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Issues of Sustainable Development in the Light of a GIS-based Assessment of the Geochemical State of the Aquatic Environment

Problematyka zrównoważonego rozwoju w świetle oceny geochemicznego stanu środowiska wodnego przy wykorzystaniu systemu GIS

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Abstract
This paper investigated issues around sustainable development in light of the assessment of the geochemical state of an aquatic environment, focussing on the accumulation of contaminants in sediments. The analysis was carried out on the concentrations of nine metals: As, Ba, Cd, Co, Cr, Cu, Ni, Pb, and Zn. Classification of results was based on geochemical criteria. The results relate to the background geochemical values characterised by natural conditions without human interference. Using GIS, maps were compiled which highlighted the spatial distribution of the contaminants, namely for the selected heavy metals (Ba, Cr, Cu, Ni, Pb and Zn). These maps enabled the relationships between these elements to be studied. Analysis of sediments contaminated by heavy metals is an important tool in environmental monitoring.
The study showed that potential contamination in sediments can reach significant levels. Therefore, systematic monitoring of metal concentrations in the sediment should encompass the greatest number of reservoirs possible. This will enable ecological equilibrium to be maintained in aquatic environments. This will help to identify, eliminate, and prevent the negative effects of human economic activities which will improve the rational utilisation of environmental resources, important from the sustainable development point of view.

Key words: sustainable development, State Environmental Monitoring, sediments, heavy metals, Geographic Information System, GIS

Streszczenie
W pracy podjęto problematykę zrównoważonego rozwoju w świetle oceny geochemicznego stanu środowiska wodnego, koncentrując się na zanieczyszczeniach kumulujących się w osadach dennych. Analizę przeprowadzono w kontekście zawartości dziewięciu metali (As, Ba, Cd, Co, Cr, Cu, Ni, Pb i Zn). Klasyfikację pozyskanych wyników badań przeprowadzono na podstawie kryteriów geochemicznych. Rezultaty analiz odniesiono do wartości tła geochemicznego charakteryzującego warunki naturalne bez piętna antropopresji. Wykorzystując system GIS opracowano mapy przestrzennego rozkładu zanieczyszczeń wybranymi metalami ciężkimi (Ba, Cr, Cu, Ni, Pb i Zn), które pozwoliły na zaobserwowanie zależności pomiędzy badanymi elementami. Analiza zanieczyszczeń osadów dennych metalami ciężkimi jest istotnym narzędziem do monitoringu środowiska.
Przedstawione badania wykazały, że potencjalny poziom zanieczyszczeń w osadach dennych może osiągnąć znaczący poziom. Systematyczną kontrolą zawartości metali w osadach warto objąć jak największą ilość zbiorników wodnych. Umożliwi to zachowanie równowagi ekologicznej w ekosystemie środowisk wodnych. Działanie to pomoże w identyfikacji, likwidacji i zapobieganiu negatywnych skutków działalności gospodarczej człowieka, co poprawi istotne z punktu widzenia rozwoju zrównoważonego racjonalne użytkowanie zasobów środowiska naturalnego.

Słowa kluczowe: zrównoważony rozwój, PMŚ, osady denne, metale ciężkie, GIS

Introduction

The current commonly used definition of sustainable development was introduced in the 1987 report *Our Common Future* by the United Nations World Commission on Environment and Development. It was defined as *development that meets the needs of current generations without compromising the ability of future generations to meet their own needs* (WCED, 1987). Sustainable development is considered on three levels: economic, social and environmental. The interactions between these aspects should be harmonious and non-invasive in relation to the remaining spheres (Miksch, 2015). Unfortunately, civilisation's dynamic progress, based on continuous growth in the consumption of goods and services, fossil fuels, the development of the automotive industry, mass production of single-use products, and accumulation of waste is often done without respecting the values and resources of the natural environment (Pawłowski, 2009; Sobczyk et al., 2012). As a result of these activities many pollutants are produced. Among them, heavy metals play a specific role, not only because of their potential toxicity, but also because once they enter into the environment they are practically impossible to remove. They remain in the natural environment circulating between its various components. This has a particularly important significance in relation to aquatic ecosystems. Rising heavy metal concentrations in oceans and seas could undermine the proper functioning of trophic chains. An example might be the inhibition of plankton growth which may result in a reduction in fish populations. Pollution associated with coal combustion, such as mercury emissions, also applies to water. In the United States, approximately 50,000 lakes, streams and ponds contain water unfit for human consumption due to their high mercury content (Berdo, 2006; Pawłowski, 2011). Elevated concentrations of heavy metals in the natural environment can cause serious health consequences, not only for current generations, but also for future ones.

This paper highlights the risks associated with the accumulation of contaminants in sediments. They provide sensitive pollution monitoring indicators (Vandecasteel, 2004). The majority of potentially harmful metals and organic compounds are retained in sediments which find their way to the surface waters. They accumulate elements that were or are currently widely used in the economy e.g. Zn, Cu, Cr, Ca, Pb, Ni, and Hg (Ekoinfonet, 2016). Knowledge of heavy metal content in sediments could be used to precisely determine the chemical characteristics of the aquatic environment and the geochemical state prevailing in the catchment area, as well as to define the spread of pollution and to identify its sources. This is primarily important for small water reservoirs, which are usually unmonitored and not included in environmental reports (Gałka, Wiatkowski, 2010).

The study made use of a Geographic Information System (GIS), which is becoming one of the most important tools in the geochemical assessment of the environment. This system allows efficient analyses to be conducted on large volumes of data with subsequent visualisation of the results. GIS also allows results to be classified and predicted on the basis of additional information (Zhang, Selinus, 1998).

Purpose

The purpose of the study presented in this paper was to demonstrate the principle in the use of GIS in meeting the requirements of sustainable development through environmental monitoring. In particular, GIS may be useful when planning activities whose purpose is to protect the natural environment, thus allowing future generations to exist appropriately.

To achieve this goal it was decided to assess contamination levels in the reservoir's sediment for the following selected heavy metals: As, Ba, Cd, Co, Cr, Cu, Ni, Pb, and Zn. Sediments were classified using geochemical criteria and maps were compiled based on the distribution of heavy metal contamination. At the same time the cause of the accumulation of individual heavy metals in the reservoir was to be determined as this contamination was inconsistent with the principles of environmental policy.

Study area and methodology

Due to the pilot nature of the study, one randomly selected object was chosen – the Ostrowy Reservoir approximately 25 km north of Częstochowa in Poland. The reservoir was built in the years 2000-2003 by damming the River Biała Oksza (White Oksza). The reservoir's surface area covers 39 ha.

Field work collecting sediment samples was carried out in July 2016. The sampling point locations are presented in the figures below. To develop a grid arrangement of sampling points the ArcGIS application, as well as the Web Map Service (WMS), accessed through the Geoportal service, were used (Rozpondek, Wancisiewicz, 2016). GIS was used to locate the selected sampling points.

Sediment samples were collected by lowering a Van Veen Grab supplied by KC Denmark A/S of Denmark. This is a grab sampler with an automatic latch lock which unlocks upon hitting the bottom (Geomor, 2016). 31 out of the 32 selected sampling points, from depths varying between 0.3-5.3 m were obtained from the Ostrowy Reservoir. A sample from sampling point 31 was not obtained due to its inaccessibility.

In the laboratory the samples were firstly dried under dry-air conditions and then sieved through a 2mm screen. They were then dried in an oven at 105°C to constant weight and ground in a vibrating mill until the grain size was less than 0.2 mm. A sample so

Table 1. Heavy metal concentrations and geochemical class in the reservoir's sediment

Sampling Point	pH H_2O	As	Ba	Cd	Co	Cr	Cu	Ni	Pb	Zn
		[ppm]								
1	7.16	0.8 class 1	91.3 class 1	0.0 class 1	0.0 class 1	20.9 class 2	16.2 class 1	13.4 class 1	20.9 class 1	142.5 class 1
2	7.29	0.0 class 1	28.5 class 1	0.0 class 1	0.0 class 1	182.3 class 3	2.8 class 1	77.1 class 3	1.8 class 1	11.8 class 1
3	7.11	0.9 class 1	129.4 class 1	0.0 class 1	0.0 class 1	10.4 class 1	12.4 class 1	8.9 class 1	18.4 class 1	106.0 class 1
4	7.02	1.0 class 1	134.1 class 1	0.0 class 1	0.0 class 1	11.0 class 1	13.6 class 1	7.9 class 1	17.6 class 1	114.8 class 1
5	7.48	0.0 class 1	18.3 class 1	0.0 class 1	0.0 class 1	190.7 class 3	2.5 class 1	81.2 class 3	0.0 class 1	10.1 class 1
6	7.25	0.0 class 1	26.3 class 1	0.0 class 1	0.0 class 1	157.9 class 3	2.2 class 1	65.8 class 3	2.8 class 1	12.8 class 1
7	7.16	0.9 class 1	102.7 class 1	0.0 class 1	0.4 class 1	44.6 class 2	12.2 class 1	23.0 class 1	21.9 class 1	100.6 class 1
8	7.36	0.0 class 1	32.7 class 1	0.0 class 1	0.0 class 1	168.3 class 3	3.6 class 1	71.4 class 3	6.9 class 1	26.6 class 1
9	7.29	0.0 class 1	42. class 1	0.0 class 1	0.0 class 1	80.4 class 2	4.0 class 1	38.2 class 2	20.2 class 1	45.7 class 1
10	7.18	2.7 class 1	138.0 class 1	0.0 class 1	0.6 class 1	16.9 class 1	17.4 class 1	11.4 class 1	29.0 class 1	160.5 class 1
11	7.56	0.0 class 1	21.6 class 1	0.0 class 1	0.4 class 1	303.5 class 3	2.1 class 1	128.0 class 1V	1.8 class 1	8.9 class 1
12	7.49	0.0 class 1	19.9 class 1	0.0 class 1	0.0 class 1	101.2 class 3	1.6 class 1	41.7 class 2	0.0 class 1	7.1 class 1
13	7.12	0.0 class 1	49.3 class 1	0.0 class 1	0.6 class 1	188.1 class 3	5.4 class 1	80.3 class 3	22.9 class 1	40.7 class 1
14	7.43	0.0 class 1	30.2 class 1	0.0 class 1	0.3 class 1	244.0 class 3	2.7 class 1	103.6 class 1V	6.4 class 1	19.4 class 1
15	7.30	0.0 class 1	42.5 class 1	0.0 class 1	0.0 class 1	180.4 class 3	3.6 class 1	78.2 class 3	5.6 class 1	43.3 class 1
16	7.25	0.0 class 1	26.6 class 1	0.0 class 1	0.0 class 1	133.3 class 3	2.5 class 1	56.6 class 3	4.5 class 1	64.0 class 1
17	7.35	0.0 class 1	34.8 class 1	0.0 class 1	0.0 class 1	76.4 class 2	1.6 class 1	32.2 class 2	3.5 class 1	18.7 class 1
18	7.51	0.0 class 1	18.7 class 1	0.0 class 1	0.0 class 1	28.8 class 2	0.8 class 1	12.9 class 1	0.0 class 1	8.9 class 1
19	7.74	0.0 class 1	22.7 class 1	0.0 class 1	0.0 class 1	66.5 class 2	2.2 class 1	30.0 class 2	1.5 class 1	7.0 class 1
20	7.27	2.3 class 1	115.7 class 1	0.0 class 1	1.2 class 1	33.4 class 2	17.9 class 1	18.8 class 1	30.7 class 1	189.7 class 1
21	7.18	1.5 class 1	171.0 class 2	0.0 class 1	1.6 class 1	23.9 class 2	19.1 class 1	13.9 class 1	35.3 class 1	225.8 class 2
22	7.26	1.9 class 1	133.8 class 1	0.0 class 1	1.4 class 1	26.6 class 2	18.4 class 1	15.9 class 1	31.7 class 1	232.8 class 2
23	7.30	0.0 class 1	48.6 class 1	0.0 class 1	0.0 class 1	114.6 class 3	4.6 class 1	48.7 class 2	6.8 class 1	46.8 class 1
24	7.41	0.0 class 1	37.6 class 1	0.0 class 1	0.0 class 1	141.9 class 3	2.4 class 1	61.0 class 3	4.4 class 1	31.6 class 1
25	7.20	5.8 class 1	264.1 class 2	1.0 class 2	5.7 class 1	50.3 class 2	28.5 class 2	26.8 class 1	57.7 class 2	355.5 class 2
26	7.11	6.4 class 1	208.8 class 2	1.0 class 2	5.7 class 1	39.8 class 2	31.9 class 2	29.6 class 1	52.1 class 2	441.6 class 2
27	6.86	0.4 class 1	43.4 class 1	0.0 class 1	0.0 class 1	42.5 class 2	3.3 class 1	19.6 class 1	9.2 class 1	52.0 class 1
28	7.04	0.7 class 1	70.6 class 1	0.0 class 1	0.0 class 1	47.5 class 2	5.1 class 1	23.0 class 1	14.2 class 1	72.2 class 1
29	6.49	0.0 class 1	106.0 class 1	0.0 class 1	0.0 class 1	52.8 class 2	13.0 class 1	20.1 class 1	12.6 class 1	70.7 class 1
30	6.91	0.0 class 1	25.4 class 1	0.0 class 1	0.0 class 1	65.2 class 2	1.3 class 1	25.5 class 1	3.8 class 1	22.8 class 1
32	7.21	4.8 class 1	225.7 class 2	0.5 class 1	6.3 class 1	56.2 class 2	25.8 class 2	31.0 class 2	49.8 class 1	317.7 class 2

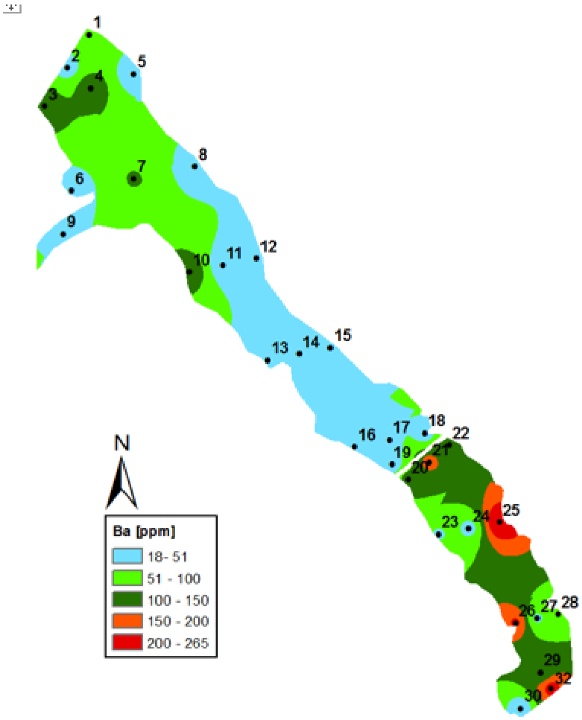

Figure 1. Spatial distribution of Ba concentrations [ppm]

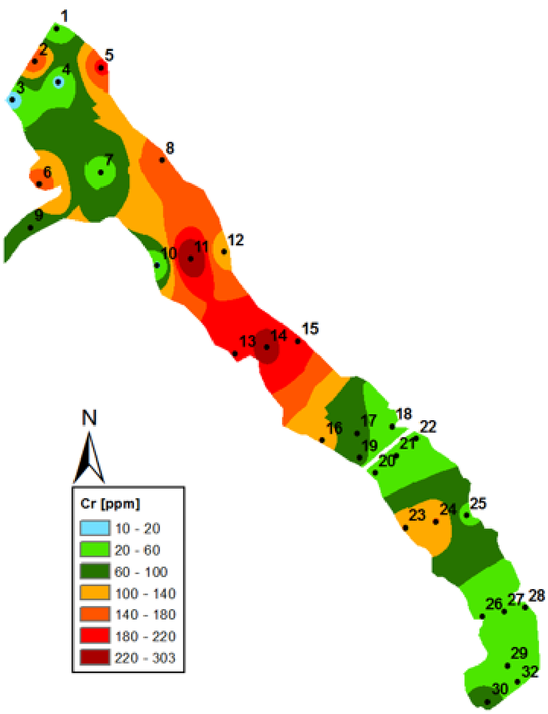

Figure 2. Spatial distribution of Cr concentrations [ppm]

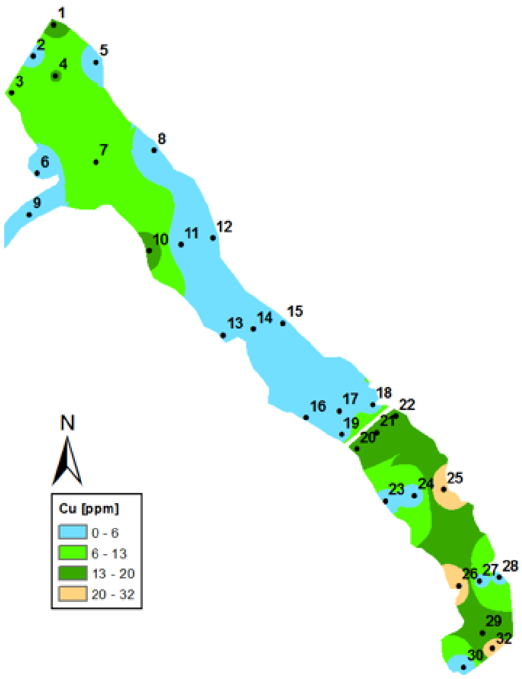

Figure 3. Spatial distribution of Cu concentrations [ppm]

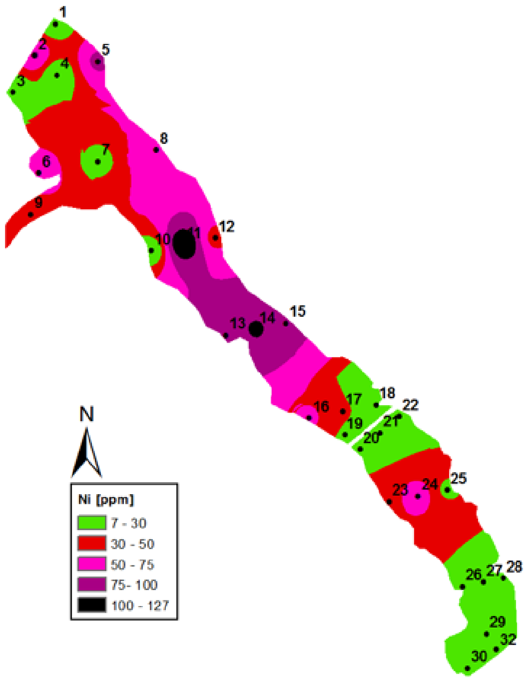

Figure 4. Spatial distribution of Ni concentrations [ppm]

prepared was used to determine the total heavy metal content. *Aqua regia* (a mixture of concentrated hydrochloric acid and nitric acid in a volumetric ratio of 3:1) was used for metal extraction. Mineralisation was carried out at 180°C, for 30 minutes in a high pressure microwave mineraliser from the German company Berghof GMBH. Three samples were prepared from each sediment sample for analysis. A plasma spectrometer (IRIS ICP-OES Thermo) determined the heavy metal content. The pH value was also recorded using a volume fraction sediment suspension in water in accordance with the PN-ISO 10390:1997 standard (Rozpondek, Wancisiewicz, 2016).

Sediment contamination was evaluated using maximum heavy metal concentration values in the classification of aquatic sediment quality as defined by the Polish Geological Institute (Bojakowska, Sokołowska, 1998; Bojakowska, 2001).

GIS was used to identify the location for the results of each sample point within the ArcMap application the ArcGIS Esri program was used to make inverse-

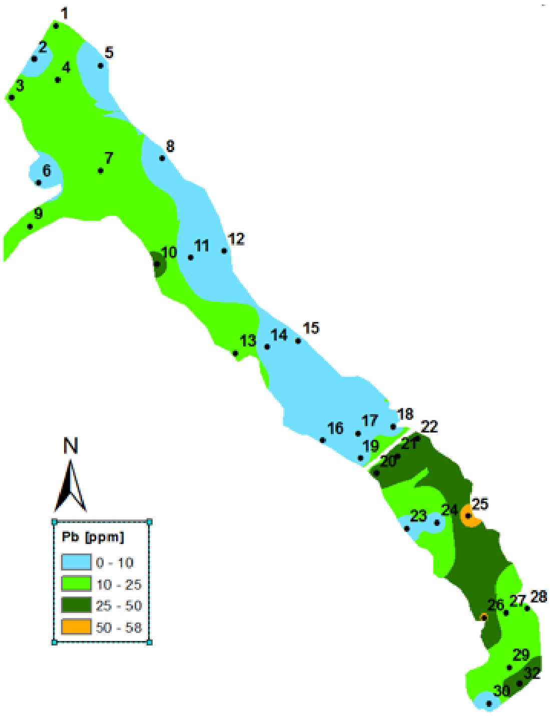

Figure 5. Spatial distribution of Pb concentrations [ppm]

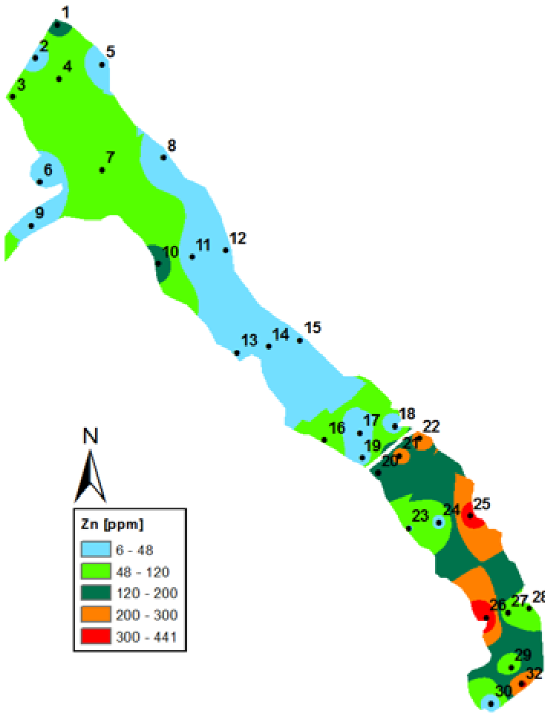

Figure 6. Spatial distribution of Zn concentrations [ppm]

distance weighting interpolations (Tomczak, 1998) for the laboratory analysis of the collected sediment samples. Afterwards, for visualisation purposes, classes were generated for the heavy metal concentrations in accordance with the geochemical criteria for aquatic sediments.

Results and discussion

Table 1 shows the results for the total concentrations of heavy metals in the sediment of the Ostrowy Reservoir, together with the classification of the aquatic sediments based on geochemical criteria (Bojakowska, Sokołowska, 1998; Bojakowska, 2001). Attention was also paid to the natural background geochemical value of the heavy metal in the environment, which is related to its geological substrate. Maps were compiled showing the differences in contamination levels for the various heavy metals (Figs. 1-6).

The reservoir's pH values were in the range 6.49-7.74 (acidic).

The samples can be considered to be uncontaminated by As, as the majority of the results for this element had a zero concentration value while the remainder were classified as Purity Class 1. The geochemical background value (<5 ppm) was exceeded only in sample points 25 (5.8 ppm) and 26 (6.4).

The Ba content exceeded the geochemical background value (<51 ppm) in 11 sampling points. The highest concentrations for this element in the sediment were noted in sampling points: 21 (171.0ppm), 25 (264.1), 26 (208.8), and 32 (225.7) which can be considered to be moderately contaminated i.e. Purity Class 2.

The Cd content in the analysed sediments was equal to zero. The exceptions were sampling points: 32 (0.5 ppm, Purity Class 1), 25 (1.0, Class 2), and 26 (1.0, Class 2).

The Co content was in the range 0.0-6.3 ppm (Purity Class 1), which means the sediment is uncontaminated. The highest cobalt concentration was recorded at sampling point 32 (6.3 ppm) which is more than three times the geochemical background value (2 ppm).

The natural Cu content (6 ppm) was exceeded at 12 sampling points. The highest concentrations were recorded at sampling points: 25 (28.5 ppm), 26 (31.9), and 32 (25.8), which can be considered to be moderately contaminated i.e. Purity Class 2

For Pb, its content in the sediment can be considered as moderately contaminating i.e. Purity Class 2. The highest recorded concentrations were at sampling points: 25 (57.7 ppm), and 26 (52.1), which exceed more than five times the geochemical background value (10 ppm).

The background geochemical Zn content in aquatic sediments is 48 ppm (as stated by Bojakowska and Sokołowska). All the tested sediment samples, with the exception of sampling points 32 (49.8 ppm, Purity Class 2), 25 (57.7, Class 2), and 26 (52.1, Class 2), did not exceed the natural zinc content in the sediments

On the basis of Figures: 1, 2, 4, and 6, it can be affirmed that the greatest concentrations of Ba, Cu, Pb, and Zn can be found in the southern part of the reservoir.

The reservoir's sediment can be regarded as being contaminated with Cr. Its concentration was in the range 10.4-303.5 ppm and therefore the sediments were classified as Class 3. The geochemical background value (5 ppm) was exceeded at all sampling points.

Ni concentrations in the sediments were classified as heavily contaminated (Purity Class 4). The highest recorded concentrations were at sampling points: 11 (128 ppm), and 14 (103.6) i.e. approximately 24 and 21 times higher than the geochemical background value (5 ppm).

On the basis of Figures 4 and 6 it can be seen that the distributions of Cr and Ni in the sediments are very similar. The highest concentrations of these elements are in the north-eastern and central parts of the reservoir.

Concentrations of the analysed elements (As, Ba, Cd, Co, Cr, Cu, Ni, Pb, and Zn) in the reservoir's sediments in the majority of cases clearly exceeded the averaged geochemical background value. This may indicate that the studied area is under the influence of harmful anthropogenic activities. Most likely, its state is linked to inadequately treated sewage from areas with open sewers created as a result of human activities related to making a living and to the economy. Another potential factor in the increased pollutants is the municipal sewerage treatment works located nearby. In addition, the increased heavy metal content in the reservoir could also be the surface runoff which introduces pollution from agricultural areas (fertilizers, pesticides) as well as sewage sludge used to fertilise farmland. This unsatisfactory geochemical situation in the reservoir may be caused by mechanisation, or more specifically, the use of fuels to drive agricultural machinery (Hazik et al., 2013; Polechoński, 2003; Kazimierowicz, Kazimierowicz, 2014; Karwacka et al., 2015) in agricultural production.

Summary and conclusions

The following conclusions can be drawn from the study results:

1. In the analysed reservoir, sediments are characterised by highly variable concentrations of the following metals: As, Ba, Cd, Co, Cr, Cu, Ni, Pb, and Zn. The most common contaminants are Cr and Ni. The lowest contaminant concentrations in the sediment were for As, Ba, and Co.
2. GIS is an important tool as an aid in monitoring sediments in reservoirs. It enables the state of the aquatic environment to be identified, and to track and forecast changes.
3. On the basis of spatial maps showing the distribution of individual heavy metal concentrations, the relationship between Cr and Ni was noted. The highest concentrations of these heavy metals occur where the reservoir is at its deepest (north-eastern and central parts). The highest concentrations of Ba, Cu, Pb and Zn occur in the southern part of the reservoir. This implies that the contaminants are introduced into the river by the inhabitants in the surrounding villages.
4. The reservoir's sediments require further study within the environmental monitoring framework.
5. Sustainable development activities for the harmonious interaction of the social, economic and environmental spheres should be controlled at the local level, in order to prevent global natural environmental problems.
6. It is important to identify the geochemical state of small reservoirs which are usually ignored and not accounted for in environmental reports, but whose sediments may be significantly contaminated. These studies allow harmful human activities to be identified and to define directions for their prevention.
7. The pilot study shows that potential contamination concentrations in sediments can reach a significant level. Further studies are therefore required to cover more reservoirs. An internationally coordinated program of such activities would be very valuable not only on a national level of individual countries, but also throughout the whole European Union.

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