

Article

Influence of Cascading River–Lake Systems on the Dynamics of Nutrient Circulation in Catchment Areas

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Abstract: Matter circulates in nature constantly, between terrestrial and aquatic ecosystems, exchanging elements between the biotope and biocenosis. Each aquatic ecosystem is resistant to a specific load, above which its degradation occurs. It seems that the resistance of cascade reservoirs is higher than that of drainless reservoirs. Changes taking place in one part of the river–lake system cause disturbances in the dynamics of nutrient circulation in another. Rivers supplying water to lakes in a river–lake system have a significant impact on their water quality and on the spatial distribution of pollutants in their bottom sediments and in macrophytes located along their route. The assimilation capabilities of cascading river–lake systems result from their reaction to environmental stressors in the form of anthropogenic factors. They act as natural biogeochemical barriers, limiting the transport of pollutants outside ecosystems. In-depth knowledge of the processes taking place in the river–lake systems enables analyses aimed at forecasting the directions and intensity of these changes and predicting the response of the river–lake systems to the loads from the catchment areas. The collected information makes it possible to create simulations of processes occurring in river–lake systems, which allows for effective action to be taken to protect surface waters. This article provides an overview of available literature, presenting significant research results which enable an understanding of these processes.

Keywords: river–lake systems; cascading reservoirs; biogeochemical barriers

1. Introduction

Matter circulates in nature constantly. Every ecosystem takes part in this circulation, and water, chemical compounds or elements circulate between the parts of the biotope and biocenosis. Disrupting the natural nutrient cycle in individual ecosystems can affect their global cycle [1]. Therefore, the progressive eutrophication of the aquatic environment is a result of these disturbances, resulting, among others, from excessive exploitation of the environment by humans. The hydrological cycle and the movement of elements in nature are modified by anthropogenic activity, both in terrestrial and aquatic ecosystems [1]; in particular ecosystems, it may be disturbed by numerous biogeochemical processes. The deteriorating quality of surface water and groundwater is a global issue, and any measures aimed at improving it must be taken at the stage of local environmental management. Each aquatic ecosystem has a defined tolerance range to progressive human threats and climate change [2]. The latter lead to the depletion of water resources [3] and a deterioration of their quality [4], which intensified the eutrophication process. Local climate change may have regional or even global consequences [5]. The presence of surface water in the landscape may affect the local climate. According to Wen et al. [6], due to their high thermal capacity, lakes release energy during a period of variable temperature, which increases the transpiration process and thus increases the precipitation

intensity in the region. The role of lakes is underestimated, as—according to Li and Yao [7]—in addition to influencing local meteorological conditions, they influence the emission of greenhouse gases, including methane. The prevailing meteorological conditions determine water availability and affect the mobility of nutrients between catchment areas and aquatic ecosystems. Depletion of water resources leads to the leaching of nutrients deep into the soil profile, down to the groundwaters which feed surface waters [8]. An excessive abundance of nutrients in water may lead to accelerated eutrophication of waters, which is a natural process leading to the slow disappearance of water bodies, but progressing much slower compared to the conditions of intensified anthropopressure [7].

The proper management of the catchment area is an important factor influencing water quality, as it properly limits the process of water and wind erosion of nutrients less related to soil particles [9,10]. Moreover, other hazards from the catchment area, including point sources, may affect the balance of nutrients, disturbing the balance between their inflow and outflow [11,12]. According to Allan [13], the problem of anthropogenic eutrophication would not exist if it were not for the development of agriculture in water catchment areas. Each water ecosystem has a specific tolerance to threats coming from the surrounding areas, and the same unfavourable use of catchment areas of different reservoirs may cause their degradation, but at different levels [14]. According to Doody et al. [14], identification of a border above which the management of a catchment area will have a negative impact on aquatic ecosystems may be helpful in responding appropriately to counteract these unfavourable changes. Therefore, apart from land use, other parameters, such as its buffer capacity (which is affected by the soil type) permeability, geology, land denivelation, type of management, land reclamation or ground supply, influence the intensity of water supply [8]. The characteristics of reservoirs and river channels also increase their tolerances. Key factors include their shape and location, morphometric conditions (such as depth and surface), supply method and water retention time [15]. The shape of the lake bowl and reduced water flow allows for the nutrients dissolved in the basin to be deposited at the bottom or, in favourable conditions, transported further. If they are eliminated from the aquatic environment by deposition on the bottom, they can still be picked up in the re-suspension process [16,17]. Likewise, in the case of plants, their natural life cycles are based on a process of mineral assimilation, death and release of organic matter [16].

Most lakes, especially in lowland landscapes, are connected by rivers or streams that introduce or drain water, hence, the issue of the role of river–lake systems appears to be relevant [7]. Hillbricht-Ilkowska and Kostrzewska-Szlakowska [18] define river–lake systems as cascading reservoirs, connected by river sections that interact continuously with each other. They are the remnants of a polygenetic valley formed as a result of the outflow of waters, which formed a canal, which is now a river route, and lakes were formed in its larger depressions [19]. There are three stages of their creation. In the first stage, lake basins were formed in depressions connected by the river, in the second stage, the riverbed between the lakes was eroded and, in the third stage, sediments carried by the river stream were deposited—first near lake deltas, which could cause a backward flow of river water and intensify its meandering and erosion, and then further sedimentation in deeper locations of the lake [19]. The substance is usually transported downstream, but various studies [7,18] have shown that a lake located along the river route may cause a backward current and the material may be deposited in the form of deltas, i.e., in the place of direct contact between the river and the lake. This combination of rivers and lakes has a cause-and-effect relationship and the whole system is subject to dynamic change [7]. Matter in the systems is transported with river waters [20] and accumulated in reservoirs, or picked up from the lake bottom and transported further. Changes occurring in one element of the river–lake system may have an impact on others.

Activities involving appropriate land use, not only within the systems themselves but also in their entire catchment areas, could be extremely important, as they improve the stability of water resources. Authors investigating river–lake systems have varying opinions on their functions, which is why it is extremely important to identify the factors that determine their role. This is very important, as it will protect aquatic ecosystems from the effects of eutrophication [19,21–26]. This article attempts to

present the most important information on the functioning of river lake systems, presented by various authors. Several studies from recent years, available in literature, have addressed very important issues concerning the effects of the specific features of these systems, i.e., their location within the environment, meteorological conditions prevailing in the catchment area, hydrological conditions, properties of the deposited bottom material and the effects of the organisms inhabiting it and of the presence of macrophytes in these aquatic ecosystems on the self-purification of surface waters.

2. Discussion

The on-going changes in climate have a very significant impact on the processes taking place in surface waters, including lakes [27]. Lakes, on the other hand, influence the local and even regional climate. Therefore, according to Huziy and Susham [27], regional climate changes in lake basins should be taken into account in all climatic models. All aquatic ecosystems struggle with the problem of progressive water eutrophication [23]. Due to their properties and location in the landscape, lakes are specific pollution traps. Therefore, it seems that the degradation of lakes is only a local problem. However, in lake valleys, these reservoirs often occur in cascade sequences connected by rivers, making up river–lake systems [23]. The problem of their degradation is more complex because, firstly, it disturbs the landscape and recreational values of the region and, secondly, eutrophogenic substances may be transported outside the examined ecosystem because of continuous water transport and exchange between these reservoirs [23]. These threats then become a regional or even global problem. The main factor exacerbating this problem is the water exchange between the elements of the system and the management of the catchment area [28]. The intensity of this exchange determines, among others, the retention capacity of river–lake systems. Due to the location of reservoirs included in the systems in the postglacial gutter, the abundance of water in the systems is mainly determined by horizontal exchange (ground and surface inflow and outflow), and the vertical exchange (precipitation and evaporation) is of minor importance [28]. Rivers flowing through lakes and their catchment areas influence the amount of inflowing water, mainly due to the presence of forest and marshy areas, which favour retention. It also affects the balance between the inflow of water to the reservoirs and its outflow [29].

2.1. *The Effect of Water Exchange Intensity on the Nutrient Circulation Dynamics*

According to Harvey and Gooseff [30], intensive water exchange in river–lake systems may determine the cycle of matter circulation in a reservoir. Horizontal exchange is the most important in the post-glacial lake water exchange, and the contribution of vertical exchange is small [29]. According to Herbst and Kappen [31], evaporation from open reservoirs is greater than from rushes. The location of reservoirs in river valleys, depressions and near forest areas additionally reduces evaporation [31].

2.1.1. Lake Basin Shape

Water exchange in the lakes takes place in their different parts, which depends on the shape and depth of their bowl [32]. According to Kuriata-Potasznik and Szymczyk [29], water exchange is different in the parts of the water body which are partially separated from the main current, whose waters do not have a direct outflow. Properties of the water body parts separated from the main current are similar to drainless lakes, mid-forest reservoirs or those located in a depression, where water exchange is much slower and vertical exchange through atmospheric precipitation and water evaporation from the open water table or from rushes may be more important (Figure 1) [29].

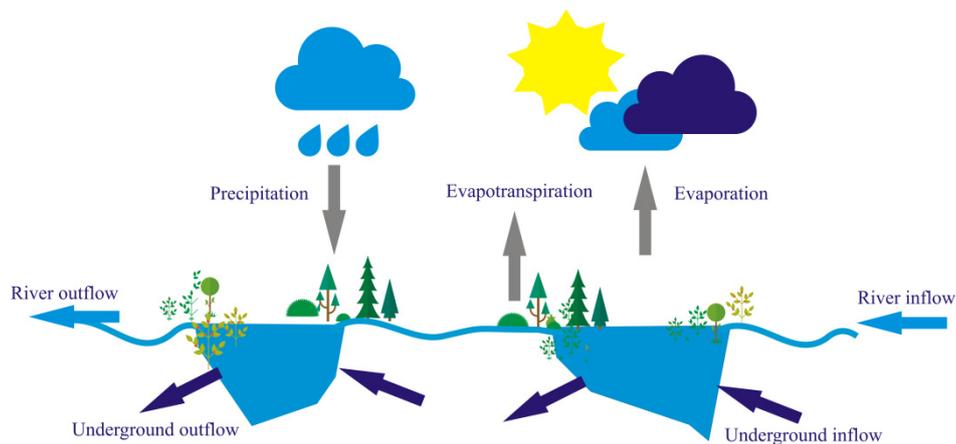


Figure 1. Water exchange in river–lake system.

2.1.2. Weather Conditions

Weather conditions are also important for water exchange [29]. Smaller amounts of precipitation may result in lower water levels and a consequent decrease in the water table level, thus reducing the reservoir surface area. They are then more susceptible to changeable hydrological conditions [33]. The amount of evaporation is proportional to the amount of precipitation onto the surface and is additionally increased by growing daily air temperature [34]. Different parts of the water mass are exchanged in water bodies, depending on its temperature. Cooler water has a higher density; it disturbs the circulation process because it "settles" in the hypolimnion [32]. Moreover, a wind direction other than in line with the lake axis reduces the mixing of lake waters [35]. The absence of surface inflows extends the period of water exchange. This results in the deterioration of water quality due to worse aeration [35].

2.1.3. Global Warming

Global warming also affects local conditions, and thus the water level, thermal properties, internal nutrient supply and trophic cycle [36]. In a study by Sahoo et al. [36] concerning the functioning of river–lake systems, climate change lowered the water level in Lake Tahoe, among other things. The authors showed that too much water heating may disturb the circulation process, with a consequent decrease in its mixing. The waters of the lakes under study were exchanged every four years, and a change of the climatic conditions could extend exchanged waters of the lake to almost two times as much, which could lead to the development of anaerobic conditions at the bottom and internal enrichment of lake waters with sediment nutrients [36].

2.1.4. Hydrological Conditions

Weather conditions affect the heating, cooling, mixing and circulation of lake waters [37]. They do not directly influence the lake water pollution, but they indirectly influence the hydrological conditions in river–lake systems [29,38] by regulating water levels in river beds and lakes, influencing dilution and accumulation of nutrients in waters and influencing the intensity of water flow in river beds. For example, lower water abundance in individual hydrological years, resulting from lower precipitation sums, contributed to the occurrence of periodic water depletion in some watercourses in the catchment area of the river–lake system under study, especially in summer, during intensive plant vegetation and increased water demand [29].

2.1.5. Water Retention

The retention of water in catchment areas is desirable because it allows its use during periods of its shortage, which is facilitated by the proper use of the catchment area [33]. Forest use and

the presence of pastures and green areas are conducive to water retention, but large differences in altitudes may be conducive to its faster outflow [29]. In typically agricultural catchments, with arable land dominating, even half of the water per one hectare of area can be retained compared to forest catchments [29], which was explained in a study by Schüller et al. [39] by the higher intensity of field evaporation with such land use. All measures aimed at water retention in river basins, as in river–lake systems, could improve water conditions in the landscape. These measures include the construction of retention reservoirs, such as those on the Yangtze River (research conducted by Zhang et al. [40]) and on the Powa River (research conducted by Sojka et al. [41]), which affect the hydrological regime of watercourses, with a beneficial effect on flood protection. Such measures may have a positive impact on water availability and exchange, mitigating, *inter alia*, the effects of drought in the catchment area [41]. Like lakes, retention reservoirs affect temporary water storage and they are thus important factors influencing the regulation of the flow of the feeding river. This contributes to the change of the hydrological regime in the lower sections of the systems by regulating the water level in such reservoirs during periods of drought [35,40]. Such measures help to preserve the natural environment in the reservoir without a significant alteration [40].

2.1.6. Nutrient Exchange

Along with water exchange, an exchange of nutrients also takes place between rivers and lakes [29]. In such cases, taking them out of the catchment area will result from the potential of the reservoirs located along the flowing rivers [26,29,42]. The concentration of nutrients in surface water depends, among others, on the way the catchment area is managed. The location of the last lakes on the route of river–lake systems makes them more vulnerable to anthropogenic pollution inflowing from the river and areas in their immediate vicinity (Figure 2). According to Tong et al. [26], the location of reservoirs in estuary sections of rivers results in their greater susceptibility to anthropogenic pressure. Therefore, Lake Bratteg, the last reservoir in the river–lake system studied by Marszałek and Górniak [24], and Lake Symsar studied by Potasznik and Szymczyk [29] and Kuriata-Potasznik et al. [42] were gradually filled with sediments transported by river waters, which resulted in them becoming shallower. Along with the sediments, components from the catchment are deposited at the bottom. The specific properties of river–lake ecosystems and their retention capacity contribute to the formation of their functions in river–lake systems. In addition to the bottom material, the river flowing through the reservoir may also carry nutrients from the river basin into the reservoir [29,38].

Therefore, the load on river–lake systems depends on the development of catchment areas and anthropogenic factors occurring not only in the direct catchment but also in the whole river–lake system [42]. Flowing rivers, often draining multi-hectare agricultural catchment areas, affect the quality of water in the reservoirs through which they flow, e.g., by introducing biogenic substances [29,38]. Significant loads are also introduced with waters of smaller watercourses, fed with sewage from housing estates and runoffs from rural homesteads located nearby [38,43]. Agricultural use of direct catchment areas of river–lake systems may result in the introduction of mineral phosphorus species into lakes [43].

Just as the intensity of water exchange in a reservoir with a diversified lake bowl is different, the content of individual nutrients dissolved in this water may be diversified. Wind-less conditions and high temperatures, especially during the growing season, favour the heating of water, making oxygen conditions deteriorate and create conditions conducive to the decomposition of organic matter, disturbing the circulation processes and creating favourable conditions for algae blooms, as in the case of Lake Erie [44]. Moreover, adverse agricultural practices in the lake basin may contribute to this phenomenon [38]. Intensive agriculture and high air temperatures later in spring and early summer are conducive to the inflow of dissolved reactive phosphorus species to the reservoirs [44]. Moreover, according to Iglesias et al. [45], phosphorus enters river channels as a result of leaching from pasture soils rich in this nutrient and the use of soils as forests lowers their phosphorus content by up to 67% than in those used for pastures. Due to the soil geological properties and structure, the transport of

phosphorus from soil to water can last from a few minutes to several years [46]. Acidification of waters is one of the causes and effects of eutrophication [47]. Tao et al. [47] also showed that biomineralisation resulted in the precipitation of calcium and magnesium carbonate from water to sediments, mainly in autumn, while in spring they were released due to acidification of the aquatic environment. In turn, higher concentrations of calcium and magnesium in surface sediments and lake water may result from soil acidification, which causes carbonate rocks to dissolve. This phenomenon may be caused by intensive agriculture in the catchment area [48]. The content of these nutrients in sediments may lead to their accumulation in the tissues of aquatic plants occurring in these sites, including *Myrriophyllum spicatum* tissues [42,48].

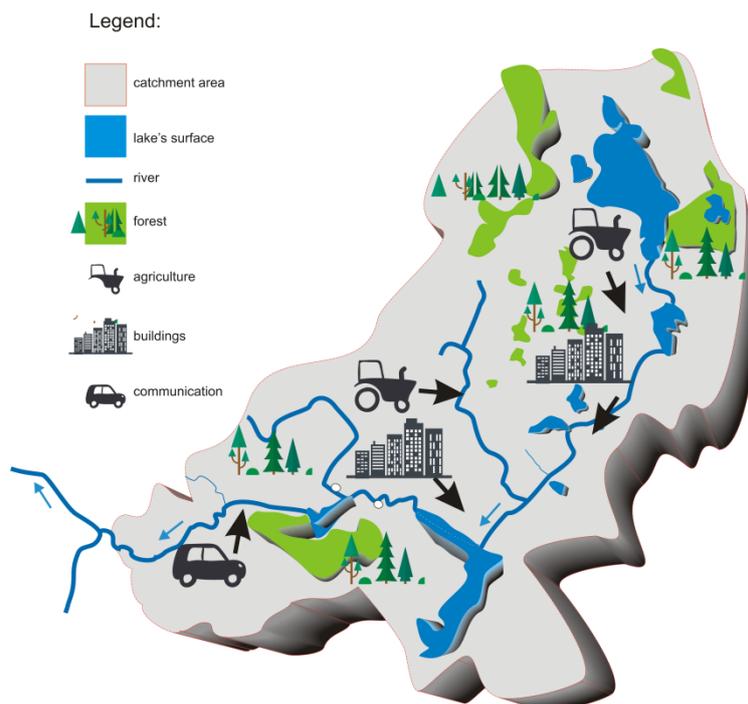


Figure 2. Impact of drainage basin management.

According to Potasznik et al. [43], a significant load of nutrients may be introduced into a lake in the river–lake system not only together with the waters of the main river flowing through it, but also as a result of the inflow of smaller watercourses, especially if they are contaminated with insufficiently purified household sewage. Andersen [21] observed a significant influence of the inflowing sewage on the quality of water in the shallow and eutrophic Lake Brassø, which was the last reservoir studied by the author of the river–lake system. He noted that all activities aimed at limiting the discharge of wastewater resulted in an improvement in the lake water quality, but only to a small extent. The processes taking place in the water bodies of river–lake systems purify river waters, especially intensifying during vegetation periods; however, it is a long-term process [44]. Nitrogen concentration in surface water can be affected indirectly by atmospheric precipitation, as it affects hydrological conditions, including water level and flow rate in watercourses [44]. Fluctuations in nitrogen concentration result from its dilution and accumulation in water during periods of excess and shortage of water [44].

The main river flowing through lakes of river–lake systems could be responsible for the quality of lake waters since it drains the surrounding areas, including agricultural areas [38].

2.1.7. Biogeochemical Barriers

The water bodies of river–lake systems act as natural biogeochemical barriers [16,38]. Water bodies located on the river route may reduce the concentration of most nutrients in the waters of the river flowing out of the lake [43,48].

The water flow through the cascade system of lakes results in its intensive self-purification [24]. In such a system, the preceding lake acts as an initial reservoir relative to the next one in the river–lake system [24,49]. In such conditions, nitrogen is eliminated from the reservoir mainly as a result of the denitrification process [50,51], which is facilitated by anaerobic conditions at the bottom [23].

Jha and Minagawa [52] showed that the denitrification process in the lake located at the end of the river–lake system was affected by hydrological properties such as depth and velocity of water flow. The process itself took place mainly in sediments and its speed depended on the amount of organic matter accumulated, which sustained the activity of bacteria in the denitrification process [52]. According to Andersen [21], 46% of total nitrogen in the Guadana system was retained in lakes located along the river route, mainly in the estuaries. Their elimination and transport outside the catchment areas was limited [21]. In the case of phosphorus, 25% of the load may be retained in bottom sediments [21]. A lower phosphorus retention rate results from the process of internal enrichment with this nutrient as a result of re-suspension from the bottom [43]. The most lakes susceptible to this process are shallow-water lakes which occupy large areas (Table 1). The size of the accumulated nitrogen load is determined by the size of the load supplied to the water body. Lake Symsar, occupying only 4.4% of the total length of the river–lake system, is able to reduce the total nitrogen load by 8.8% and the total phosphorus load by 21.6% [40,43] (Table 1). Intensive water exchange does not always result in the transport of nutrients outside the system, the functions of the reservoirs depend on their load, and their functioning in the landscape depends on it [38]. In a study by Australian scientists [53], lakes in the Lower Lakes system (Lakes Alexandria and Albert) retained approximately 55% of the annual total phosphorus load and 7% of the total nitrogen load.

Table 1. Nutrient retention in different river–lake systems.

No.	River–Lake System	Special Features of System	Nutrient Retention (% Per Year)		Literature
			TN	TP	
1.	Marózka River–Lake Mielno	Catchment: arable land, agricultural	40.5	7.7	[54]
2.	Marózka River–Lake Maróz	Catchment: arable land, agricultural	11.1	9.1	[54]
3.	Łyna River–Lake Łańskie	Catchment: forests	23.8	17.4	[54]
4.	Kortówka River–Lake Kortowskie	Arable land, point and non-point sources. Lake area: 89.7 ha with mean depth: 5.9 m	56.0	26.0	[55]
5.	Havel River–Havel Lakes	Point and non-point sources. Polyrophic, large interconnected shallow lakes with mean depth: 3.5 m	30.0	Increase (internal loading)	[56]
6.	Krzemionka River–Lake Wierzchołek	Shallow of lake with area: 17.3 ha and mean depth: 1.8 m, catchment area: 26.5 ha	Increase (internal loading)	42.0	[57]
7.	Symsarna River–Lake Symsar	Agro-forestry catchment with area: 129.1 km ² . Last lake with area: 1.29 km ² and mean depth: 4.9 m.	8.8	21.6	[38]
8.	River Gudena–Danish system	149 km, Natura 2000	46.0	25.0	[21]

Since shallow lowland lakes of river–lake systems appear to be less susceptible to the accumulation of nutrients due to limited bottom phosphorus deposition as a result of continuous water exchange, an incorrect assumption is often made that a reduction in the inflowing phosphorus load will result in quicker improvement in water quality as the internal feed load has to be taken into account [43]. The internal supply was higher during the period of low phosphorus inflow to the reservoirs, as in Havel Lakes in Germany [56] (Table 1). As lakes are parts of river–lake systems, the outflow of water was conducive to the removal of excess load from water supply and, consequently, to the depletion of phosphorus resources in sediments [56]. This mechanism in flow-through water bodies may lead to a process opposite to eutrophication, producing long-term positive effects [58].

2.1.8. Role of Water Body

Appropriate measures to eliminate point pollution may affect the function of water bodies [38]. Their role depends on the balance between the inflow and outflow of substances from the system. If the balance is positive, then the lake is a place of accumulation, if negative, it transports substances [38]. Measures aimed at delaying the outflow of water are desirable, as this affects, to a certain extent, the transport of nutrients outside the catchment area. Accurate identification of mechanisms determining the response of river–lake systems to the excess of nutrients may allow taking appropriate actions in the future to minimise the negative effects of eutrophication [38]. Tong et al. [26] indicated that short retention times are conducive to the rapid removal of nutrients. Retention times in fluvial lakes are shorter, but the hydraulic load is high [23]. Moreover, the load coming from the catchment area is high. However, Li and Yao [7] found that the share of external factors, apart from horizontal exchange, was insignificant [24]. Kuriata-Potasznik [40] found that the role played by the water body would be different if the nitrogen load coming from the inflow and outflow of the river itself was taken into account. According to those authors, the nitrogen load would be quickly removed from it, and the balance would be negative. According to their research, this statement applies to the last lake of a river–lake system with a typically agricultural catchment; however, it may also apply to other lakes that meet similar conditions [40]. This would be the case if the water and wastewater management in the catchment area were to be streamlined and the wastewater load eliminated. A significant part of the load coming from the river inflow and sewage inflow was retained in the reservoir, so its accumulation function is dominant [40]. Li and Yao [7] also found that point pollution sources play a very important role, even more important than the inflow from a catchment area, even a very large one. According to the study conducted by Aighewi et al. [59], reduction of phosphorus levels in surface waters was caused mainly by a decrease in arable land use and—to a lesser extent—by the reduction of wastewater discharge from a treatment plant to the lower Wicomico River. In a study conducted by Jaskuła et al. [60], the modernization of the sewage treatment plant and the reorganization of the sewage system in the Ner River had a positive impact on the condition of its waters. The authors emphasized the negative impact of agriculture in the catchment area on the water quality and the need to solve this problem. The climate changes, which caused a prolonged drought in the river–lake system studied by Cook et al. [53], would change the hydrological conditions, reducing the flow intensity and thus reducing the load being carried off outside the system.

2.2. *The Role of Bottom Sediments in the Nutrient Cycle in the River–Lake System*

2.2.1. Nutrients

Despite intensive water exchange in the lakes of river–lake systems, biogenic nutrients can be retained in water depths, sediments or macrophytes. The factors determining the capacity of the body of water for this process included nutrient load [43] and morphometric conditions of the reservoirs [61]. Nutrient accumulation in bottom sediments could be closely correlated with morphometric conditions, inter alia with depth [61]. These, in turn, are affected by the flowing river, which, depending on the flow direction, may divide the reservoir into the main part, from whose bottom material may be picked

up or brought in by the current [38]. Apart from the morphometric conditions, the spatial distribution of accumulated sediments in the reservoir [61] may also have a significant impact. The sediments located along the flowing river may contain higher concentrations of nutrients than the bottom material of the whole lake [38]. This suggests that the river is responsible for the variability of accumulation of these nutrients at the bottom of the system, especially near its estuary to the reservoir. For example, small fractions, being lighter, can be transported deep into the reservoirs along with the river current [38,61]. In turn, organic carbon content may depend on the location of sediments in the reservoir; carbon is accumulated along the river flow path through the lake [61].

Due to the continuous exchange of nutrients between the river and the lake, the lake may contribute to the retention of nutrients during the periods when they may cause the quality of the river system downstream of the lake to deteriorate [61]. It seems that deltas, i.e., the material accumulated at the mouth of the rivers, play a very important role [62]. Their role is based on intensive sedimentation of the fluvial suspension and its further chemical transformation [23]. The significance of the delta, in the form of wetlands, located before the inlet of the Selenga River into Lake Baikal, was very large in the process of self-purification of surface waters [63]. The retention of nutrients in the lake sediments leads to their temporary immobilisation, which inhibits the transport of pollutants outside the catchment area [61]. The observed decrease in the amount of pollution in the sediments downstream of the flow-through lake may indicate that the reservoir improves water quality [42].

2.2.2. Metals

The content of metals in aquatic ecosystems may result from natural processes taking place in the catchment area, but their excess in the environment is mainly a consequence of anthropogenic factors, such as wastewater discharges and agricultural activity [64–66]. From an ecological point of view, the response of water bodies in river–lake systems to an inflow of heavy metals is also very important, as they may cause much greater damage to the aquatic environment than other elements [61]. Feeding lake waters with the waters of the flowing river affects the deposition of metal fractions on the bottom of the reservoir. Wang et al. [64] observed that the presence of zinc, nickel and cadmium may result from natural processes. In a study conducted by Ciazela et al. [65], the variability of nutrient content in bottom sediments of the old river basin perfectly illustrates the impact of the inflowing river, which used to be connected with it and is now separated from it. According to those authors, the impact of the threat resulting from the development of transport and industry in the last 50 years was manifested by the accumulation of heavy metals such as Cu, Cd, Pb, Zn, Ni and Cr in sediments near the mouth of the river, and the separation of old river beds from pollution sources limited their degradation. The heavy metal contamination of the reservoirs depended on their distance from the pollution sources, but also on the prevailing hydrological conditions [65] (Table 2). For example, the lead content in the bottom sediments resulted from the distance from the pollution sources, namely from the location of the road in a short distance from the lakeshore [42].

Table 2. Heavy metal content in sediments in different river–lake systems.

No.	River–Lake System	Special Features of System	Metal Content in Sediments (mg kg ⁻¹)				Literature
			Ni	Cu	Zn	Pb	
1.	Powa River- Stare Miasto Reservoir	Catchment covered of arable land with area: 1.46 km ²	2.7	1.7	10.9	3.8	[25]
2.	Lake Jezewo	Agricultural catchment. Lake area: 73 ha with mean depth: 2.9 m and 72 days of water retention	5.9	10.1	903.7	17.6	[41]
3.	Lake Środa	Agricultural catchment. Lake area: 39 ha with mean depth: 2.3 m and 23 days of water retention	3.5	4.6	357.5	7.4	

Table 2. Cont.

No.	River–Lake System	Special Features of System	Metal Content in Sediments (mg kg ⁻¹)				Literature
			Ni	Cu	Zn	Pb	
4.	Lake Września	Agricultural catchment. Lake area: 39 ha with mean depth: 0.9 m and 4 days of water retention	5.5	9.4	678.4	15.2	
5.	Symsarna River- Lake Symsar	Agro-forestry catchment with area: 129.1 km ² . Last lake in system with area: 1.29 km ² and mean depth: 4.9 m.	32.6	19.2	120.0	84.0	[66]
6.	Masurian Lakeland	Small surface area of lake below 100 ha with mean depth: 5.1–17.4 m.	9.1	12.8	75.5	15.6	[67]
7.	Suwałki Lakeland		13.7	16.9	124.7	28.9	

2.2.3. Granulometric Structure

The structure of sediments, including grain size and sediment density, also had a significant influence on the content of nutrients and metals contamination [61]. The contents of some metals such as chromium and zinc depended on the content of very fine fractions in the granulometric composition of the deposit [42,66–68]. According to Ciazela et al. [65], the highest metal content is observed at sites with the smallest grain size in the deposits, but the metals are poorly bioavailable due to the stability of these complexes. The river flowing through a body of water differentiates the deposition of individual fractions in the lake bowl [42]. Varol [69] and El-Amier et al. [70] found that metal sedimentation processes can take place at the estuaries to reservoirs, which depends on the location of the delta and of the rushes. Sedimentation processes take place individually for each reservoir in the river–lake system and depend on water retention time, morphological conditions and other factors [25]. River sediments usually contain larger fractions than lake sediments [23]. Larger sediment fractions are deposited near the estuary of the river flowing into the reservoir, while smaller fractions, being lighter, are picked up from the bottom, transported and deposited farther [25]. The size of fractions, siltation and the abundance of organic matter are the factors that Sojka et al. [25] found that determine the metal content in deposits, hence—according to their research—higher concentrations are found in lake sediments, especially deeper ones, further downstream from the inflow than in river sediments, due to the presence of fine fractions in them. Metal deposition in sediments of flow-through lakes is mainly affected by suspended sediments transported by the river [42]. The content of individual nutrients depends on the strength of complexes with fractions present in sediments, mainly with the finest ones [42]. Thorslund et al. [71] showed that the variability of metal content in sediments was determined by their organic matter content. According to these authors, the solubility of iron, lead and zinc increased with an increasing amount of organic matter in them. The content of organic matter may fluctuate significantly as a result of changes in land use, caused, among others, by deforestation [61]. Most metals accumulated at the bottom of the flow-through lake, because the natural response of the reservoir to the excess of environmental stressors in the form of metals, is their temporary immobilization [42,64], which manifests itself in a decrease in their content at the bottom of the river after flowing through the reservoir. Most of the metals were removed from the lake ecosystem because of its high hydrodynamic energy associated with intensive water exchange [72]. A lake ecosystem, which is part of a river–lake system, can be a place of accumulation for some nutrients, and others can be transported through it, which depends mainly on the abundance of these nutrients, caused by the accumulation in sediments as a result of long-term degradation [61,66].

2.3. The Role of Macrophytes in Nutrient Circulation in River–Lake Systems

Pollutants entering lakes can be retained in the water, accumulated in sediments or taken up by aquatic plants [42]. Their excessive accumulation in plants is associated with the properties and abundance in these nutrients of the ground in which they grow [73]. According to Liu et al. [74],

a high content of nutrients may contribute to the inhibition of macrophyte population growth. When organic matter in sediments is abundant, the availability of metals is lower [72]. Moreover, the content of substances in plant tissues may be influenced by the granulometric composition of sediments and the content of organic matter is correlated with the particle size [72]. According to Liu et al. [74], sediment type may have a significant impact not only on the accumulation capability of rush vegetation but also on the distribution and development of specific plant communities. According to Barroso et al. [35], deliberate modification of the composition of bottom sediments may stimulate the growth of macrophytes.

2.3.1. Species of Macrophytes

The species composition of macrophytes in river–lake systems may depend on the morphometric and hydrological conditions of the reservoirs as affected by the flowing river. According to Marchetti and Scarabotia [75], the distribution of macrophytes in lakes, even periodically connected with the river, depends on seasonality and related changes in water levels. An increase in the abundance and range of macrophytes was observed near the river estuary. According to those authors, deeper lakes contain living species of greater diversity. On the other hand, plants grow faster and the range of their occurrence is wider in shallower locations [75]. There are macrophyte species characteristic for flowing and standing waters in the river–lake systems. Low and medium water flow rates usually stimulate macrophyte growth, while high ones, such as in rivers, usually reduce their growth [76]. A river flowing through a reservoir affects hydrological conditions indirectly, including the intensity of water flow in the lake and the shape of the lake bowl of the reservoir under study [66]; it has no immediate effect on the species composition of macrophytes present in the lake. The macrophytes located along the river flow contained larger loads of, *inter alia*, nitrogen than at other sites [42]. The content of individual nutrients in plant tissues was mainly differentiated by the conditions prevailing at the sites where they grew, which affected the content of nutrients in their tissues [42]. Metal content depended mainly on the abundance of these nutrients in bottom sediments [66]. Individual rush vegetation species can accumulate different biogenic nutrients to a varying extent [42].

2.3.2. Impact of Sediments

According to Kuriata-Potasznik et al. [66], the sediment type, particularly its granulometric composition, has the greatest effect on the accumulation capacity of aquatic plants. The finest fractions contained in the sediments affect their stability and assimilation of nutrients from them is difficult. A flowing river plays a very important role, as the strength of its current determines the granulometric composition of lake sediments through transport and deposition of fractions [66]. By slowing down the flow, waters support the sedimentation of nutrients and reduce turbidity [76]. Apart from flow regulation, macrophytes determine the distribution of the particles and indirectly improve water quality, as they stabilize sediments and limit their re-suspension and bottom erosion [76]. The growth of macrophytes on organic sediments is much faster than on inorganic sediments, but it can be limited by low sediment density [77]. Plant growth and the accumulation of nutrients in plants depend on the concentration of the substance in the sediment [66]. In low-density sediments, the diffusion distance (the distance of particles from each other) is greater, hence the uptake of organic substances is limited [77]. On the other hand, plants themselves also determine the composition of sediments, as they favour the deposition of fractions by slowing down the outflow of water, especially at the estuary [66]. This process is influenced by the extent to which the sediment is covered with biomass, as the presence of plants will reduce the water flow rate and facilitate the sedimentation of particles [78]. The location of macrophytes at the estuary and along the river route makes these sediments more abundant in the finest fractions. According to Li et al. [11], the content of clay and fine sand may be affected by the type of vegetation, but also by the way of its removal from the reservoir, while the content of coarse-grained fractions is only affected by the type of vegetation. However, according to Barroso et al. [35], the granulometric composition of sediments is also determined by the shape of

reservoir shores. Shores with mild slopes favour small fractions to be easily transported by the wind and deposited at their bottoms, while those with steep slopes enable the erosion of larger particles, which in consequence will reduce the biomass of macrophytes [50]. The steep bottom of Lake Palmas and the elongated shape of the lake bowl decreased the littoral zone, and the possibility of rushes rooting in it was limited. In a study conducted by Kozerski et al. [50], the last reservoirs of river–lake systems acted as traps in which excess nutrients present in the aquatic environment were retained, e.g., they were deposited in sediments, water depths and macrophytes, but they were also transformed due to favourable conditions. This is evidenced, among other things, by the diverse deposition of nutrients in bottom sediments [60].

2.4. The Role of Bioindicators in Nutrient Circulation in River–Lake Systems

Physico-chemical methods enable the examination of the instantaneous quality of fluvial waters, which is variable over time. On the other hand, biological methods enable the determination of the environment quality at large time intervals [79]. The species used as bioindicators are those with a low tolerance to variable environmental conditions, which respond in a specific way to an increase or decrease in the content of a particular compound in the environment [80]. In addition to the above-mentioned macrophytes, other biological indicators, e.g., phytoplankton, phytobenthos and ichthyofauna are used as bioindicators. Among others, Obolewski et al. [81] in their research used groups of small-sized organisms inhabiting, inter alia, the submerged parts of the shoots of *Phragmites australis*, i.e., a species characteristic of river–lake systems of northern Poland. The structure and number of these indicators may indicate the trophic state of aquatic ecosystems, which is very important when assessing the ecological status compliance with the Water Framework Directive [80].

River–lake systems create variable conditions for aquatic organisms. The exchange of species between river and lake zones is characteristic of them; however, a greater species abundance is characteristic of the river sections [82]. Studies by various scientists indicate great diversity in terms of the species composition, density and variability over time for certain species. No species variability over time may be indicative of stabilised environmental conditions [82].

Living organisms are directly dependent on the local environment, and their presence reflects the ecological conditions of inhabited aquatic ecosystems. The size of a particular species also reflects the water quality [83]. A study by Szmigielska et al. [84] uses specific properties of these conditions and their susceptibility to the changing natural environment conditions which result from its pollution. Most bioindicator organisms are characterised by a long life-cycle and habitat preferences [84]. Species diversity is also characteristic of the lake basin. A study by Mimier et al. [85] shows that the species composition abundance as well as the macrozoobenthos diversity and density decreased with the depth. The most abundant zone is the littoral. Mimier et al. [85] assumed that the macrozoobenthos structure would be different as compared to eutrophic lakes.

Obolewski et al. [86], carried out studies on ox-bow lakes, which showed that linking water bodies with a main river channel contributed to an improvement in water quality in these bodies, which is reflected inter alia by an increase in macrozoobenthos diversity and abundance. A high diversity index indicates the good condition of the aquatic environment, including proper conditions for the development of fauna and flora [87]. Obolewski et al. [81] concluded that the most important factors that affect these relationships included water flow and the variability of physico-chemical conditions. The formation of deltas and the colonisation by rush-plants affected the species structure.

3. Summary

- River–lake systems are characterised by intensive water exchange which is determined by meteorological conditions. In turn, these indirectly affect hydrological conditions (Sections 2.1.1 and 2.1.2).
- The water exchange is accompanied by the exchange of components between elements of the systems (Section 2.1.6).

- Rivers flowing through water bodies affect their morphometric conditions. The deposition of various rock-debris fractions affects the lake bed shaping and renders them a barrier to the matter which is temporarily deposited in bottom deposits found in the contact zone between rivers and water bodies (Section 2.2.3).
- The structure of deposits and their granulometric composition have an effect on the component content in macrophyte tissues. The assimilation of pollutants by the tissues of plants growing in river–lake systems is determined by their abundance in the substrate (Section 2.3.2).
- River–lake systems act as natural biogeochemical barriers, thus limiting the transport of pollutants outside the ecosystem; this, however, results in the degradation of the water bodies (Section 2.1.7).
- Not only is the role of water bodies being part of a river–lake system determined by the size of its external load of components originating from the catchment area but also by morphometric, hydrological and meteorological conditions (Section 2.1.8).
- Rivers feeding lakes of a river–lake system have a significant effect on the quality of water in the water bodies themselves as well as on the distribution of pollutants in their bottom deposits. Agricultural development and unregulated water and wastewater management within the catchment area contributes to an increase in the transport of components along with their waters (Section 2.2.1, Section 2.2.2, and Section 2.2.3).

In summary, the function of a reservoir in a river–lake system depends on its load, the weather and hydrological conditions. The accumulation role leads to degradation of river–lake reservoirs, and they themselves play the role of a biofilter. This situation leads to the degradation of the reservoirs but improves the quality of the downstream waters, which is desirable in surface waters feeding other rivers. Literature data show that the river transported pollutants and the lake, being the last reservoir on its route, retained the transported substances, which are affected by macrophytes and bottom sediments of river–lake systems. This eliminated the adverse effect of anthropogenic activity on aquatic ecosystems. Anthropogenic factors present in the catchment areas of river–lake systems upset the balance between inflowing and outflowing loads, thus influencing the role of this system.

The development of agriculture in catchment areas is not always accompanied by good water quality. Therefore, it is essential to set priorities to optimise management in the catchment area. It is also recommended that rational land management measures should be implemented in river–lake systems, which should help to mitigate unfavourable local potential and contribute to improving water relations, not only locally, but also regionally, and even globally. Rational management in a catchment area will help to improve its retention capacity, which will improve the state of water resources.

Based on the acquired knowledge, it is recommended that measures, among other things, should be taken to slow down the water outflow from river–lake systems, as extending its retention time will extend the time during which nutrients in the reservoirs of such systems will be stored. Intensive accumulation may accelerate their degradation, but at the same time, it will help to protect the surface waters downstream, which is a desirable effect.

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