conditions.

The issue of component assimilation in river–lake systems is very important, as continuous exchange and transport of components take place in individual parts of the system. A closer understanding of the processes occurring in the hyporheic zone may allow the processes of water self-purification within these systems to be supported in the future, which will contribute to the improvement of surface water quality.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/ 10.3390/w13243499/s1, Table S1: Mean values and standard deviation of individual indicators of interstitial water and the granulometric composition of sediments collected at individual locations of the river–lake system. Table S2: Mean values and standard deviation of individual indicators in relation to the bottom sediment deposition depth. Table S3: Mean values and standard deviation of individual indicators for the day of experiment.

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