

## CHAPTER III

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# POTENTIAL FOR SEWAGE WATER PURIFICATION IN AN AQUEOUS ENVIRONMENT BY A CONSTRUCTED WETLAND

### Introduction

Modern development and improvement of the quality of life has been accompanied by increasing populations outside big cities. Formerly rural areas are frequently assuming non-agricultural functions such as settlement, services, logistics, industry and recreation. This has resulted in an increase in the amount of waste matter and acceleration of its circulation; as sewage and waste it also becomes a threat to the environment. Many years without sewerage systems and sewage treatment plants or systems of waste collection and disposal, with waste management systems based on makeshift septic tanks and rubbish dumps, has resulted in an accumulation of waste in the environment, mainly in the soil and subsurface water. Contaminants have been spreading and contributing to increased fertility of underground waters and small streams. Such streams are also fed with discharges from sewage treatment plants, which has negative consequence because systems of lower treatment effectiveness and higher biogenic element concentrations in post-treatment waters are acceptable due to a low building density and the small amounts of sewage for treatment (Ministry Regulation of 29.11.2002). As a result, waters are polluted by the following types of contaminations (KOC 1994):

– from natural sources

- products of rock erosion;
- products of organic matter transformations in soil;
- secretions and excrements of living organisms;
- substances contained in atmospheric precipitation;

– from agricultural sources

- components or mineral and organic fertilizers which have not been taken up by plants;
- remains of pesticides which have not been decomposed;
- remains of fuels and products of their combustion;
- animal excrements as sewage from animal breeding farms;
- runoff from fodder silos and fodder storage houses;
- excrements of animals which are permanently grazing, washed down by rain;

– from non-agricultural sources

- rainwater runoffs from roads and hardened areas;
- contaminations of transport-related origin from transport routes;
- runoff from legal and illegal rubbish dumps;
- products of fuel combustion;
- sewage treatment plant discharges;
- inflow of contaminated rainwater from urban areas;

In this case, water carries elements of natural matter circulation combined with contaminants from the environment and those produced by day-to-day activities of rural area inhabitants. Sewage discharges from treatment plants often cause the quality of water in small streams to deteriorate due to higher acceptable limits of contaminations and biogenic element concentrations as well as a higher contribution of sewage discharge in flowing water than is the case with large urban agglomerations, where discharges from treatment plants flow off to bigger rivers (TUCHOLSKI et al. 2007). Therefore, rural area sanitation schemes are being carried out to prevent increases in environment pollution, but their effects are below expectations.

The unsatisfactory rate of improvement of water quality puts Poland at odds with the commitments it has made under international agreements (GUS, 2009). By ratifying the Helsinki Convention, Poland committed itself to take steps to arrest the growth fertility of the Baltic Sea by improving the quality of inflowing rivers (which are largely dependent on the quality of their tributaries), including the elementary watersheds in the upper parts of the drainage basins.

Consequently, a crucial task is to improve the water quality in small streams. It is a difficult problem and closely dependent on the natural factors which govern the matter and energy circulation in the environment which has been considerably transformed throughout the country.

### **Natural factors affecting water quality in rural areas**

The transformation of primeval landscape into agriculturally-utilized areas has affected hydrographic conditions by shortening and simplifying water circulation cycles. The gradual increase in field and pasture areas at the expense of forests has brought about a reduction of soil retention and deterioration of infiltration conditions, while at the same time facilitating surface runoff of rainwater. These processes have resulted in negative transformations of natural biogeochemical cycles (STACHOWICZ 1997). The situation has been aggravated by drainage run-off, which accelerates substance outflow from the soil (BOROWIEC, ZABŁOCKI 1990, KOC, SZYMCZYK 2001).

Agricultural contaminates are primarily area-related. They include mineral and organic fertilizers applied in field cultivation as well as erosion-related surface runoff from rural areas (PAWLIK-DOBROWOLSKI 1990; WODNO-BILANSOWE... 1998). Agricultural contaminates also originate in dispersed point sources, such as homesteads (residential buildings and septic tanks) and objects related to animal production (livestock buildings, manure heaps, tanks of animal slurry and liquid manure, silos and silage heaps, etc.). The intensity of contaminate inflow to water

from the sources scattered around the area depends on various factors, including: land use, size of the area and its inclination, soil type, vegetation, population density. Substance migration from soil with water is largely affected by the type of agricultural activity, including: type of cultivated plants, coverage of soil with vegetation, level and manner of organic and mineral fertilization, mass of post-harvest remains decomposed in autumn and in winter and livestock density (PAWLIK-DOBROWOLSKI 1990; GIERCUSZKIEWICZ-BAJTLIK 1990; WODNO-BILANSOWE... 1998). An important role in the process is also played by hydrological and soil-related factors, i.e. the amount and distribution of rainfall and spring thaw water, occurrence of torrential rain, intensity of surface run-off, type of soil, organic matter content in soil and air-water relations (WODNO-BILANSOWE... 1998).

It is of fundamental importance for the quality of water in elementary drainage basins how many nutrients are discharged by small sewage treatment plants and how many nutrients are supplied to rural areas in order to boost agricultural production. This can be controlled by calculating a balance of biogenic elements on different scales: for the country, the region, the drainage basin and by monitoring water condition.

According to DYMACZEWSKI et al. (1997) and HARTMANN (1999), specific saprobic zones, with different types of organisms dominating, form in the stream flow below the sewage discharge inflow, depending on the stream load with impurities. The following saprobic zones are identified: a deoxidation and degradation zone, situated immediately below the discharge site of improperly treated or untreated sewage (polysorbic zone); intermediate zones, where aerobic conditions are being restored, ( $\alpha$ - and  $\beta$ -mesosaprobic zones); a water restoration zone or unpolluted zone (oligosaprobic).

Impurities flowing into the streams and water bodies are reduced, but this is the case only until the threshold of water ability to self-purify is exceeded. The process results in the formation of mineral forms of biogenic elements. Those which flow in from various sources form the base of primary production, whose size exceeds the consumptive capabilities of higher links in the food chain. Excess primary production is decomposed by destruents, often under a shortage of oxygen, with toxic substances excreted and non-mineralized organic substance accumulated. In effect, biogenic inflow in excess of absorptive capabilities in hydrobiocenoses results in secondary water contamination, especially in water bodies with low water exchange indices in a lake-river system.

Degradation of aqueous ecosystems results in upsetting the balance between the amount of contaminations of human origin and the capability of their neutralization in the environment, i.e. of self-purification. This is the reason for increasing environment pollution, excessive eutrophication and water productivity.

The decrease in pollution growth rate and reduction of pollution in small streams is insufficient given the necessity to achieve a significant improvement in water quality and lowering of the concentration of contaminations and biogenic elements carried with water to the Baltic Sea. More effective sewage management should include highly effective biological processes which stimulate biological transformations and result in water purification (WÓJCIK 1993, STRUTYŃSKI 1997).

Each undertaking aimed at reducing the load of impurities in surface waters is worth considering, especially if it requires small investment outlays. It is of great

importance in reducing the migration of nutrients to waters to properly manage the banks of streams and coasts of water bodies and to create buffer zones (SÖDERGREN 1993; HAYCOCK et al. 1996; KOC et al. 2001).

Seeking new methods of effective utilization of existing objects in environment protection involves studies of constructed wetlands. Characteristic features of such objects include shallow depth, high heating/cooling rate and intense mixing –factors which play an important role in matter transformations. The intensity of biogenic elements absorption in a water body depends mainly on the season of the year, the size of inflowing loads of impurities and the retention time. Studies have been carried out in order to determine the reduction of concentrations and loads of impurities in a stream carrying water from a forest and agricultural area which was additionally contaminated with sewage from a sewage treatment plant, after flowing through a constructed wetland. Rural area sanitation schemes provide the possibility of channelling off sewage to larger, more effective treatment plants to reduce impurity loads in this type of object. It is also important to determine how a constructed wetland and the sludge accumulated in it will behave both during and after a period of sewage discharge to the stream.

### **Fundamentals of constructed wetlands operating as biogeochemical barriers in the environment**

When seeking methods of surface water protection against eutrophication, a possibility was suggested of using small constructed wetlands as impurity eliminators (CZAMARA 2002). The amount and temporal variability of impurities inflowing to water bodies depends on:

- use of watersheds above a constructed wetland;
- seasons of the year and the related periods of vegetation and agricultural procedures;
- torrential rains and erosion-causing run-offs during intensive thaws;
- intensity of run-off from the drainage systems which supply water bodies;
- sewage inflow from settlements and loads of impurities carried by it.

Constructed wetlands should be situated below the existing inflows carrying increased loads of impurities.

A newly constructed wetland in a stream valley results in the following:

- changes in matter and energy circulation within the system;
- creation of a new eco-system with a clear tendency to self-organize which is intended to achieve stable equilibrium;
- change of intensity of factors which regulate the matter and energy circulation rate.

The presence of a constructed wetland along the stream flow route reduces the water flow rate, which results in sedimentation of impurities carried with water (PARZONKA 1991, MADEYSKI, TARNAWSKI 2004). A decrease in the water flow rate in the initial part of the wetland results in separation of sedimenting particles by size and specific weight. The largest mineral particles sediment first, followed by smaller and smaller ones in consecutive sections of the stream. Organic-mineral and organic

(colloidal) particles do not sediment until they reach the middle part of the wetland and before the weir, where the flow rate is the lowest. The substances dissolved in water may form insoluble deposits of calcium sulphates and phosphates and aluminum and iron phosphates.

Biogenic substances dissolved in water are taken up by plants and contribute to the production of organic mass (primary production) in the wetland. After being consumed, plants are returned to water as excrements of herbivores and predators. A special role is attributed to macrophytes, which act as filters of suspensions in the littoral zone. CHUDYBA and KALWASIŃSKI (1998) claim that retaining inflowing matter in the littoral zone is closely connected with the presence of higher plants. Their morphological structure, combined with appropriate growth density, turns them into mechanical filters. This effect applies mainly to dispersed impurities with high levels of suspension. Settlement of suspensions on plants is closely related to decreased water flow in the littoral zone. The largest amount of suspensions is retained by spiked water-milfoil (*Myriophyllum spicatum* L.), and the smallest is retained by aquatic moss (*Fontinalis antipyretica*). Higher plants also retain oil and petrochemical impurities. Discussion of the role of littoral as a filter must not be confined to mechanical action of macrophytes. Higher vegetation can take up organic and mineral substances and use them in metabolism, or accumulate them in cells. Many authors claim that macrophytes are a fundamental factor which affects water quality in water bodies, and the more of them there are, the more capable the water bodies are of self-purifying (SZYPEREK 2003). As the eutrophication and primary production increases, the food chain breaks down due to biomass excess, reduced amount of light reaching the depth of water as well as a shortage of oxygen in the water during periods when no photosynthesis takes place (night, winter) and its consumption for plant respiration. The living conditions of herbivores and predators deteriorate. Unconsumed plants settle and become part of bottom deposits. Sedimenting substances carried with water which are produced in the constructed wetland form a deposit layer, which is initially resuspended and decomposed. As time passes, the deeper layers of more intensely mineralized sediments stabilize and fresh layers are superimposed on them. Water movement in the constructed wetland causes deposits to accumulate in its deepest places where deposits containing more organic matter settle due to slower sedimentation in the flowing water and its easy transport with water currents. An excessively high content of biogenic substances in water contributes to development of vegetation in the littoral and sub-littoral zone and in shallow waters. Due to intensive eutrophication, competition is won by plants with high nutritional needs and those which produce high levels of biomass. Impurities are absorbed and substances sediment in the overgrown zone of the constructed wetland. Water and macrophyte movement, caused mainly by wind, disturbs the sediments and brings about their mineralization and transfers them to deeper layers of the wetland (SIWEK et al. 2009). However, intense growth of phytoplankton in over-fertile wetlands reduces light access to the water depths and brings about extinction of submerged and partly submerged plants. Oxygen shortage in water may occur as it is consumed in respiration.

Impurities carried with water are removed by sedimentation, precipitation of insoluble compounds, coagulation of dispersed colloids and biosorption. This produces sediments which are transferred, resuspended and decomposed – resulting

in the release of accumulated substances. The initial period of the constructed wetland existence is dominated by the processes of water purification and its renewal. This is followed by a period of equilibrium of the processes of impurity trapping and release from sediments. The wetland then stops playing the role of a biogeochemical barrier. This is preceded by a transition period when the wetland plays its role only during the vegetation period. The biological, physicochemical and chemical processes mentioned above, and especially the equilibrium between impurity absorption and release, are considerably affected by weather conditions, including temperature, wind and light, as well as the amount of inflowing impurity loads. Therefore, after the initial period of the wetland existence, when water is purified all year round, it is highly effective in water purification during the vegetation period, but its effectiveness is reduced outside it, especially in winter. When the phase begins with water being purified in summer and contaminated in winter due to the domination of impurity release from sediments, it is a sign that the water body has to be rehabilitated by sediment removal or stabilization.

The equilibrium between impurity absorption and release depends on its concentration in flowing water. If impurity inflow to a constructed wetland (which purifies strongly contaminated waters) ceases, e.g. because sewage treatment plant effluent is channeled off outside the drainage basin, such a wetland may become a source of impurities due to a shift in the equilibrium towards impurity release from sediments. The wetland is supplied with biogenic substances and impurities from within (BORÓWKA 2007). Hence, after a period when the wetland is used as a biogeochemical barrier for the impurities carried with water, its control (and frequent rehabilitation) is necessary.

The high effectiveness of water purification by macrophytes has encouraged the use of artificial systems mimicking marsh ecosystems in the purification processes of sewage and sewage-contaminated waters. Natural treatment facilities make use of the ability of the soil and vegetation of marshy ecosystems to retain and decompose impurities present in waters and sewage. Constructed wetlands which mimic marshy ecosystems are more effective in purification than natural water bodies (COVENEY 2002).

Using constructed wetlands to reduce impurity loads inflow leads to their degradation. Water bodies situated in urban drainage basins and those in the vicinity of farms are particularly susceptible to degradation. Surface run-off from built-up areas carries impurities at high concentrations, including nitrogen and phosphorus. It is important to determine the threshold values and impurity loads absorbable by these systems. They could provide a basis for calculating the maximum acceptable anthropogenic loads in systems of small streams and constructed wetlands on their way. Such systems usually receive effluent from rural sewage treatment plants. Failure to find an accurate solution to the problem results in progressive degradation of the rural areas where small streams are particularly valuable, performing many functions that no other systems can perform.

Owing to their features, small water bodies are specific ecosystems which are significantly different from each other and different from other environments in our climatic zone. They can perform several valuable and complex functions. These include: biocenotic, hydrologic, zoologic, landscape-related, educational, economic, leisure-related (KOC et al. 2001). Consequently, their use in order to

improve water quality has to be subordinated to its broader biocenotic role in the environment. It seems that the complicated relations that govern them have not been sufficiently explored and require new research into their operation, natural importance and transformation.

### **Studies of the operation of a constructed wetland situated in a stream flow**

The issue of the effectiveness of a constructed wetland as a filter of impurities carried with the stream water is illustrated by a study conducted in the Olsztyn Lake District. The operation of a constructed wetland situated on a stream carrying water contaminated with effluent from a sewage treatment plant was examined in a small closed-circulation object, typical of rural areas – the drainage basin of the stream of Sząbruk, whose waters flow into Lake Wulpińskie. The stream is 5.1 km long and its drainage basin area is 13.2 km<sup>2</sup>; it is an agricultural area with human settlements, forest accounts for 30% of its area. There are 630 people living there.

The study determined the relationship between the environment components and the factors affecting the operation of the stream-constructed wetland system, including especially: hydrological relationships, variability of water and sewage composition caused by various factors (intensified anthropo-pressure, season of the year, topographic and weather conditions), as well as the effect of various ecosystem parts (water, bottoms, vegetation) on self-purification of flowing water.

In the backwater area, the water of the stream of Sząbruk may flow into the pond or through the surrounding ditch which is a continuation of the stream around the pond, or divided into the outflow into the pond and the surrounding ditch. Agricultural area runoff flows into the main stream, to the surrounding ditch and directly to the pond. The outflow from the pond and from the surrounding ditch below the pond join and flow on as the Sząbruk stream to Lake Wulpińskie.

A constructed wetland, where fish used to be bred, is now a water body which intercepts point and area impurities flowing in with the stream, which collects water from the drainage basin. This creates a peculiar aspect of the wetland as a specific biogeochemical barrier for biogenic substances inflowing directly to Lake Wulpińskie. The wetland acts as a biofilter – it intercepts and accumulates biogenic substances, thereby protecting the lake waters, and evolves as its eutrophication level, biocenosis and bottom deposits change.

Evaluation of the water quality was based on the physicochemical analyses in 4 cross-sections of the water in the Sząbruk stream on two tributaries flowing in from the drainage basin and on the outflow from the constructed wetland (Fig. 1). During the period covered by the study, samples of water were taken from the stream and from the constructed wetland every month.

The studies were conducted during a period when two sewage treatment plants – no. 1 in Unieszewo and no. 2 in Sząbruk – were in operation, when their outflows were channeled off to the Sząbruk stream (2002-2003). This was also when a sewerage system was operating in the area and the sewage from the settlements was channeled off to a treatment plant situated outside the drainage basin (2006-2007).

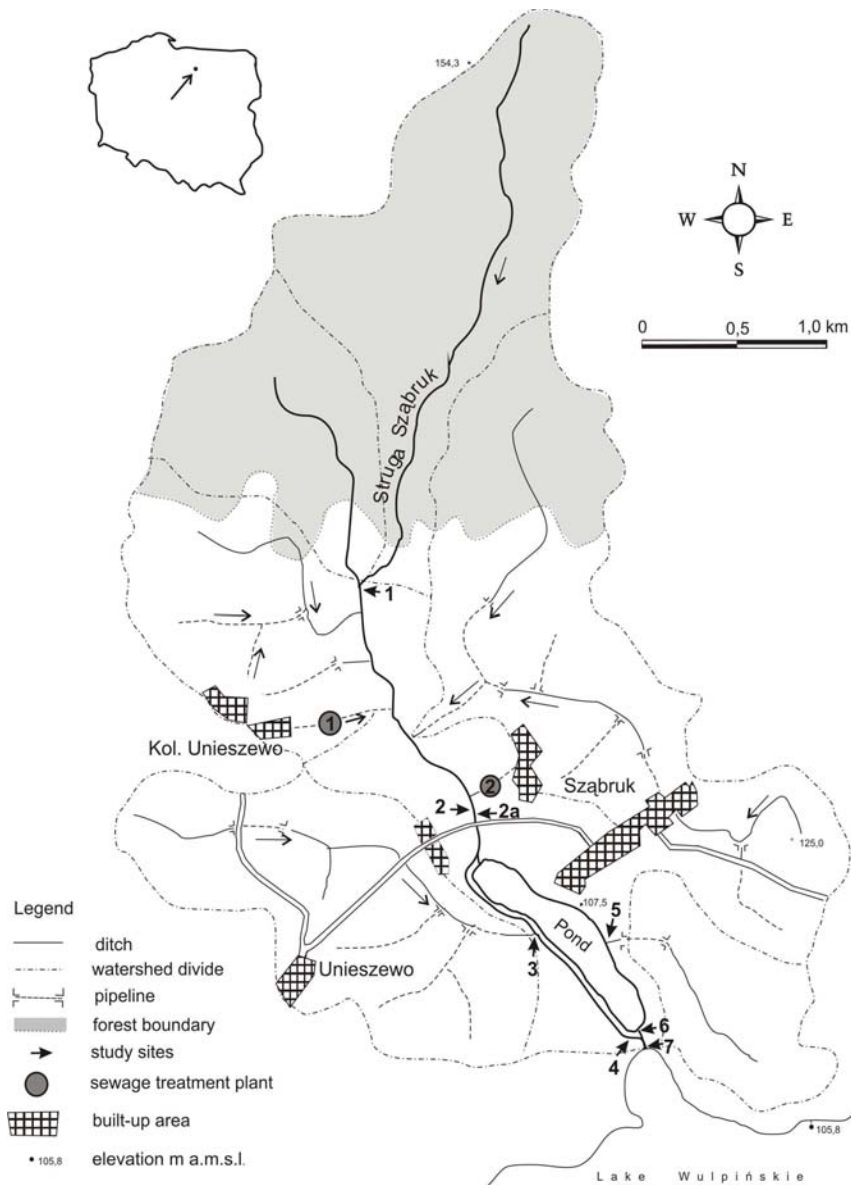


Fig. 1 Positions of measurement sites in the Sząbruk stream drainage basin

Water flow was measured with an electromagnetic flowmeter manufactured by Valeport, model 801 (UK).

Unit water outflow at different measurement sites varied throughout the study period. The unit inflows determined in the study were affected by the size of the drainage area above the flow measurement site.

The water flow up to the place where it was divided into the surrounding ditch and the constructed wetland increased with the size of the drainage basin, which is consistent with the fundamental relationship between the increase of waterflow in a stream with the increasing area of its drainage basin. Such streams are referred to



as draining streams (BYCZKOWSKI 1996). Different situation was in the case of the flow in the surrounding ditch supplied from the agricultural drainage basin and in the outflow from the constructed wetland. This was caused by evaporation from the water surface and by transpiration of emergent vegetation. The highest (extreme) fluctuations of water inflow – from no inflow to the highest observed in the system – were recorded in the inflow to the drained areas. The constructed wetland may play the role of outflow regulator because its structure reduces rapid outflow fluctuations; it can also receive large amounts of water and release it after a period of delay (Fig. 2).

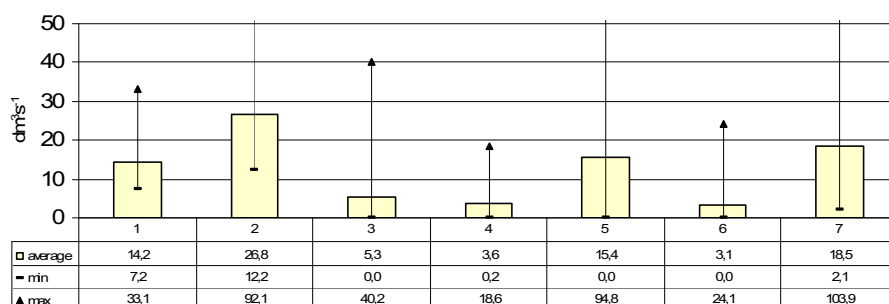


Fig. 2 Water flow at specific flow measurement sites [ $\text{dm}^3 \cdot \text{s}^{-1}$ ], description of flow measurement sites as per Table 1

### The effect of the constructed wetland on impurity concentrations and loads in flowing waters

It is very difficult to monitor the processes of impurity loads flowing through water bodies in natural conditions due to their complexity and temporal variability. The processes' dynamics are associated with the variability of factors which affect the supply of external impurity loads and changes that take place inside the water bodies.

In general, the lowest values of the parameters were determined in the upper parts of the Sząbruk stream (measurement site no. 1) where it carries waters from the agricultural and forest drainage basin (Table 1). The water is regarded as good quality water [REGULATION ...]. The concentration of impurities grew with the increase in the drainage basin area and was especially high during the period when the treatment plants were in operation.

Discharge from the Unieszewo treatment plant, which consisted of three filtration plots and two tanks, supplied  $7.8 \text{ m}^3$  of pre-treated sewage a day, which is equivalent to  $0.09 \text{ dm}^3 \cdot \text{s}^{-1}$ . These amounts did not significantly increase the flow. The Sząbruk treatment plant, which worked periodically with two stoppages for clearing and sewage discharge to the stream, daily discharged  $50 \text{ m}^3$  of pre-treated sewage. The sewage was discharged twice a day for 30 minutes. First, it reached the intermediate ditch, which considerably prolonged the time of inflow of pre-treated sewage to the Sząbruk stream (measurement site no. 2). This prevented any

significant flow increase in the stream and made it dilute, which favours self-purification. The total daily inflow of sewage from both treatment plants to the Sząbruk stream was 58 m<sup>3</sup>. Sewage contributed 2.5% to the temporary flow and 33% at the time of discharge (Fig. 2).

Effluent from the first treatment plant lowered the water quality, which manifested itself in an increase in the analyzed parameter values. However, the increase was small compared to the impact of effluent from treatment plant no.2; this allowed the stream to retain its ability to self-purify. It was only after sewage was discharged from treatment plant no. 2 (in Sząbruk) that water quality dramatically deteriorated, with a resulting oxygen deficit (KOC ET AL. 2004). The tested parameters values increased, and those of ChOD<sub>Cr</sub>, N<sub>tot</sub>, P<sub>tot</sub>, K, Na, Cl even multiplied during the sewage discharge. The water quality in the stream deteriorated at that time and was classed as category III (medium quality water).

Water contaminated with sewage, self-purified while flowing through the constructed wetland situated below (Table 1). Ash content was reduced by 28%, ChOD<sub>Cr</sub> by 40%, conductivity by 45%, total nitrogen by 88%, total phosphorus by 84%, potassium by 68%, magnesium by 7%, sodium by 76%, chlorine by 59% and sulphates by 61%, calcium concentration increased by 33%. However, the quality improvement in the part of water that flowed through the surrounding ditch was much smaller. The dry residue content decreased by 13%, ash content by 8%, ChOD by 51%, conductivity by 30%, total nitrogen by 70%, total phosphorus by 90%, potassium by 56%, sodium by 74%, chlorine by 52, sulphates by 58%, calcium concentration increased by 55% and that of magnesium - by 1%. The better water quality improvement in the constructed wetland as compared to the surrounding ditch must be attributed to slower water flow, which ensured more favourable conditions for biological and physicochemical processes. A decrease in the concentration of water impurities during the water flow through their wetland is not fully equivalent to the actual effect of the process due to a significant reduction in water volume as a result of evaporation (Fig. 2).

Only after flowing through the constructed wetland, where its oxygenation improved and suspension sedimentation and mineral substances phytosorption took place, did the tested parameters return to the values from before the sewage discharge from the treatment plant. The water quality can be regarded as restored. During the sewage discharge from the treatment plant in Sząbruk, the values of all the parameters at the outflow to the lake, except for Ca and Mg, were lower than at the site before the inflow to the constructed wetland, despite an increase in the drainage basin area and inflow of impurities. The constructed wetland not only reduced the load of impurities discharged from the treatment plant, but also that inflowing from the drainage basin. The nutrients present in the contaminated water (and subsequently flowing through the constructed wetland of considerable area – 24.8 ha) were used for primary and secondary production in those ecosystems and accumulated in their bottom deposits (ALLAN 1998).

Table 1

Concentration of substances dissolved in the water of the stream of Sząbruk, carrying water from agricultural areas and from sewage treatment plants (mg·dm<sup>-3</sup>)

Measurement site	Dry residue	Ash	ChOD	Conductivity	Ntot	Ptot	Potassium	Calcium	Magnesium	Sodium	Chlorine	Sulphates
Forest runoff (1)	<u>216*</u> 192-272**	<u>137</u> 102-164	<u>14.6</u> 8.4-26.0	<u>241</u> 155-281	<u>1.73</u> 1.02-2.81	<u>0.19</u> 0.11-0.31	<u>1.0</u> 0.6-1.7	<u>43.4</u> 40.8-46.4	<u>5.5</u> 3.7-6.7	<u>4.3</u> 3.6-4.8	<u>7</u> 6-8	<u>52.8</u> 23.9-117.8
	±23***	±20	±5.8	±43	±0.57	±0.069	±0.3	±1.7	±0.9	±0.3	±1	±30.71
Before the wetland (2)	<u>350</u> 220-948	<u>215</u> 140-532	<u>23.9</u> 8.4-56.8	<u>360</u> 291-555	<u>4.51</u> 1.05-19.88	<u>0.565</u> 0.22-2.84	<u>3.2</u> 1.0-8.4	<u>53.2</u> 40.8-69.6	<u>8.2</u> 4.5-17.6	<u>8.0</u> 4.4-23.5	<u>9</u> 7-12	<u>57.4</u> 33.4-134.1
	±207	±112	±12.7	±74	±5.63	±0.76	±2.4	±8.4	±3.6	±5.2	±2	±31.6
Before the wetland at the time of sewage discharge (2a)	<u>420</u> 312-784	<u>261</u> 128-496	<u>67.6</u> 21.6-136	<u>675</u> 419-1230	<u>26.25</u> 12.60-41.58	<u>3.55</u> 1.02-7.82	<u>10.8</u> 1.3-34.2	<u>49.4</u> 35.6-67.4	<u>9.4</u> 5.1-19.2	<u>32.6</u> 4.8-97.8	<u>27</u> 9-42	<u>121.16</u> 25.0-280.9
	±138	±100	±43.2	±224	±10.65	±2.48	±8.5	±9.5	±4.0	±25.9	±12	±84.0
Before the wetland – 24 h average (2b)	<u>365</u> 231-923	<u>222</u> 145-516	<u>25.4</u> 13.3-56.7	<u>373</u> 315-556	<u>5.42</u> 2.51-20.02	<u>0.69</u> 0.32-2.88	<u>3.5</u> 1.3-8.5	<u>53.0</u> 40.9-69.5	<u>8.4</u> 4.7-17.7	<u>9.0</u> 5.2-23.7	<u>10</u> 8-12	<u>60.06</u> 37.71-131.27
	±203	±110	±12.1	±74	±5.27	±0.74	±2.3	±8.4	±3.7	±5.1	±1	±29.48
Inflow through the drain pipe to the wetland (3)	<u>529</u> 212-936	<u>447</u> 112-692	<u>43.8</u> 23.2-59.2	<u>639</u> 205-888	<u>7.82</u> 2.30-23.30	<u>0.15</u> 0.04-0.28	<u>4.0</u> 2.2-6.9	<u>101.2</u> 31.4-188.0	<u>14.1</u> 4.4-26.2	<u>7.6</u> 1.8-10.5	<u>15</u> 5-22	<u>138.5</u> 34.7-529.4
	±270	±191	±11.1	±267	±6.81	±0.095	±1.6	±56.1	±7.1	±2.7	±5	±149.5
Outflow from the wetland (4)	<u>372</u> 236-604	<u>189</u> 144-284	<u>40.9</u> 30.0-69.2	<u>372</u> 264-527	<u>3.16</u> 1.66-7.30	<u>0.36</u> 0.17-0.67	<u>3.5</u> 0.9-6.2	<u>65.8</u> 36.2-103.0	<u>8.8</u> 5.7-12.0	<u>7.9</u> 4.8-12.0	<u>11</u> 9-16	<u>46.8</u> 18.1-74.2
	±130	±41	±11.5	±77	±1.86	±0.15	±1.9	±21.8	±2.1	±1.9	±2	±17.7
Inflow through the drain pipe to the surrounding ditch (5)	<u>630</u> 344-784	<u>371</u> 160-572	<u>42.6</u> 25.0-56	<u>775</u> 361-1042	<u>8.50</u> 4.99-13.04	<u>0.33</u> 0.08-1.36	<u>10.1</u> 8.2-13.4	<u>104.2</u> 53.1-152.0	<u>14.7</u> 6.7-23.6	<u>11.6</u> 4.0-15.8	<u>28</u> 19-38	<u>122.7</u> 64.8-414.2
	±138	±131	±10.8	±190	±2.78	±0.43	±2.0	±33.1	±5.7	±3.5	±6	±110.4
Outflow from the surrounding ditch (6)	<u>365</u> 236-464	<u>240</u> 136-292	<u>33.1</u> 24.8-47.6	<u>471</u> 220-629	<u>3.85</u> 1.79-6.51	<u>0.36</u> 0.10-0.92	<u>4.8</u> 1.3-8.4	<u>76.9</u> 31.3-101.0	<u>9.5</u> 4.2-14.6	<u>8.5</u> 2.9-10.5	<u>13</u> 9-18	<u>51.1</u> 24.0-82.8
	±81	±52	±6.5	±115	±1.71	±0.21	±2.2	±20.3	±3.6	±2.2	±4	±18.7
Outflow to the lake (7)	<u>332</u> 248-408	<u>236</u> 132-316	<u>31.7</u> 24.0-39.6	<u>442</u> 291-540	<u>3.53</u> 1.14-6.66	<u>0.35</u> 0.19-0.48	<u>4.4</u> 1.0-7.6	<u>74.9</u> 43.4-111.0	<u>9.5</u> 5.2-11.7	<u>8.0</u> 2.5-10.5	<u>13</u> 9-18	<u>47.0</u> 23.8-92.5
	±58	±53	±4.0	±70	±1.91	±0.11	±2.1	±17.6	±1.9	±2.3	±3	±19.6

\* average, \*\* min-max, \*\*\* ±SD

An analysis of the impurity load carried with water showed that it was considerably reduced after the water had flowed through the constructed wetland (Table 2). The dry residue load decreased by 87%, ashes – by 90%, ChOD<sub>Cr</sub> - by 80%, total nitrogen - by 93%, total phosphorus - by 92%, potassium - by 87%, calcium - by 85%, magnesium - by 87%, sodium - by 88%, chlorine - by 86% and sulphates - by 91%. The reduction level of the load of impurities were found to be lower in the surrounding ditch: 55% for dry residue, 54% for ash, 54% for ChOD<sub>Cr</sub>, 53% for total nitrogen, 25% for total phosphorus, 67% for potassium, 58% for calcium, 56% for magnesium, 48% for sodium, 67% for chlorine and 59% for sulphates. The system consisting of the surrounding ditch and the constructed wetland brought about reduction of the dry residue by 70%, ash - by 73%, ChOD<sub>Cr</sub> by 67%, total nitrogen - by 75%, total phosphorus - by 86%, potassium - by 60%, calcium - by 67%, magnesium - by 70%, sodium - by 74%, chlorine - by 61% and sulphates - by 71%.

Table 2

Load of dissolved substances in the water of the stream of Sząbruk carrying impurities from sewage treatment plants and agricultural areas (kg·year<sup>-1</sup>)

Measurement site	Dry residue	Ash	ChOD	Ntot	Ptot	K	Ca	Mg	Na	Cl	Sulphates
Forest runoff (1)	96932	61487	6566	777	86	450	19505	2463	1937	3005	23764
Before the wetland, 24-hour average(2)	309230	188061	21525	4588	584	2987	44882	7116	7655	8498	50853
Stream inflow to the wetland (2)	222893	135554	15515	3307	421	2153	32351	5129	5518	6125	36655
Stream inflow to the surrounding ditch (2)	86337	52507	6010	1281	163	834	12531	1987	2137	2373	14198
Drain pipe inflow to the wetland (3)	59377	50128	4913	878	16	450	11360	1582	853	1628	15548
Outflow from the wetland (4)	36367	18486	3997	309	35	347	6434	859	767	1089	4574
Drain pipe inflow to the surrounding ditch (5)	106292	62594	7185	1433	55	1708	17582	2482	1961	4777	20714
Outflow from the surrounding ditch (6)	176908	116355	16027	1861	172	2306	37208	4616	4138	6447	24726
Outflow to the lake (7)	192647	137153	18378	2049	201	2548	43435	5507	4647	7464	27257

## Load of biogenic substances in bottom deposits

Bottom deposits in rivers and water bodies are a useful geomedium used in control of the quality of surface waters in terms of the level of eutrophication and contamination with heavy metals and harmful chemical compounds. Since the concentrations of harmful substances in deposits are several times higher than in water, an analysis of deposits enables detection and monitoring of changes of their content even when the level of contamination is relatively low (URBAN et al. 1997; BAUDO, BELTRAMI 2001). Therefore, analyses of deposits near various sites of contamination, e.g. near the sites of sewage discharge, are important in monitoring the level of environment pollution.

Impurities and detritus settle on a continuous basis and form bottom deposits, which are a kind of “archive”. Deposit particles bind both biogenic substances and heavy metals, which are among the most persistent toxic substances entering aqueous ecosystems (BAUDO, BELTRAMI 2001; SOBCZYŃSKI, SIEPAK 2001). The process of settlement of particles, formation of a deposit layer on the water bodies bottom and consolidation of such a layer depend on a number of factors (Parzonka 1991), which can be divided into geomorphologic, hydraulic, hydrodynamic and exploitational factors. The processes are greatly affected by the particle features, their accumulation, organic matter content and the presence of soluble salts in water.

The bottom deposit sampling sites are shown in Fig. 3. The bottom deposits varied in terms of thickness and physicochemical properties (Table 3, 4). The highest thickness was recorded for the cores taken in the middle of the constructed wetland – up to 20 cm at a water depth of 1.51 m, whereas the lowest thickness was recorded in the stream flow. In fact, there was no typical layer of bottom deposits as is usually the case with water bodies. The stream bottom is covered with a coarse material, as finer particles are washed away, especially with increased flow, and are transported along the stream. They settle when the flow rate decreases or when they meet with the vegetation resistance or when flowing through the constructed wetland (MADEYSKI, TARNAWSKI 2004).

Due to the small thickness and low variability in terms of the colour and structure of the bottom deposits from the stream and the constructed wetland (probably due to their age), the cores of those deposits were not divided into layers.

The pH value of the sediments in the research site ranged from 4.98 in KCL (5.34 in H<sub>2</sub>O) to 7.66 (7.45 in H<sub>2</sub>O). The lowest values were found at the first line in the wetland where contaminated water flows in (Table 3). The pH value was recorded in the 10-20 cm layer of the water body (Table 4). The lowest concentration of carbonates was recorded in the initial sections of the wetland in the 10-20 cm layer (0.13%) whereas the highest (67.89%) was in the final section of the surrounding ditch.

The bottom deposits varied in terms of the content of biogenic compounds (Table 5, 6).

Of the elements whose content in the bottom deposits were analyzed, calcium dominated, which is a consequence of it flowing in from the drainage basin. In general, the largest concentrations of Ca were recorded in the sample taken in the final section of the surrounding ditch (measurement site no. 8), where the parameter value was 100100 mg Ca·kg<sup>-1</sup> d.m. The lowest concentrations of the element were

recorded below the forest runoff inflow –  $858 \text{ mg Ca}\cdot\text{kg}^{-1} \text{ d.m.}$  The chemical compositions of the sediments can modify the substrate, which was the case with Ca. Calcium content was the most variable, both in the vertical and horizontal profile. An over 4-fold difference in the element concentration was recorded in the wetland between the neighbouring measurement sites.

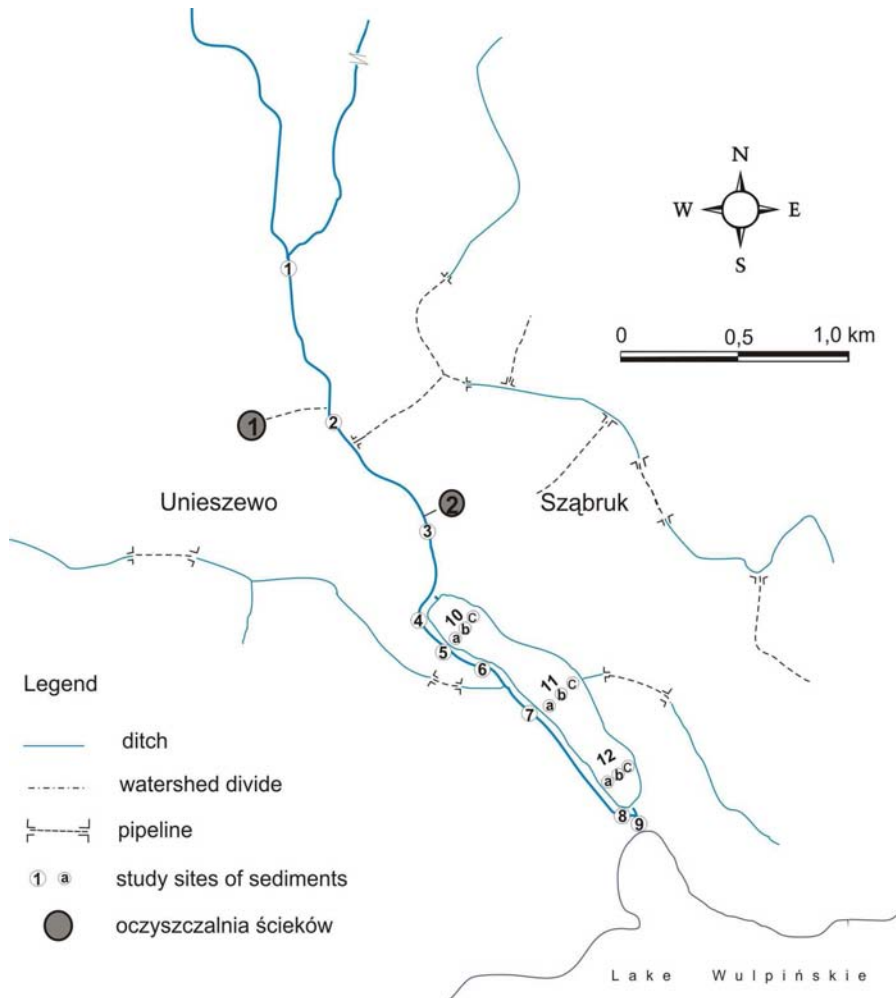


Fig. 3. Sites of bottom deposits sampling in the stream and in the constructed wetland

Nitrogen is another element whose content differs from that of the others; however, it dominates mainly in the wetland, both in the 0-10 cm and in the 10-20 cm layers. This shows that the element accumulates in the pond bottom, which considerably contributes to the protection of the next system component – the lake. The highest concentrations of nitrogen were recorded in the sediments of the central part of the pond, close to the depths. The values were the highest both in the surface layer 0-10cm ( $15.6 \text{ g}\cdot\text{kg}^{-1} \text{ d.m.}$ ) and in the layer 10-20cm ( $16.0 \text{ g}\cdot\text{kg}^{-1} \text{ d.m.}$ ); this

shows that sediments flow and settle in the deepest places of the wetlands. It is in the central part of the pond (measurement site 11b) that bottom deposits of up to 20 cm thick were recorded, whereas 3-cm layers occurred in the extreme lines of sediment sampling - 10 a, c and 11 a, c. SKWIERAWSKI (2003) showed the concentration and distribution of nitrogen to be strongly correlated with the amount of organic matter, which indicates that the nitrogen in the sediments is mainly found in organic compounds. The dominant position of nitrogen in bottom deposits has been reported by SZYPEREK (2004), who recorded the highest contents of nitrogen in tributaries, MÜLLER et al. (1998) in lakes of Central Europe (63-Switzerland, 2-France, 3-Italy), and GAWROŃSKA (1989) in sediments of Lake Bęskie.

Phosphorus content ranged from 218 mg·kg<sup>-1</sup> d.m. below forest runoff inflow to 1788 mg·kg<sup>-1</sup> d.m. in the initial section of the pond and at the outflow to the lake, which – as was the case with nitrogen – is indicative of the effect of the drainage basin on biogenic compounds depositing in sediments. That the pond was supplied by runoff from the drainage basins is indicated by a decrease in the phosphorus concentration with increasing distance from the inflow site. The concentration of the element in bottom deposits may result from its intense exchange in the sediment-water interface. The amount of phosphorus released from sediments to water may be particularly high, especially during the vegetation period, when primary production demand for the element is high, but also when conditions favour re-suspension and with oxygen deficit (KAJAK 2001). Accumulated in sediments and being the main factor in water eutrophication, phosphorus plays a double role in bottom deposits. On the one hand, the considerable amounts of phosphorus retained in the deposits shows that deposits are effective as a trap for phosphorus migrating in the environment but, on the other hand, high concentrations of phosphorus may trigger processes which take place in a water body, accelerating its turning into land (SKWIERAWSKI 2003). Under anaerobic conditions or under such that favour resuspension (water rippling at small depths), the amount of phosphorus released to water may be very high, especially during the vegetation period (KAJAK 2001).

Potassium is not regarded as an element which affects the process of eutrophication, but it is used in agriculture and may be an indicator of the intensity of agricultural soil use in the drainage basin. Its content ranged from 996 mg·kg<sup>-1</sup> d.m. in the bottom deposits below the forest drainage basin to 6308 mg·kg<sup>-1</sup> d.m. in the deposits of the central part of the pond. No significant differences were recorded between the surface and subsurface layers.

The highest concentrations of magnesium were found in samples taken in the central part of the pond – 5126 mg·kg<sup>-1</sup> d.m. in the layer 10-20 cm. The lowest concentration was found below the forest drainage basin 362 mg·kg<sup>-1</sup> d.m.

As compared to other macroelements, the concentration of Na and S in the analyzed samples was less varied.

Analysis of bottom deposit cores provides grounds for examination of the abundance of selected macroelements in the deposits. They show the variability of component concentration through the pond bottom in the cross section and the longitudinal section, from the inflow to the outflow. It is a general tendency that larger amounts of macroelements accumulate along the pond axis and their accumulation depends on the deposits thickness. The concentration of elements, i.e. Mg, Na, decreased as the distance from the supply site increased.

Table 3

Some physical properties and selected elements (mg·kg<sup>-1</sup> d.m.) in the surface layer of the bottom deposits – 0-10 cm

Nr	Sampling site	pH in KCl	pH in H <sub>2</sub> O	% CaCO <sub>3</sub>	% d.m.	% Org. matter	N	P	K	Ca	Mg	Na	S	Cl	
1	After the flows join below the forest	7.14	7.25	0.42	80.3	0.51	240	218	996	858	362	134	200	4	
2	Below the Unieszewo treatment plant	7.18	7.13	0.25	74.5	2.59	-	-	-	-	-	-	-	-	
3	Below the Sząbruk treatment plant	7.38	7.31	12.26	75.4	3.50	1290	610	3652	59345	4824	475	900	16	
4	Beginning of the surrounding ditch	6.93	6.86	3.70	66.5	3.65	-	-	-	-	-	-	-	-	
5	Surrounding ditch	7.54	7.31	2.22	75.1	2.00	-	-	-	-	-	-	-	-	
6	Surrounding ditch	7.39	7.30	0.72	70.5	3.65	1390	610	2324	24668	2050	230	1100	13	
7	Surrounding ditch below the agricultural drainage basin inflow	7.27	7.22	4.65	54.2	7.10	-	-	-	-	-	-	-	-	
8	End of the surrounding ditch	7.23	7.25	67.89	46.8	6.00	2060	1395	2656	100100	3377	653	1700	22	
9	After joining the wetland outflow	7.02	7.15	11.24	53.8	6.30	3170	1788	3984	52910	3377	490	1400	23	
10	Constructed wetland, beginning	a	6.72	6.87	2.25	26.1	23.63	9630	1788	3320	10296	4040	475	1600	22
		b	5.77	6.03	0.25	34.9	13.75	4940	1788	3320	2574	1387	341	1700	18
		c	4.98	5.34	0.42	20.3	33.13	13210	1177	4980	5148	1447	326	2300	30
11	Constructed wetland, center	a	6.79	7.07	16.07	19.0	26.85	-	-	-	-	-	-	-	-
		b	6.10	6.41	0.32	18.8	35.53	15550	1003	4980	2860	4703	549	2900	52
		c	6.49	7.12	7.64	31.4	16.75	-	-	-	-	-	-	-	-
12	Constructed wetland, end	a	7.03	7.15	10.4	42.5	9.43	4370	610	2988	35750	2472	475	1400	22
		b	6.73	6.91	6.26	20.6	25.80	11420	610	4980	25025	4824	564	2900	44
		c	7.09	7.30	2.21	56.4	6.39	3070	785	2324	10010	2653	326	1000	15

- not determined



Table 4

Some physical properties and selected elements (mg·kg<sup>-1</sup> d.m.) in the layer of the bottom deposits from 10 to 20 cm

Nr	Sampling site	pH in KCL	pH in H <sub>2</sub> O	% CaCO <sub>3</sub>	% d.m.	% Org. matter	N	P	K	Ca	Mg	Na	S	Cl	
10	Constructed wetland, beginning	a	7.08	7.37	3.82	52.7	11.67	5160	785	2988	12870	4040	371	900	14
		b	6.77	6.99	0.85	56.4	7.49	2900	1177	3320	4433	1387	223	1000	9
		c	5.24	5.78	0.13	37.6	23.06	10080	1003	4980	1430	4100	482	1900	22
11	Constructed wetland, center	a	6.83	7.22	38.6	33.0	16.20	-	-	-	-	-	-	-	-
		b	5.43	5.93	0.32	22.9	30.77	16030	785	6308	1430	5126	549	2300	33
		c	6.89	7.28	4.12	46.5	13.55	-	-	-	-	-	-	-	-
12	Constructed wetland, end	a	7.05	7.27	20.37	45.6	9.66	4240	610	3320	42900	3075	519	1500	25
		b	6.79	7.27	6.79	42.4	14.18	7030	610	3320	92950	3980	564	1500	25
		c	7.00	7.38	3.73	60.3	7.29	3670	610	2988	10010	3678	341	900	17

- not determined

Of all the determined elements, it was calcium that had accumulated in the bottom deposits of the pond in the largest amounts – 37525 kg (Table 5). The weight of the deposits reached 2515 tones, containing several tones of each of the elements.

Table 5

Accumulation of selected elements in the pond bottom deposits [kg]

Layer	N	P	K	Ca	Mg	Na	S	Cl
0-5 cm	13110	1636	5669	19323	4538	644	2909	43
5-10 cm	5398	674	2334	7956	1869	265	1198	18
10-15 cm	2399	273	1330	8111	1240	149	489	7
15-20 cm	631	72	350	2135	326	39	129	2
Total	21538	2655	9683	37525	7973	1097	4725	70

The thickness of the pond bottom deposits is associated with its depth. The largest thickness (reaching 20 cm) was found near the depths. The thickness of the bottom deposits decreased as the pond became more and more shallow so, in effect, the layer of 0-5 cm occupied the largest area of 11.9 ha (Fig. 3). Consequently, the highest concentrations of the analyzed elements were determined in that layer.

One hectare of the pond bottom was covered by 101 tones of deposits, containing: 868.5 kg N, 107.0 kg P, 390.5 kg K, 1513.1 kg Ca, 321.5 kg Mg, 44.3 kg Na, 190.5 kg S, 2.8 kg Cl.

### **The effect of a constructed wetland on the quality of water after sewage discharge had ceased**

After contaminations stopped inflowing with the purified sewage, their concentrations in the stream water significantly decreased. The total nitrogen content decreased in the constructed wetland by 45%, that of total phosphorus - by 44 %, calcium - by 21%, magnesium content increased by 3% (Table 6). The dynamic equilibrium between water and deposits shifted towards releasing impurities from sediments deposited in the pond, especially in the surrounding ditch, which accelerated mineralization when the water oxygenation was sufficient. During the period when the impurity load in water was reduced, the impurities concentration and their loads were found to be reduced to a lesser extent (Table 7). Soluble substance concentrations were even found to have increased, which is indicated by the higher electrical conductivity in outflowing water as compared to the water before the pond. The dry matter inflowing the Sząbruk stream from its drainage basin was found to have decreased by 18%, ashes - by 6%, total nitrogen - by 17%, total phosphorus - by 25%, potassium - by 25%, calcium - by 19%, magnesium - by 16%, sodium - by 25%, chlorine - by 21% and sulphates - by 24%;

Table 6

Concentration of dissolved substances in the water of the stream of Sząbruk carrying impurities from agricultural area, after the treatment plants had been shut down ( $\text{mg}\cdot\text{dm}^{-3}$ )

Measurement site	Dry residue	Ash	ChOD	Conductivity	Ntot	Ptot	Potassium	Calcium	Magnesium	Sodium	Chlorine	Sulphates
Forest runoff (1)	<u>220*</u> 168-272**	<u>176</u> 124-200	<u>14.8</u> 6.4-18.8	<u>283</u> 247-318	<u>1.45</u> 0.3-2.2	<u>0.15</u> 0.01-0.44	<u>1.0</u> 0.7-1.3	<u>41.2</u> 24.2-49.2	<u>6.6</u> 5.1-7.8	<u>4.0</u> 3.6-4.4	<u>5.1</u> 5.0-6.0	<u>54.1</u> 25.5-95.1
	±45***	±28	±4.8	±26	±0.8	±0.1	±0.2	±9.3	±1.0	±0.4	±0.4	±29.4
Before the wetland (2)	<u>281</u> 208-352	<u>197</u> 144-244	<u>23.4</u> 16.4-28.0	<u>393</u> 299-554	<u>3.61</u> 0.8-7.5	<u>0.25</u> 0.01-0.45	<u>1.9</u> 0.7-2.8	<u>58.6</u> 43.4-72.4	<u>8.1</u> 5.9-9.5	<u>6.6</u> 4.8-8.8	<u>9.8</u> 8.0-12.0	<u>69.9</u> 31.2-113.9
	±50	±32	±4.1	±88	±2.5	±0.2	±0.8	±11.3	±1.4	±0.6	±1.5	±30.4
Drain pipe inflow to the wetland (3)	<u>640</u> 502-764	<u>589</u> 448-596	<u>42.9</u> 33.7-50.8	<u>914</u> 854-957	<u>8.93</u> 0.1-19.7	<u>0.38</u> 0.1-1.01	<u>7.3</u> 5.4-9.7	<u>104.9</u> 81-137	<u>14.7</u> 11.9-16.5	<u>9.7</u> 7.2-13.2	<u>21.2</u> 13.0-38.0	<u>53.2</u> 29.6-76.8
	±204	±64	±11.9	±143	±8.9	±0.3	±0.5	±23.4	±2.1	±1.7	±9.5	±36.3
Outflow from the wetland (4)	<u>241</u> 220-276	<u>174</u> 144-240	<u>27.8</u> 18.7-37.2	<u>359</u> 302-493	<u>1.99</u> 0.1-2.6	<u>0.14</u> 0.01-0.45	<u>2.2</u> 0.7-3.7	<u>46.5</u> 34.8-57.8	<u>8.3</u> 4.0-10.5	<u>5.5</u> 4.8-6.3	<u>9.5</u> 8.0-11.0	<u>43.2</u> 12.3-107.6
	±19	±36	±7.1	±51	±0.9	±0.1	±0.6	±10.7	±2.3	±0.7	±1.4	±34.0
Drain pipe inflow to the surrounding ditch (5)	<u>546</u> 523-740	<u>518</u> 416-596	<u>41.0</u> 28.7-58.2	<u>852</u> 600-941	<u>6.21</u> 0.44-14.3	<u>0.53</u> 0.1-1.97	<u>3.7</u> 3.0-4.9	<u>108.1</u> 86.9-131	<u>16.4</u> 14.3-20.2	<u>7.7</u> 6.0-10.5	<u>14.3</u> 12.0-18.0	<u>52.3</u> 26.5-77.8
	±111	±53	±7.2	±40	±5.8	±0.5	±0.7	±19.3	±1.7	±2.5	±1.5	±33.3
Outflow from the surrounding ditch (6)	<u>397</u> 344-556	<u>356</u> 292-468	<u>38.7</u> 27.5-54.8	<u>692</u> 620-758	<u>6.02</u> 0.8-12.5	<u>0.41</u> 0.01-1.17	<u>5.5</u> 1.0-7.4	<u>81.0</u> 65.2-91.4	<u>10.4</u> 8.8-13.0	<u>7.2</u> 6.3-9.2	<u>12.0</u> 11.0-15.0	<u>84.5</u> 16.6-131.2
	±79	±77	±9.8	±51	±5.1	±0.3	±0.7	±10.2	±1.7	±1.2	±1.5	±45.0
Outflow to the lake (7)	<u>292</u> 224-400	<u>258</u> 204-296	<u>31.6</u> 25.0-42.4	<u>509</u> 365-720	<u>3.90</u> 1.1-9.7	<u>0.37</u> 0.01-0.43	<u>3.5</u> 0.9-7.1	<u>72.5</u> 65.2-81.0	<u>9.4</u> 7.9-10.8	<u>7.0</u> 5.6-9.2	<u>11.5</u> 10.0-14.0	<u>52.7</u> 25.9-96.12
	±58	±34	±7.8	±120	±3.9	±0.2	±0.7	±5.9	±1.2	±1.3	±1.4	±25.2

\* average, \*\* min-max, \*\*\* ±SD

however,  $\text{ChOD}_{\text{Cr}}$  increased by 5%. This was the result of sediment re-suspension and mineralization, as well as primary production in the pond. The study showed that the initially achieved good effects of purification of highly contaminated waters in the pond gradually worsen.

Passing water of lower contamination level through a constructed wetland previously used for water purification results in reduced process effectiveness. The decrease in the water contamination level in a ditch system shows that if clean water is introduced in the next stage, its quality may deteriorate as a result of the object washing-out.

Table 7

Load of dissolved substances in the water of the stream of Szabruk, carrying impurities from an agricultural area ( $\text{kg}\cdot\text{year}^{-1}$ )

Measurement site	Dry residue	Ash	ChOD	Ntot	Ptot	K	Ca	Mg	Na	Cl	Sulphates
Forest runoff (1)	75900	60720	5117	500	51	357	14225	2271	1380	1783	18653
Before the wetland(2)	165143	115835	13746	2119	147	1859	34388	4735	3854	5772	41007
Stream inflow to the wetland (2)	66057	46334	5498	848	67	744	13755	1894	1542	2309	16402
Stream inflow to the surrounding ditch (2)	99086	69501	8247	1271	80	1115	20633	2841	2313	3463	24604
Drain pipe inflow to the wetland (3)	12864	12422	985	214	9	91	2595	394	184	344	1251
Outflow from the wetland (4)	56472	40872	6501	466	40	449	10873	1958	1291	2223	10119
Drain pipe inflow to the surrounding ditch (5)	30736	25848	2046	298	25	350	5035	706	464	1016	2553
Outflow from the surrounding ditch (6)	113810	104120	11043	1715	96	1278	23076	2955	2071	3420	24088
Outflow to the lake (7)	170282	144992	17545	2181	136	1726	33949	4912	3362	5643	34208

Table 8

Load of substances carried in the water of Sząbruk stream (kg·year<sup>-1</sup>)

Load	Dry residue	Ash	ChOD	Ntot	Ptot	K	Ca	Mg	Na	Cl	Sulphates
During the period of sewage discharge											
Inflowing to the wetland	282270	185682	20428	4185	437	2603	43711	6711	6371	7753	52203
Outflowing from the wetland	36367	18486	3997	309	35	347	6434	859	767	1089	4574
Difference	245903	167196	16431	3876	402	2256	37277	5852	5604	6664	47629
Inflowing to the ditch	192629	115101	13195	2714	218	2542	30113	4469	4098	7150	34912
Outflowing from the surrounding ditch	176908	116355	16027	1861	172	2306	37208	4616	4138	6447	24726
Difference	15721	-1254	-2832	853	46	236	-7095	-147	-40	703	10186
During the period without sewage discharge											
Inflowing to the wetland	78921	58756	6483	1062	76	835	16350	2288	1726	2653	17653
Outflowing from the wetland	56472	40872	6501	466	40	449	10873	1958	1291	2223	10119
Difference	22449	17884	-18	596	36	386	5477	330	435	430	7534
Inflowing to the ditch	129822	95349	10293	1569	105	1465	25668	3547	2777	4479	27157
Outflowing from the surrounding ditch	113810	104120	11043	1715	96	1278	23076	2955	2071	3420	24088
Difference	16012	-8771	-750	-146	9	187	2592	592	706	1059	3069

### Summary

A constructed wetland situated on a small stream may also play the role of a biogeochemical barrier for point and non-point contamination inflow in an agricultural and forest drainage basin in a low-population area. The constructed wetland improved the water quality up to the quality level of water outflowing from the forest area throughout the period of its existence, both when sewage was discharged to the stream and after the sewage discharge ceased.

Water flow through the pond resulted in a decrease in contamination and eutrophication indexes. The dry residue content decreases by 12%, ashes - by 28%, ChOD<sub>Cr</sub> - by 40%, conductivity - by 45%, total nitrogen - by 88%, total phosphorus - by 84%, potassium - by 68%, magnesium - by 7%, sodium - by 76%, chlorine - by

59% and sulphates - by 61%. Except for the dry matter content, the reduction of these parameters was considerably greater in the water flowing through the pond than in the surrounding ditch.

Water flow through the pond resulted in reduction of dry matter content by 87%, ashes - by 90%,  $\text{ChOD}_{\text{Cr}}$  - by 80%, total nitrogen - by 93%, total phosphorus - by 92%, potassium - by 87%, calcium - by 85%, magnesium - by 87%, sodium - by 88%, chlorine - by 86% and sulphates - by 91%. Reduction of impurities load is much greater than that of the concentrations, as water loss by evaporation and plant transpiration is greater.

The effectiveness of water purification is higher in the vegetation period than in winter, which is a confirmation of the thesis that the main role in water purification is played by biological processes, which depend on temperature and solar exposure.

The pond was degraded over the many years of its existence, which is indicated by its being overgrown by nitrophilous rush vegetation and sediment accumulation on the bottom, which are more abundant in nitrogen and phosphorus than are typical sediments in lakes which are not loaded with sewage.

Water movement in the pond and the biological processes result in accumulation of mainly mineral deposits at the water inflow to the pond, with the contribution of organic matter and biogenic substances increasing in the further parts of the pond. The highest accumulation of deposits was recorded in the depths and before the weir.

Reduction of the pond load with impurities by diverting the sewage discharge outside the drainage basin resulted in a change of relations between the processes of accumulation and release of impurities due to their lower concentration in the inflowing water; the effectiveness of impurities and biogenic compounds reduction in the water flowing through the pond decreased.

Accumulation of deposits in the lake cove where the water from the stream flows in is a sign that the water quality improvement is insufficient. Further quality improvement can be achieved by passing all the stream water through the pond (but, in that case, it would have to be larger) or by a series of ponds ("bead-on-a-string" system) on the stream.

Constructed wetlands which act as natural sewage treatment plants should be rehabilitated as the effectiveness of water purification decreases over time, with the intensity dependent upon the impurity load-to-wetland volume ratio. A non-rehabilitated wetland may periodically reduce the water quality as a result of lowering the accumulation/release ratio, which may happen during unfavourable periods, such as a rapid flow increase in winter or water waving.

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## References

- ALLAN J. D. 1998. *Ekologia wód płynących*. Wyd. Nauk. PWN, Warszawa pp. 451.
- BAUDO R., BELTRAMI M., 2001. *Chemical composition of Lake Orta sediments*. J. Limnol., 60(2): 213-236.
- BOROWIEC S., ZABŁOCKI Z. 1990. *Czynniki kształtujące chemizm wód powierzchniowych i odcieków drenarskich obszarów rolniczych Polski północno-wschodniej*. Mater. semin. IMUZ, 27: 25-30.
- BORÓWKA R., 2007. *Geochemiczne badania osadów dennych w jeziorach strefy umiarkowanej*. Stud. Limn. Et. Tel. 1(1): 33-42.
- BYCZKOWSKI A. 1996. *Hydrologia*. Wydaw. SGGW Warszawa pp. 375.
- CHUDYBA H., KALWASIŃSKI K. 1998. *Samoooczyszczanie wody*. Nowocz. Roln. 05.06. pp. 48.
- COVENEY M. F., STITES D. L., LOWE E. F., BATTOE L. E., CONROW R. 2002. *Nutrient removal from eutrophic lake water by wetland filtration*. Ecological Engineering 19: 141-159.
- CZAMARA W., WIATKOWSKI M. 2002. *Zastosowanie zbiornika wstępnego w Mściwojowie do ochrony retencjonowanej wody*. Roczniki Akademii Rolniczej w Poznaniu, CCCXLII: 43-52.
- GAWROŃSKA H., 1989. *Skład chemiczny osadów dennych Jeziora Bęskiego*. Acad. Agricult. Tech. Olst. ProtectioAquarum et Piscatoria, No 17: 35-43.
- GIERCUSZKIEWICZ-BAJTLIK M. 1990. *Charakterystyka obszarowych źródeł zanieczyszczeń w Polsce*. W: Zanieczyszczenia obszarowe w zlewniach rolniczych. Mater. semin. IMUZ Falenty 26: 143-161.
- GUS 2009. *Ochrona Środowiska*. GUS Warszawa
- HAYCOCK N.E., PINAY G., BURT T.P., GOULDING K.W.T. 1996. *Buffer zones: Current concerns and future directions*. W: *Buffer zones: their processes and potential in water protection*. Proc. Int. Conf. Buffer Zones, Quest Environmental, Hertfordshire, UK: 305-312.
- KAJAK Z., 2001. *Hydrobiologia, limnologia. Ekosystemy wód śródlądowych*. Wyd. Nauk. PWN Warszawa, pp. 359.
- KOC J. 1994. *Zagrożenia środowiska rolniczego. Rodzaje źródła rozmiary i skutki*. Ośrodek Doradstwa Rolniczego w Olsztynie pp 146.
- KOC J., CYMES I., SKWIERAWSKI A., SZYPEREK U. 2001. *Znaczenie ochrony małych zbiorników wodnych w krajobrazie rolniczym*. Zesz. Probl. Post. Nauk Roln., 476: 397-407.
- KOC J., SZYMCZYK S. 2001. *Wpływ użytkowania obszarów rolniczych na eutrofizację wód. Agrarna oświata i nauka na początku trzeciego tysiąclecia*. Materiali Międzynarodnej naukowo-praktycznej konferencji, 18-21 IX 2001, Lwów, t. I: 68-76.
- KOC J., TUCHOLSKI S., SKONIECZEK P. 2004. *Znaczenie zbiornika wstępnego w ochronie jeziora przed zanieczyszczeniami ze zlewni rolniczo-leśnej*. Cz. I Ogólne wskaźniki zanieczyszczeń. Zesz. Probl. Post. Nauk Roln., 499: 137-143.
- MADEYSKI M., TARNAWSKI M., 2004. *Przebieg procesu sedymentacji osadów dennych małych zbiorników wodnych*. Roczn. AR Poznań, Melior. Inż. Środ. 25 (357): 345-353.
- MÜLLER B., LOTTER A. F., STURM M., AMMANN A., 1998. *Influence of catchment quality and altitude on the water and sediment composition of 68 small lakes in Central Europe*. Aquat. Sci. 60: 316-337.
- PARZONKA W., 1991. *Erozja, transport i sedymentacja rumowiska w rzekach i zbiornikach*. Materiały XI Szkoły Hydrauliki IBW PAN, Gdańsk: 81-99.
- PAWLIK-DOBROWOLSKI J. 1990. *Źródła substancji chemicznych w zlewni, ich klasyfikacja i metody obliczania*. In: *Zanieczyszczenia obszarowe w zlewniach rolniczych*. Mater. semin. IMUZ Falenty 26: 7-16.

- Rozporządzenie Ministra Środowiska z dnia 20 sierpnia 2008 r. w sprawie sposobu klasyfikacji stanu jednolitych części wód powierzchniowych. Dz. U. Nr 162, poz. 1008.
- SIWEK H., WŁODARCZYK M., BRZOSTKOWSKA ŚELECHOWSKA D., WACHOWICZ M. 2009. *Wpływ wybranych parametrów fizyko-chemicznych osadu na zawartość nieorganicznych form fosforu w osadach dennych małych zbiorników polimiktycznych*. Acta Agrophysica, 13(2), 497-503.
- SKWIERAWSKI A., 2003. *Skład chemiczny osadów dennych małych zbiorników wodnych jako odzwierciedlenie nasilenia procesów antropopresji w krajobrazie rolniczym*. Chem. Inż. Ekol., 10 (S1): 159-169.
- SÖDERGREN A. 1993. *Role of aquatic surface microlayer in the dynamics of nutrients and organic compounds in lakes, with implication for their ecotones*. Hydrobiologia 251: 217-225.
- SOMOROWSKI CZ. (Red). 1998. *Wodno-bilansowe kryteria kształtowania siedlisk w ciekach w krajobrazie rolniczym*. SGGW Warszawa.
- STACHOWICZ K. 1995. *Migracja wodna składników pokarmowych ze zlewni rolniczych*. Człowiek i Środowisko. Instytut Gospodarki Przestrzennej i Komunalnej. Warszawa, 19 (1): 125 – 141.
- STRUTYŃSKI J., GAŁKA A. 1997. *Stawy rybne jako bariery dla zanieczyszczeń wnoszonych z wodami zasilającymi*. Roczn. AR Poznań: 319 – 325.
- ZYPEREK U. 2003. *Oczka wodne jako bariera biogeochemiczna w krajobrazie pojeziernym*. Praca doktorska, UWM w Olsztynie, pp. 163.
- ZYPEREK U. 2004. *Zawartość i akumulacja składników biogenych w osadach dennych oczka wodnego w zlewni intensywnie użytkowanej rolniczo*. Nawozy i Nawożenie 2 (19): 108-117.
- TUCHOLSKI S., DUDA M., SKONIECZEK P. 2007. *Self-purification of waters polluted with sewage in the retention reservoir*. Ecol. Chem. And Eng. T14. Nr 52: 147-157.
- URBAN N. R., DINKEL CH., WEHRLI B. 1997. *Solute transfer across the sediment surface of a eutrophic lake: I Porewater profiles from dialysis samplers*. Aquat. sci. Birkhäuser Verlag, Basel, 59: 1–25.
- WÓJCIK D., JARZĄBEK A. 1993. *Wpływ zbiorników wodnych o zróżnicowanych parametrach przepływu wody na wybrane substancje pokarmowe*. „Współczesne problemy inżynierii wodnej”, Szklarska Poręba: 237-244.

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