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Methods of management of bottom sediments from selected water reservoirs – a literature review

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Abstract

Sediment accumulation is a process that is typical of all types of water reservoirs. The rate and pattern of such accumulation are related to processes taking place in catchments that produce the sediments and to those within reservoirs that determine the percentage of the inflowing load that is trapped and where it is deposited. To keep reservoirs in working order requires desilting and managing of such bottom sediments once they are removed. The choice of strategy for sediment management depends on chemical and physical properties which result from both natural and anthropogenic processes. To varying degrees, these sediments may be contaminated with chemical compounds, especially trace metals. Therefore, research is needed in order to assess the quality of sediments, which will allow to opt for the proper management strategy. Based on an analysis of the available literature, the possibility of using sediments from reservoirs has been determined, using quality criteria and in accordance with applicable law and regulations.

Key words: reservoir sedimentation, contaminated sediments, legal aspects of management

1. Introduction

Bottom sediments are an integral functional component of aquatic ecosystems. Given their ability to adsorb and absorb pollutants, such sediments are often referred to as geosorbents of pollutants in aquatic environments (Małachowska-Jutsz & Wollek, 2015). They typically contain organic, inorganic as well as natural and anthropogenic substances (Maj & Koszelnik, 2016), which makes sediments an important source of information for aquatic environmental monitoring and assessment of pollution levels and ecological risk (Sojka et al., 2019).

Harmful organic and inorganic compounds enter the aquatic environment through, among others, (1) atmospheric deposition, (2) surface runoff, (3) percolation through soils to groundwater and then to surface water, and (4) direct discharges to surface water (Winter et al., 2019). Pollutants are able to accumulate in bottom sediments as a result of sorption and sedimentation processes. Then, by participating in transformations such as disaggregation, dissolution, physical, chemical and biological transformation, they can affect the functionality of a given ecosystem (Tomczyk-Wydrych & Rabajczyk, 2019).

The progressive environmental pollution of surface waters and the associated accumulation of trace metals in bottom sediments poses a major threat to the biosphere because of the persistence, bioaccumulation tendency and high toxicity of trace metals and persistent organic pollutants (Bojakowska & Sokołowska, 1998; Madeyski & Tarnawski, 2006; Sojka et al., 2019). Excessive sediment accumulation results in a decrease of reservoir depth and volume, diminishing and eventually eliminating the benefits obtained from the reservoir (Tarnawski et al., 2017; Kida et al., 2019; Morris, 2020). The rate of sedimentation and composition of bottom sediments depend on many factors such as the geological structure of the catchment, the catchment geomorphology, reservoir size, hydrological and climatic conditions and catchment management (Winter et al., 2019).

Due to the effects of excessive accumulation of bottom sediments, it is necessary to remove sediments so as to maintain reservoirs in an adequate functional condition (Tarnawski et al, 2017). Several methods of bottom sediment removal can be found in the literature, such as (1) flushing – sediment scoured out of the reservoir during periods of emptying; (2) dredging – removal of submerged sediment by hydraulic suction or using excavators or other equipment on floating platforms, or (3) excavation – removing sediment from an empty reservoir using earth-moving equipment (Zawadzki et al., 2017; Morris, 2020).

Depending on the composition, amount and content of toxic substances in bottom sediments, an appropriate strategy for their management should be selected (Mikołajczyk & Nawrocki, 2019). Therefore, to evaluate the options for bottom sediment management, it is vital to carry out an analysis of ecological risks, determining the concentration of toxic substances (e.g., trace metals, polycyclic aromatic hydrocarbons, polychlorinated biphenyls) to assess ecotoxicity, and taking into account legal standards that define requirements or limitations for handling and disposal (Tarnawski et al., 2017).

The present paper is a review of the available literature on the management of bottom sediments from water reservoirs.

2. Methods of bottom sediment management

The grain size characteristics of sediments typically vary along the length of a reservoir, with coarse sediment (sand and coarse silt) dominating in the upstream delta area, and fine sediments (silt and clay) accumulating in the deeper areas and closer to the dam (Fig. 1). Utilisation strategies will differ for sandy sediments and fine-grained sediments (i.e., muds), making it is important to understand the distribution of sediments within the reservoir in order to develop an appropriate scheme for either using the sediments or disposing of them, developing both the sampling programme and the removal and disposal activities taking the variation in grain size into account, and also the variability in both physical and chemical characteristics, within each zone along the length of the reservoir (Morris & Fan, 1998).

Sediments within each zone of the reservoir should be analysed for both physical and chemical composition prior to usage, in order to insure that the material is not contaminated with potentially toxic compounds (Dróżdż et al., 2020a). Literature items characteristically report that, if bottom sediment extracted from a water reservoir does not pose a threat to the environment, it is reasonable to use it (Tarnawski et al., 2017).

The literature items consulted offer numerous examples of using reservoir sediments in different sectors of our economy: agriculture, reclamation, construction and energy (Fonseca et al., 1998; Canet et al., 2003; Baran et al., 2011; Koś & Zawisza, 2012; Walter et al., 2012; Bartoszek et al., 2015; Haque et al., 2016; Tarnawski et al., 2017; Wyrwicka et al., 2019; Dróżdż et al., 2020b; Bounouara et al., 2020; Koś et al., 2021) (Table 1).

According to Wyrwicka et al. (2019) and Canet et al. (2003), fine-grained sediments can be used as fertilisers because they are a rich source of organic and mineral matter, including nitrogen and phosphorus compounds that are essential for plant life. Soils with a higher organic matter content show bet-

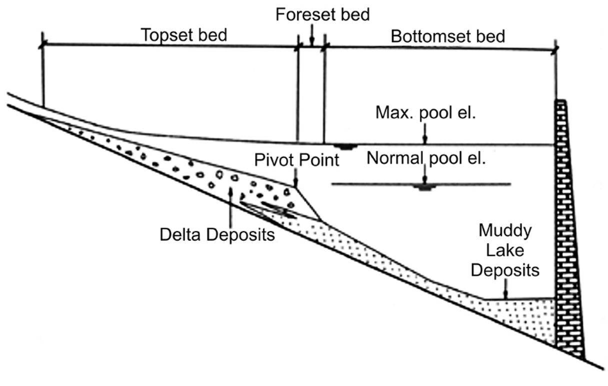

Fig. 1. Longitudinal profile showing typical variation in sediment characteristics along the length of a reservoir (Morris & Fan, 1998; used with the authors' permission).

ter structure, a greater water-holding capacity and increased soil nutrient availability (Wyrwicka et al., 2019; Canet et al., 2003). Similar conclusions were drawn by Fonseca et al. (1998), who studied sediments with high levels of total, exchangeable and soluble forms of nutrients and concluded that sandy sediments alone could be agriculturally useful soil substrates, while sediments with a clay composition could be used as additives to enhance poorer quality (sandy) soils (Fonseca et al., 1998). This thesis is also supported by the research of Baran et al. (2011), who focused on an evaluation of the agricultural

Table 1. Characteristics of bottom sediments.

Study area	Properties of bottom sediments	References
	Agriculture	
Maranhão reservoirs, Monte Novo reservoirs, Portugal	– pH 5.5–7.2 – organic matter: Maranhão 2.5–6%, medium: 3.7%; Monte Novo 2.2–3.3%, medium: 2.8% – Kjeldahl N: Maranhão: 0.115–0.35%; Monte Novo: 0.12–0.30% – Maranhão: Fe 3.85%; Mn 800 ppm; Cu 27, ppm; Zn 69 ppm, Mo 2.5 ppm, K 60 ppm–285 ppm – Monte Novo: Fe 4.9%; Mn 1139 ppm; Cu 26.1 ppm; Zn 75 ppm; B 73 ppm, K 40 ppm–392 ppm	Fonseca et al. (1998)
Albufera Lake, Spain	– pH 7.8 – organic matter 5.43% – organic N 0.173% – available P 18 mg kg^{-1}; Na 0.28%; K 0.79%; Ca 17.7%; Mg 1.65%; Cu 15 mg kg^{-1}; Zn 46.2 mg kg^{-1}; Mn 322 mg kg^{-1}; Fe 19.7 mg kg^{-1}; Cd 0.19 mg kg^{-1}; Ni 16.3 mg kg^{-1}; Pb 10.9 mg kg^{-1}	Canet et al. (2003)
Besko Reservoir, Poland	– pH 7.19–7.29 – organic matter 11.40 – 23.20 g kg^{-1} d.m – total N 1.30–1.50 g N kg^{-1} d.m – Zn 69.20–180.30 mg kg^{-1}; Cu 4.45–55.06 mg kg^{-1}; Ni 9.80–88.05 mg kg^{-1}; Cr 30.65–75.00 mg kg^{-1}; Cd 0.05–1.55 mg kg^{-1}; Pb 15.60–75.35 mg kg^{-1}; Fe 1.68–47.95 g kg^{-1}; Mn 0.02–1.10 g kg^{-1}	Baran et al. (2011)
Gallito Ciego Reservoir, Peru	– pH 7.7 to 8.0 – N <0.1 –35.0 mg kg^{-1} (littoral sediments), 9.9 – 44.1 mg kg^{-1} (profound sediments) – P 99–132 mg kg^{-1} (littoral), 111–181 mg kg^{-1} (profound) – K 22–116 mg kg^{-1} (littoral), 17–98 mg kg^{-1} (profound) – Fe 31000–45000 mg kg^{-1}, Mn 200–1000 mg kg^{-1}, Cd 0.06–0.86 mg kg^{-1}, Cr 31–127 mg kg^{-1}, Cu 24–86 mg kg^{-1}, Hg <0.1–0.16 mg kg^{-1}, Ni 8.8–39.1 mg kg^{-1}, Pb 20–80 mg kg^{-1}, Zn 99–968 mg kg^{-1}	Walter et al. (2012)
Złoty Potok (organic fish farm), Poland	– pH 7.61 – organic matter 30.38% – total N 0.41% – organic carbon 10.19% – Cd 0.55 mg kg^{-1}, Cr 10.6 mg kg^{-1}, Cu 7.72 mg kg^{-1}, Fe 1411.9 mg kg^{-1}, Mg 334.7 mg kg^{-1}, Mn 19.3 mg kg^{-1}, Ni 58.4 mg kg^{-1} , Pb 13.7 mg kg^{-1}, Zn 80.2 mg kg^{-1}	Dróżdż et al. (2020)
Dhanikhola Union under Trishal Upazila of Mymensingh district, Bangladesh	– pH 6.86 – organic carbon 3.15% – total N 0.30% – available P 115.6 mg kg^{-1}; S 86.06 mg kg^{-1} – K 106.80 mg kg^{-1}	Haque et al. (2016)
	Environmental purposes (agriculture, reclamation)	
Rożnów Reservoir, Poland	– pH 7.07–7.41 – $CaCO_3$ 1.60–5.68% – organic carbon 5.34–26.28 g kg^{-1} d.m – N 0.16–1.77 g kg^{-1} d.m – P 1.8–6.42 g kg^{-1} d.m – S 0.13–0.88 g kg^{-1} d.m – K 0.5–6.27 g kg^{-1}, Ca 6.28–29.88 g kg^{-1}; Na 0.04–0.33 g kg^{-1}; Mg 2.48–7.58 g kg^{-1}	Tarnawski et al. (2017)

Study area	Properties of bottom sediments	References
	Non-agricultural land reclamation	
Rzeszów Reservoir, Poland	– pH_{KCl} 7.04–7.42 – organic matter 6.5–11.6% – total N 0.12–0.37% – total P 0.003–0.067% – organic carbon 1.61–4.39% – Zn 103.9 mg kg^{-1}, Cu 32.7 mg kg^{-1}, Pb 53.5 mg kg^{-1}, Ni 35.6 mg kg^{-1}, Cr 56.3 mg kg^{-1}, Cd 2.5 mg kg^{-1}; benzo[a]pyrene 0.0605 – 0.1436 mg kg^{-1}; PCBs 0.0005–0.0028 mg kg^{-1}	Bartoszek et al. (2015)
	Civil engineering	
Bouhanifia dam, Algeria	– sediments enriched with bentonite (2, 4, 6, 8 and 10%) can be used as passive clay barriers in hazardous waste landfills	Bounouara et al. (2020)
Rzeszowski Reservoir, Poland	– fraction content: sand 9.0%, silt 83.0%, clay 8.0% – specific density 2.609 g cm^{-3} – organic parts content 2.85% – optimum moisture content 27.0% – cohesion 39.5 kPa – bottom sediments can be used as a construction material for engineering purposes	Koś & Zawisza (2012)
Rzeszowski Reservoir, Poland	– fraction content: sand 1–2%, silt 86–92%, clay 6–13% – organic matter 3.33% – maximum dry density 1.4 g cm^{-3} – optimum moisture content 27% – cohesion 42.7 kPa (silt) – bottom sediments can be used for sealing elements in hydraulic engineering embankments	Koś et al. (2021)

use of bottom sediments. Briefly, bottom sediments with a large proportion of clay fractions, alkaline reaction, good sorption and buffer properties allow these to be used as an amendment to sandy, acid soils so as to improve their productivity (Baran et al., 2011). Similar conclusions were reached by Tarnawski et al. (2017), i.e., the use of sediments from the Rożnowski Reservoir increased the productivity of sandy soils by improving their physio-chemical properties such as the water-retention capacity (Tarnawski et al., 2017). There are many examples in the literature of using bottom sediments from fish ponds. These sediments are subjected to biological processes and then used as fertilisers in the cultivation of, for example, *Lilium perenne*, *Lolium multiflorum* and feed grasses (Dróżdż et al., 2020a; Dróżdż et al., 2020b; Haque et al., 2016).

Sediments with a low nutrient content (nitrogen, phosphorus and potassium), low organic carbon concentration and with a trace metal concentration below toxicity thresholds, can be used as a supplement so as to improve the quality and productivity of arable land. However, if the sediment is deficient in nutrients it cannot replace fertilisers (Walter et al., 2012; Baran et al., 2016).

Important barriers limiting land application of sediments include the high cost of excavating and transporting these, the high moisture content of dredged sediment which makes them difficult to handle, contamination with organic and inorganic compounds, and generation of leachate that can adversely affect soils and groundwater (Tarnawski et al., 2017). However, according to Fonseca et al. (1998), if the removal of sediments from reservoirs becomes profitable, their suitability for agricultural use may eventually solve important problems such as extending the functional life of reservoirs, enhancing water quality and offsetting the shortage of cultivatable soils in some regions of the world.

There are indications that sediments rich in nutrients and organic carbon can be used as fertiliser substitutes in crop production (Karanam et al., 2008). Results of studies conducted by Karanam et al. (2008), of bottom sediment samples collected from reservoirs under a government water conservation programme in the Medak district of Andhra Pradesh State, India, showed an average of 720 mg nitrogen, 320 mg phosphorus, 310 mg potassium and 9.1 g organic carbon per kg of sediment. That study suggests that the use of bottom sediments for agricultural purposes is not only justified by the positive environmental impact but also in terms of economics (Karanam et al., 2008).

In addition to the agricultural use of bottom sediments, there are also papers on the use of reservoir sediments for land reclamation. The study by Bartoszek et al. (2015) confirms that sediments that are relatively poor in nutrients and characterised by increased trace metal concentrations are not suitable for agricultural use. However, they may be a valuable resource for use in non-agricultural land reclamation (Bartoszek et al., 2015). According to Wyrwicka et al. (2019), the use of bottom sediments can be particularly useful in urban areas for the reclamation of degraded areas, transportation sites and recreational areas mainly intended for flower beds and lawns (Wyrwicka et al., 2019). Another example of using submerged sediments for reclamation is the renovation of a manor park in Wrocław-Pawłowice (Poland). The bottom sediments from water features in this park were analysed; no pollutants exceeding the permissible values were found. The excavated sediments were then used to level ground surfaces and for access roads. This material was also used to improve soils, without negatively changing the growth conditions of trees and shrubs (Gałka, 2010).

However, other authors have indicated that sediments which meet the geotechnical criteria can be used to form sealing screens at municipal landfills (Koś & Zawisza, 2012), to seal elements of hydrotechnical embankments (Koś et al., 2021) and constitute a valuable source of material necessary in civil engineering, e.g., for road construction (Maj & Koszelnik, 2016). Bounouara et al. (2020) confirmed that bentonite-treated sediments can be used as passive clay barriers in hazardous waste landfills (Bounouara et al., 2020). In turn, the results obtained by Chiang et al. (2008) suggest the possibility of using sediments from water reservoirs to produce bricks for building purposes (Chiang et al., 2008). Based on an analysis of the suitability of bottom sediments from the Rzeszów reservoir in Poland for civil engineering purposes, it was concluded that this can be used as sealing material in hydrotechnical embankments. Geotechnical testing showed that these sediments would meet most of the criteria required for their use in sealing layers (Koś et al., 2021).

The research also focused on an analysis of bottom sediment potential for use in anaerobic digestion and biogas production (Dróżdż et al., 2020b). It is worth mentioning that the use of sediments as a binding material, when added to biocomponents (e.g., wood pulp, sawdust), was also tested, producing a fuel material with high energy parameters (Borsuk et al., 2012). The authors concluded that, for economic and ecological reasons, most of the uncontaminated or poorly contaminated sediments should be used in a variety of applications (Canet et al., 2003; Karanam et al., 2008; Baran et al., 2011; Bartoszek et al., 2015). Research on bioavailability of pollutants is necessary to select the appropriate methods for sediment management, and if that is not possible, appropriate methods of sediment treatment before disposal should be indicated (Jancewicz et al., 2014).

3. Legal aspects of bottom sediment management in Poland

Before reservoir sediments are to be used, their quality needs to be assessed. This allows for a twofold subdivision into contaminated and uncontaminated sediments (Maj & Koszelnik, 2016). National legal regulations on sediment contamination were included, among others, in the Regulation of the Minister of Environment of 9 September 2002 on soil quality standards and land quality standards (consolidated text, Journal of Laws 2002.165.1359) and the Regulation of the Minister of Environment of 16 April 2002 on types and concentrations of substances that cause excavated material to be contaminated (consolidated text, Journal of Laws 2002.55.498). However, these regulations are no longer valid, but have not yet been replaced by a new act.

The quality of bottom sediments is also assessed under the national programme "Monitoring of river and lake seabed sediments". For the purposes of monitoring, the assessment of bottom sediment quality in terms of its contamination with heavy metals or harmful organic compounds is based on geochemical criteria. In geochemical assessments of sediment quality, anomalous content of an element in the environment is defined as concentrations higher than the sum of average content of this element and two standard deviations defined for the studied population. The bottom sediment is considered to be contaminated even if only one elements is found to exceed the permissible content level. In order to assess the effects of harmful trace elements, PAHs, PCBs and organochlorine pesticides contained in sediments on aquatic organisms, threshold contaminant contents, i.e. PEC values (Consensus-Based Sediment Quality Guidelines) – the content of an element or chemical compound above which toxic effects on organisms are frequently observed, were used (Siebielec et al., 2015).

Uncontaminated dredged spoil (sediments from the bottom of superficial bodies of standing water or flowing water), if used for the purposes indicated in Article 2, point 7 of the Waste Act of 14 December 2012 (consolidated text, Journal of Laws 2021.779 as amended), i.e., associated with the water or waterway management, water or water facility management, or flood protection or flood and drought mitigation, reclamation, revegetation, land acquisition or land treatment, is not regulated under this Act unless the sediments would exhibit characteristics of hazardous waste. If, based on sediment tests, it turns out that the substance concentration values are exceeded, such sediments should be treated as waste. Pursuant to Article 101r of the Act of 27 April 2001. Environmental Protection Law (consolidated text, Journal of Laws 2020.1219 as amended), it is prohibited to use soil or ground for earthworks, including sediments from the bottom of superficial reservoirs of standing water or flowing water used for these works, if they exceed the permissible content of risk-causing substances, specified in regulations issued pursuant to Article 101a paragraph 5, for the grounds occurring at the place of usage of that soil or ground.

Currently, in Poland there is one Regulation of the Minister of Environment of 11 May 2015 on the recovery of waste outside installations and devices (consolidated text, Journal of Laws 2015, item 796). This regulation defines the types of waste and conditions of their recovery in recovery processes R3, R5, R11 and R12 listed in Annex No. 1 to the Act of 14 December 2012 on waste outside installations or devices. The above-mentioned regulation refers to dredged material and specifies precisely the sole possible method of its management. Pursuant to the Regulation, dredged material (codes 17 05 06 and 17 05 05*) may be recovered through the R5 process (recycling or recovery of other inorganic materials) upon meeting certain conditions regarding the concentration of specific metals and organic compounds. Therefore, it should be noted that in all other ways of sludge management in Poland the presumptive mode should be adopted, and the ones we have quoted propose potential options. Indication of possibilities for other management of selected sediments may indicate paths for legislative discussion on solving this growing problem.

4. Conclusions

On the basis of the present literature review, the following conclusions can be drawn:

- Removal of sediment from water reservoirs may become an increasingly common practice in order to sustain reservoir volumes needed for their primary functions.
- Bottom sediment may be contaminated with chemical compounds to varying degrees. The most harmful compounds are trace metals, polycyclic aromatic hydrocarbons and polychlorinated biphenyls. Therefore, studies to determine the contamination levels in sediments are necessary before choosing a strategy for sediment management.
- The issue of sediment management is of growing concern, which has led to investigations and attempts to use sediments in a variety of economic applications. The reservoir sediments are most often used in agriculture, land reclamation and civil engineering.
- Clear and precise methodologies and criteria for assessment and classification of sediments can help make their management more beneficial for the environment.

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