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Self-purification of water in the Soła River dam cascade and the possibility of supporting activities

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ABSTRACT

In this article, the water quality problem in dam reservoirs is discussed. The first aim of this work was to recognize the self-purification ability of water during flow through the Soła cascade. It is a system of three dam reservoirs (Tresna, Porąbka, and Czaniec), which were built on the Soła River in southern Poland. The second aim was to indicate the actions that can be performed by humans to improve the self-purification effects. The field research was conducted in the period from May to October 2019. The quality of river and reservoir water was analysed once a month. The following water parameters were determined: temperature, pH, electrolytic conductivity, total hardness, oxygenation, the concentration of phosphates and concentration of chlorophyll *a*. Research has shown that the Soła cascade plays a purifying role in river water. The change in the environment of flowing water to standing water resulted in a decrease in pH (on average from 8.05 to 7.68) and water hardness (on average from 95.7 to 63.7 mg $CaCO_3$/L) in the Tresna Reservoir. Water in the following reservoirs in the cascade had better quality – oxygenation of water increased (on average from 9.2 to 11.8 mg O_2/L), while the contents of chlorophyll *a* and phosphates decreased (on average from 6.92 to 2.44 µg/L and on average from 0.46 to 0.31 mg PO_4/L, respectively) and the content of dissolved mineral substances also slightly decreased. The pH changed from approximately 7.7 (alkaline) to approximately 7 (neutral). Natural self-purification of water in the Soła cascade should be supported by different activities performed by humans, especially in the Tresna Reservoir. They can rely on the mechanical removal of pollution, their chemical neutralization, and the intensification of biochemical and assimilation processes.

Keywords: Dam reservoir; Water quality; Self-purification of water; Purification of the water body

1. Introduction

Self-purification processes occur in both surface water [1] and during infiltration to groundwater [2]. Self-cleaning increases the possibilities of using water (e.g., for bathing, practising water sports, and fishing); however, this is not usually sufficient to achieve drinking water quality [3,4]. The monitoring of water quality is needed for water supply use. In addition, the analysis of the support possibilities by human natural self-purification processes is needed. In this article, the problem of water self-purification in dam reservoirs was analysed.

The creation of the dam reservoirs influences the transport of chemical substances in river systems. This concerns, that is carbon, which is responsible for primary production. Wang et al. [5] showed a vertical stratification of the dissolved inorganic carbon concentration in the reservoirs on the Pearl River (Southern China) – this concentration increases from epilimnion to hypolimnion. A common opinion is that dam reservoirs play a purifying role in river

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water, especially in the context of retention of the debris transported by the river. However, a review of the research indicates that in the case of a single reservoir, self-purifying of the water does not always occur, and purification may be selective (which may concern some specific pollutants), and even a general deterioration in water quality can be found. For example, Siemieniuk and Szczykowska [6] found a negative impact of the Sokółka Reservoir on water quality. Similar conclusions were presented by Ling et al. [7] for the Bakun Reservoir. In turn, Jaguś and Rzętała [8] showed the comprehensive self-purification of water in the Pogoria Reservoir and the selective self-purification in the Dzierżno Duże Reservoir – this reservoir decreased phosphate, suspended sediment and zinc contamination but increased ammonia, lead and cadmium contamination. Information on the selective self-purification of water has also been provided by other authors, for example, Wiejaczka et al. [9] for the Teesta Reservoir. The deterioration of water quality often results from the long-term supply of pollutants into the reservoir and loss of the possibility of their accumulation and neutralization in the reservoir [8].

Cascade systems fulfill the role of purification definitely better [10]. The matter transported by the river (debris, organic matter, and dissolved substances) is delivered to the first reservoir, which accumulates a significant part of the matter – mainly sedimentation of the floats – but also other physical, chemical, biochemical and biological processes of a cleansing character (e.g., coagulation, sorption, and assimilation) occur here. Further self-purification of water follows in subsequent reservoirs. A significant improvement in water quality is recorded in the case of two reservoirs, even if the first reservoir is a small pre-reservoir. The pre-reservoir mainly purifies the water of incoming debris and suspended matter, but they also contribute to the removal of biogenic [11] and organic substances [12] if they have a sufficiently long retention time in the water. Purifying actions at least in the first reservoir to maintain this effect may be needed.

The purpose of this research was to recognize the self-purification ability of water during flow through the Soła River three dam cascade. The problem of self-purification of water is very important because the lowest located reservoir is the source of drinking water supply, and simultaneously, the highest located reservoir is rated as contaminated [13]. Therefore, in addition to the analysis of the results of research on water quality, the possibilities of human activities supporting the natural processes of self-purification were presented.

2. Research methods

2.1. Study area

The Soła River dam cascade is a system of three dam reservoirs: Tresna (49°43′ N, 19°12′ E), Porąbka (49°47′ N, 19°12′ E), and Czaniec (49°50′ N, 19°13′ E), which were built on the Soła River in southern Poland (Fig. 1). The basic parameters of the reservoirs [14] are presented in Table 1.

The catchment of the Soła cascade is a mountain catchment with an area of 1,119 km^2, which is located in the Polish Carpathians. The highest mountain in the watershed in the catchment reaches a height of 1,557 m a.s.l., while the water table level in the Czaniec Reservoir occurs at a height of 295–298 m a.s.l. The Soła River flows from its source to the Tresna Reservoir with an average slope of 9.8‰ – it is the upper course of the river with a length of 40.7 km. The Soła cascade covers the valley at a length of 19.75 km and is treated as the middle course of the river. The lower course of the river – below the Czaniec Reservoir – is 28.75 km long. The Soła River is the right tributary of the Vistula River.

2.2. Methodology adopted

The selected quality parameters of water in dam reservoirs were defined within the framework of the experimental research. The six-monthly measurement series were realized in the period from May to October 2019. The points of water collection were located in such a way as to avoid river and shore influences (Fig. 1). The water was collected by boat using the bathometer – the samples were collected from a depth of 1 m. A total of 18 water samples were collected from the reservoirs.

The water temperature and pH (potentiometric method), water electrolytic conductivity (measurement with a conductometer), and content of dissolved oxygen (measurement with a microcomputer oxygen metre) were measured immediately after collection of the water samples. Then, the water samples were transported under refrigeration conditions to the water laboratory at the University of Bielsko-Biała. Laboratory analyses (i.e., determination of water

Table 1
Characteristics of reservoirs based on data in the monograph of the Soła River dam cascade [14]

Feature of the reservoir	The Tresna Reservoir	The Porąbka Reservoir	The Czaniec Reservoir
Year of handover to exploitation	1967	1938	1967
Maximum water table level (m a.s.l.)	344.86	321.49	298.06
Total capacity (mln m^3)	98.11	27.19	1.32
Reservoir area (ha)	964	333	54
Maximum depth (m)	28.0	19.0	5.5
Average depth (m)	9.9	8.2	2.4
Length of the coastline (km)	33.7	15.2	4.9

Fig. 1. Situational sketch of the Soła River dam cascade.

hardness and content of phosphates and chlorophyll *a*) were performed on the same day. In total, 126 individual analyses of water from the reservoirs were performed.

The total hardness was determined by the colorimetric method with calmagite by using a spectrophotometer (the total hardness determination was preceded by measurements of magnesium and calcium hardness). Calmagite is an indicator dye that changes colour from bluish-purple to red in a strongly alkaline environment in the presence of calcium and magnesium. The EGTA solution causes calcium chelation. Then, the red calcium complex decomposes with calmagite. This facilitates the determination of magnesium. The EDTA solution causes decomposition of the red complex of both calcium and magnesium. The final results were given in mg $CaCO_3$/L with an accuracy of 0.1.

The phosphates were determined by the amino acid method with molybdate reagent and amino acid reagent by using a spectrophotometer. As a result of the orthophosphate reaction with ammonium molybdate, molybdenophosphoric acid was formed. Then, molybdenophosphoric acid was reduced to molybdenophosphorus blue by using the amino acid. The accuracy of the method is 0.01 mg PO_4/L.

Determining chlorophyll *a* as water-insoluble required filtering the water sample (1 L) and obtaining the seston with phytoplankton. Whatman glass fibre filters (type GF/A, diameter 1.6 μm) were used for this purpose. From the filtered and ground material, chlorophyll was extracted by using a solution of acetone and distilled water (9 mL acetone and 1 mL distilled water). The extraction time was 10–15 min while grinding and 24 h while storing in the refrigerator. The chlorophyll extract was analysed spectrophotometrically. The wavelengths 663, 750, 665, and 750 nm were used to measure the absorbance of the obtained extracts. The concentration of chlorophyll *a* was calculated in accordance with the Polish Standard (the formula). The final results were given in μg/L with an accuracy of 0.01.

$$X = \frac{26.73 \cdot \left[\left(A_{663b} - A_{750b}\right) - \left(A_{665a} - A_{750a}\right)\right] \cdot V_E}{V_w \cdot l} \tag{1}$$

where X – concentration of the chlorophyll *a* (mg/L), A_{663b}, A_{750b} – the absorbances of the extract, which were determined before adding of hydrochloric acid (0.12 mol/L), A_{665a}, A_{750a} – the absorbances of the extract, which were determined after adding of hydrochloric acid, V_E – the volume of the prepared extract (L), V_W – the volume of the filtered water (L), l – thickness of the cuvette absorbing layer (cm).

The pH, conductivity, total water hardness and phosphate content were also determined for the water of the Soła River, which flows to the Tresna Reservoir (Fig. 1). This allowed better recognition of the water self-purifying process in the first reservoir. Water was drawn into the container, which was lowered on a rope from the bridge. A total of 6 river water samples were collected, and 24 individual analyses were performed.

The dates of water sampling from the river and reservoirs depended on the hydrological conditions. The samples were collected during the rainless periods when the flows had stabilized for at least a week and the water was very transparent. This allowed for the omission of the short-term extreme conditions, which are related to flood situations.

2.3. Literature studies

In this article, except for presenting the results of field and laboratory research, it was decided to show the possibilities of human activities improving the quality of dam reservoir geosystems. These activities can therefore intensify the water self-purification processes. Literature studies were conducted, and these activities were selected, which can be used in the Soła cascade taking into account the environmental and technical conditions. The description of the activities has an informative character.

3. Results and discussion

The best visible (also visually) effect of water self-purifying while flowing through the Soła cascade is the reduction of the amount of suspension, which is carried by the water. Łajczak [15] demonstrated that the Tresna Reservoir retains as much as 91% of the debris brought to it. In turn, thanks to the Porąbka Reservoir, only 1.1% of the debris (which is carried into the Tresna Reservoir) is transported to the Czaniec Reservoir. Sedimentation also includes particles of dead organisms, as well as particles that are formed by chemical precipitation, coagulation and sorption. Therefore, the formation of bottom sediments has an impact on water quality. Several other processes (occurring in the environment of the stagnant water) also occur, that is, synthesis, decomposition, transformation, and assimilation. The changes in the water quality parameters in subsequent cascade reservoirs are the result of these processes (Table 2). The problem of self-purifying water in the Soła cascade has been mentioned by Stachowicz and Czernoch [16], that is, in the context of reducing the concentrations of dangerous substances, for example, detergents, ether extracts and heavy metals, which pose a health risk in drinking water [17]. Unfortunately, one of the consequences of self-purifying water is the high pollution of bottom sediments, especially in the Tresna Reservoir [18].

3.1. pH and hardness

The pH of the mountain river water is a consequence of the natural carbonate system (which results from the geological subsoil) and anthropogenic influences. Nowicki and Sadurski [19] classified the Soła cascade catchment as located in a hydrogeological area with calcium bicarbonate water. In their study, the Soła water was alkaline (at pH values of approximately 8.0), but the pH changed to neutral when flowing through the reservoirs. The pH values were approximately 7.0–7.1 at temperatures of 15°C–20°C in the Porąbka and Czaniec Reservoirs. This change is consistent with the results, which concerned the total water hardness, dependent mainly on the presence of calcium and magnesium cations. The water of the Soła River can be classified as soft (total hardness: 68–115 mg $CaCO_3$/L), while the reservoir water can be classified as very soft (35–88 mg $CaCO_3$/L) based on the research. Thus, the amount of alkaline cations decreased in the analysed reservoirs. These alkaline cations are chemically bonded (e.g., by HCO_3^- ions), and they are easily precipitated in the form of carbonates or phosphates in an alkaline/neutral environment. These alkaline cations are also subject to other transformations, for example, biochemical bonding by plant organisms, which develop in reservoirs on a much larger scale than in mountain rivers.

3.2. Dissolved substances

The conductivity of water results from the presence of ions, which originate from the dissociation of inorganic compounds. This parameter, therefore, reflects the general occurrence of dissolved mineral substances in water. The proper conductivity was usually greater than 200 μS/cm for the water in the Soła River and the Tresna Reservoir, while the proper conductivity was 15–40 μS/cm for the water in the Porąbka and Czaniec Reservoirs (Table 2). The results obtained do not indicate a problem of general mineral pollution in the analysed water. The self-purifying effect was visible but on a small scale.

3.3. Oxygenation and chlorophyll a

The free oxygen dissolved in water is derived from both the atmosphere and photosynthesis. In the first case, oxygen diffusion depends on thermal conditions and the movement of water. The intensity of the photosynthetic process depends on the development of the plant organisms (mainly phytoplankton) and light conditions. The availability of oxygen is very important for self-purifying processes, as demonstrated by Puklakov et al. [20] by conducting research in the winter season. After the formation of ice cover on the Mozhaisk Reservoir, the self-purification of water was the best within the first month, when the oxygen resources were still large.

Oxygenation measurements were performed only in reservoirs due to extremely different conditions, which occur in the river environment. The oxygen content determined was beneficial for the development of organisms, but less oxygen was recorded in the water from the Tresna Reservoir (from 8.4 to 10.2 mg/L) compared with that from the Porąbka (from 9.6 to 12.9 mg/L) and Czaniec Reservoirs (from 10.7 to 12.3 mg/L). The oxygen content was favourable; however, the research only included a subsurface layer of water.

The oxygen content was the lowest in the water from the Tresna Reservoir despite the most intensive phytoplankton development. This may have been the result of water contamination with organic substances and oxygen consumption during their biochemical decomposition. The Tresna Reservoir has often been described as eutrophic [21],

Table 2
Water quality parameters (arithmetic average/standard deviation) in the Soła River dam cascade in May–October 2019

Parameter/Unit	The Soła River AV/SD	The Tresna Reservoir AV/SD	The Porąbka Reservoir AV/SD	The Czaniec Reservoir AV/SD
Temperature (°C)	–	18.8/3.3	18.5/3.2	17.8/2.5
pH	8.05/0.17	7.68/0.50	7.08/0.29	6.99/0.26
Conductivity (μS/cm)	208/10.4	220/25.4	194/27.7	183/28.4
Total hardness (mg $CaCO_3$/L)	95.7/17.8	63.7/15.8	50.3/11.6	51.2/10.1
Phosphates (mg PO_4/L)	0.06/0.01	0.46/0.17	0.38/0.21	0.31/0.21
Dissolved oxygen (mg O_2/L)	–	9.24/0.65	11.26/1.20	11.79/0.76
Chlorophyll *a* (μg/L)	–	6.92/2.17	3.53/1.85	2.44/1.60

which was confirmed by the results from the research on the content of chlorophyll *a*. In the water from the Tresna Reservoir, chlorophyll *a* has usually been twice as much as in the water from the Porąbka Reservoir and two or three times more than in the Czaniec Reservoir (Table 2). It follows that in the successive reservoirs in the cascade, the conditions for the development of phytoplankton deteriorated, that is, the water quality improved (self-purifying effect). The approximate trophic state of the reservoirs can be given based on chlorophyll *a* concentrations and the OECD water eutrophic classification. The chlorophyll *a* concentrations in the Tresna Reservoir (3.23–9.36 μg/L) indicated mesotrophy and eutrophy, in the Porąbka Reservoir (1.56–6.85 μg/L) they indicated mesotrophy and oligotrophy, and in the Czaniec Reservoir (1.02–5.34 μg/L) they indicated oligotrophy and mesotrophy.

3.4. Phosphates

In the case of phosphates, an increase in their content in the reservoir water in relation to river water was found. The water of the Soła River contained 0.04–0.08 mg PO_4/L, while 0.22–0.71 mg PO_4/L was recorded in the water from the Tresna Reservoir (Table 2). The concentration of phosphates in the influent water seemed low; however, according to Jaguś's calculations [13], approximately 0.3 tons to approximately 2 tons of phosphorus per month enter the Tresna Reservoir in this way. In the case of the Tresna Reservoir, these are the quantities that repeatedly exceed the limited quantities for inducing eutrophication. Vollenweider [22] reported that the annual inflow of phosphorus over 0.07 g per 1 m^2 in the reservoir surface threatens eutrophication, and over 1 g/m^2 of phosphorus contained in phosphates flows into the Tresna Reservoir during the year [13].

The phosphorus supplied is used in biological production but is also precipitated to bottom sediments. Higher concentrations of phosphates in reservoir water testify to the accumulation of large amounts of phosphorus during several dozen years of exploitation of these reservoirs. Currently, phosphorus is likely subject to circulation in reservoir ecosystems. The slight self-purifying effect is visible – the concentrations of the phosphates decrease slightly in the subsequent reservoirs in the cascade; however, in every case, they are enough that they can cause frequent and long-lasting water blooms.

4. Self-purifying support activities

Due to the water supply destiny in the Czaniec Reservoir, most activities supporting the self-purification of water should be realized within the Tresna Reservoir. The Porąbka Reservoir should constitute a buffer facility for possible pollutants from the Tresna Reservoir, which are derived as a result of human activities. Self-purifying processes in the Soła cascade can be supported by the removal of the bottom sediments (delta and deep water), biomanipulation treatments, creating habitats for aquatic organisms (i.e., artificial substrates), biological regeneration of the reservoir geosystem, purification of water by using chemical agents, stabilization of bottom sediments, and aeration of bottom water.

Support activities the purifying of the water reservoirs are very important because reservoirs can be a significant source of greenhouse gas emissions, for example, N_2O, CH_4, CO_2 [23]. Kumar and Sharma [24] propose an assessment of the risk of greenhouse gas emissions from water reservoirs with the use of an appropriate tool – model GRAT. This risk depends, that is, on river discharge. Substances from the soil flow to reservoirs with the river's water and they are a source of greenhouse gas creation. Therefore, it is also important to appropriate management and purifying of the catchment area [25].

4.1. Removal of the bottom sediments

The Tresna Reservoir is intensely silted by material, which is carried by the Soła River. The larger-size fractions mainly accumulate in the zone of the river inflow to the reservoir, and they form a delta. The small fractions spread in the water of the reservoir and participate in the formation cover of the deep-water sediments. According to the technical documentation of the reservoir, the amount of silt was as high as 0.31 million m^3/y in the early years of the 21st century [26]. Dredging of the reservoir for many years was conducted on a small scale in the delta zone. Debris was exploited for the production of construction aggregates by using coastal excavators and floating multi-bucket dredgers (Fig. 2). Realization of the state of the comprehensive dredging project of the river mouth zone of the reservoir started only in 2020. This work will take at least several years. The extraction of delta sediments will be synonymous with the removal of a large amount of organic matter, which during decomposition is the source of gaseous air pollutants and biogenic substances in the aquatic environment. In this zone, sludge removal can be conducted by using floating dredgers and lowering the water level in the reservoir by using land machines [27]. The entry of equipment (excavators, bulldozers, loaders, and trucks), however, is possible on dried and preferably frozen ground in the winter season.

In the future, it is worth considering the extraction of deep-water sediments, which have particularly high accumulation abilities of micropollutants and phosphorus compounds [28,29]. If it is not possible to completely empty the reservoir and use land machines, then this treatment may be done by using floating suction dredgers. Other methods cause the mixing of the sediments, which poses a risk of entering the Porąbka Reservoir.

4.2. Biomanipulation activities

Due to the occurrence of water blooms, biomanipulation activities in the Soła cascade should be targeted to reduce phytoplankton abundance, which serves to improve water quality. Fish are the best group of reservoir organisms for biomanipulation activities because their structure and number can be shaped by appropriate fishery management. Biomanipulation at the fish level, aimed at reducing the amount of phytoplankton, is consistent with the assumptions of the "top-down" theory, indicating the formation of a trophic pyramid from top to base [30].

Large zooplankton organisms (such as cladocerans) are the main group of organisms that can keep the development

Fig. 2. Multi-bucket dredger in the Tresna Reservoir (photo by A. Jaguś).

of phytoplankton at a low level (through consumption). Large zooplankton organisms are consumed by juveniles of practically all fish species (especially perch and carp fish) and by older individuals of nonpredatory species. Thus, to achieve the goal, the number of appropriate predators (pikes, zanders, European catfish, and asps) should be increased, and the brooding of carp fish and perch should be reduced. It is recommended to intensively fish for cyprinids (approximately 75% of cyprinids should be removed) and to restock with fry of predatory fish [31]. The reduction of the nonpredatory fish population will be the effect, which will cause the development of zooplankton, which consume phytoplankton. The reduction of the nonpredatory fish population (especially feeding on the bottom (bream and carp)) brings an additional benefit to water quality because this fish disturbs the bottom sediments and induces a recirculation of nutrients to the water in this way [32].

The presence of macrophytes is a factor that intensifies the effect of the proposed biomanipulation because they increase the survival of fry predatory species and water purification [33]. In the case of the Tresna and Porąbka Reservoirs, which are poor in macrophytes, planting them may be considered. In addition, the transport of sediments containing the surviving organs of these plants may also be considered.

4.3. New habitats for the periphyton

Periphyton is formed by sedentary aquatic organisms (bacteria, protozoa, ciliates, rotaria, nematodes, fungi, and algae), which are attached to underwater objects, especially the stems and leaves of macrophytes and any construction below the waterline. The creation of habitat places for these organisms serves to purify water due to the use of nutrients by these organisms in life processes. In the case of the Tresna and Porąbka Reservoirs, a shortage of habitat objects for periphyton can be stated. Considering the use of artificial substrates is therefore advisable. They are usually installed in shallow water zones, where good light conditions occur. In mountain reservoirs, artificial substrates should be installed rather in the zones closer to the dams to protect against destruction through the swollen water of the supplying watercourses.

Different forms of substrates are proposed in the literature – it may be a plastic grate. Szlauer et al. [34] suggested the creation of foil substrates that transmit light and do not rot. From the foil fragments (1 m^2 or 2 m^2), hoods were formed. These hoods were equipped with a bag of sand weighing them down, and they had a piece of styrofoam attached to them, which served as a swimmer. These substrates were anchored at the bottom and stayed under the water surface. These substrates were inhabited by numerous organisms that carried out their own life processes but were also food for snails, insect larvae and fish. The use of hoods gives very good results in terms of improving water quality - they constitute an internal treatment plant for the reservoir. Calcium carbonate, calcium phosphate and detritus (i.e., dead organic matter) accumulate on the hoods. In practice, various artificial substrates are used: bamboo, aquamats, and carbon ecofibres [35–37].

The current research shows that the best substrates for periphyton development are natural substrates, most often in the form of submerged or floating plants [38]. The macrophyte islands are the best solution. The underwater zone of these islands is a place of development and existence for fouling organisms, as well as for zooplankton and fry.

4.4. Biological regeneration

When considering the possibilities of supporting natural self-purifying processes, attention should be given to the method of the comprehensive regeneration quality of water reservoir geosystems. This method was elaborated in Japan by Professor Teruo Higa. It is based on a composition of microorganisms called effective microorganisms (EMs), which are introduced into a water reservoir (natural or anthropogenic) [39]. In practice, biological preparations are introduced into reservoirs and contain various strains of bacteria (e.g., *Lactobacillus plantarum*, *Lactobacillus casei*, and nitrifying and denitrifying bacteria), actinomycetes (e.g., *Streptomyces albus*) and fungi (e.g., *Saccharomyces cerevisiae*). The mixture is stable and has a broadly defined purifying action [40,41].

The processes resulting from the development of microorganisms lead to the restoration of the biological balance of the ecosystem. For example, microorganisms supply enzymes whose action serves to decompose organic matter and stops rotting. Organic pollutants are a source of food for these microorganisms. This biological method of regeneration occurs without the use of chemical agents, and the introduced microorganisms are not invasive. The use of preparations does not require any prevention or grace periods. They are safe for aquatic organisms and do not affect the normal use of reservoirs. The preparations are prepared individually for each reservoir depending on the prevailing ecological conditions. The improvement of water quality after using EMs has been found in many reservoirs in Poland, for example, Głuchów [42] or Słoneczko [43], and around the world, for example, Pandan Perdana Lake [41] or Putrajaya Lake [44].

4.5. Chemical water treatment

The treatments of chemical water purification rely on surface dosing of the appropriate chemical substances into the water. These substances are dosed from the watercraft or with the use of agricultural aviation equipment.

Magnesium chloride is an example of a chemical substance that is recommended for use [45]. This chemical compound in the presence of ammonium and phosphate ions forms insoluble magnesium ammonium monophosphate, that is, struvite. Additionally, magnesium creates insoluble bonds with phosphorus. Both nitrogen and phosphorus can therefore be removed from the water through these reactions because the created compounds succumb to sedimentation to the bottom sediments.

Lanthanum bentonite should also be classified as a substance of interest [46]. It is a clay material that is mainly composed of montmorillonite minerals. It has high absorption abilities and, together with the absorbed biogenic matter and micropollutants, succumbs to sedimentation to the bottom sediments. This material was used, for example, in the Lake Bärensee Reservoir in Germany and in Gołdap Lake in Poland [47]. A decrease in the phosphorus content in water was found during the year after application. The downside of this method is the high cost of the treatment.

Particular caution should be taken in the case of inducing coagulation of suspensions/colloids, which are dispersed in the water, because aluminium coagulants can be a source of toxic aluminium from lowering the pH, and iron coagulants can be a source of iron, which stimulates the development of phytoplankton (especially diatoms and cyanobacteria). Copper sulfate is not currently recommended for algae elimination (during water blooms), but was used in the past. It is dangerous to introduce toxic substances into the environment, and the effect is short-lived; phytoplankton are reborn quickly. A safe and effective way to eliminate cyanobacterial blooms is using the natural material barley straw, which acts as a natural algistatic material [48,49].

4.6. Stabilization of the bottom sediments

Natural self-purifying processes and supporting activities often lead to the growth of a cover on the bottom sediments. In a situation where it is impossible to remove bottom sediments (especially deep water sediments), it is worth stabilizing them, that is, blocking the entry of pollutants (especially phosphorus) from sediments to the water. This can be done by chemical interference or capping, that is, isolating sediments from water.

Chemical interference relies on dosing coagulants directly on the sediments, possibly to over-sediment the water. One of the first methods of chemical interference in sediments was elaborated by Ripl [50]. This researcher dosed directly onto sediments the following substances by using a device, which was pulled along the bottom:

- Iron chloride as a source of iron for the formation of iron(III) phosphate that is difficult to dissolve;
- Calcium nitrate as an oxidant and a source of calcium for the formation of hard-to-dissolve calcium phosphate;
- Sodium hydroxide (in case of too low pH).

Favourable conditions not only for the binding of phosphorus but also microbiological reduction of nitrates to molecular nitrogen were created in this way. The blocking of phosphorus in bottom sediments by using coagulants is commonly applied in different water reservoirs; in Poland, a special device called Proteus was constructed for the application of this method [51].

The capping method relies on covering the sediments with a layer of material, which makes it impossible to chemically exchange substances. It can be a sand or bentonite layer. This method is intended for calm water zones so that its movement/flow does not disturb the isolated sediments [52].

4.7. Aeration of the bottom zone

An alternative to deep-water sediment stabilization is water purification in the bottom zone by supplying oxygen. For this purpose, the aeration method in the deepest layer of water is used. These layers of water stagnate for a large part of the year. These layers of water also do not contact atmospheric air, and they are characterized by a high content of nutrients and rotting products of organic matter (organic compounds, methane, and hydrogen sulfide). This treatment should rely on taking deoxygenated bottom water, aeration in a closed aerator (e.g., floating on the surface of the water), and re-entry into the same water zone. The precipitation of phosphorus compounds from the water (with Fe^{3+}), inhibition decay processes, aerobic mineralization of the organic matter and increasing capacity of the ecological habitat occur as an effect of improved oxygenation.

Pollution with organic matter and phosphates is reduced (which reduces the fertility of the water) from a long perspective on the condition that the treatment is repeated. However, the cessation of aeration causes the rapid deterioration of reservoir ecological quality and the return to the previous state [53]. The aeration method in the deepest layers of water is applied all over the world. The latest information comes from, that is, reservoirs in the USA: Camanche Reservoir, Pleasant Lake, and Vadnais Lake [54,55] and from China: Lijiaheg Reservoir [56].

5. Conclusions

Research has shown that the Soła cascade plays a purifying role in river water. The change of the flowing water environment to standing water resulted in a decrease in the pH and water hardness. The pH changed from alkaline to neutral, and the water hardness changed from soft to very soft. The concentration of phosphates in the water increased after the river flowed into the first reservoir.

The water in the subsequent reservoirs in the cascade was characterized by better quality; oxygenation increased, while the contents of chlorophyll *a*, phosphates and dissolved mineral substances decreased.

The water fertility in the following reservoirs decreased. The decreasing phosphate concentrations and lower biological production were expressed. The problem of eutrophication concerns the first reservoir in the cascade (Tresna Reservoir). This problem is worsened by undesirable water blooms, which are mainly observed in the Tresna Reservoir. Water blooms in the Porąbka and Czaniec Reservoirs are very rare.

Natural self-purification of water in the Soła cascade should be supported by different activities conducted by humans, especially in the Tresna Reservoir. They can rely on the mechanical removal of pollutants, their chemical neutralization, and the intensification of biochemical and assimilation processes. The expected improvement in water quality in the cascade can bring the realization of the state dredging project in the Tresna Reservoir, which started in 2020.

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