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METHODS OF RECLAMATION OF WATER RESERVOIRS

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Abstract. The paper describes the most common methods used for reclaiming water reservoirs. It reviews the most important publications from recent years, outlines the historical background to the problem in question, and provides some examples of the practical applications of each method. The reclamation methods were characterised in detail, taking into account general assumptions, usability, efficiency and cost. Reclamation should be considered as the last resort and employed in cases when earlier protective activities within a catchment have not produced the desired effect. For some strongly eutrophic reservoirs, however, such a measure is necessary in order to achieve improvement in water quality. Reclamation activities should always be preceded by a thorough, interdisciplinary examination of the catchment and the reservoir itself.

Key words: reclamation of water reservoirs, surface water protection

INTRODUCTION

The precursor of the reclamation of water reservoirs was the Swiss scientist P. Zigerli who in 1939 explained the rules for removing deep water rich in nutrients with the use of a siphon method. In 1970−1971, the Swedish limnologist S. Björk applied to Lake Trumen in Sweden a method of eliminating internal load by means of removing bottom sediment. In 1974, the Swiss scientist P. Mercier developed and applied to Lake Brett a prototype technology which consisted in pumping out deep water and aerating it in a special chamber, and then pumping it back deep into the lake. In 1973, G. Barroin employed an agricultural method of injecting aluminium sulphate into the sediments in Lake Marillon with the use of a double plough. In 1975, W. Ripl used the same method to inject calcium nitrate into the sediments of Lake Lillesjön in Sweden [Barroin 1991].

In 1956, Prof. Przemysław Olszewski started the operation of a pipeline on the bottom of Lake Kortowskie in Olsztyn, which drained water of the hypolimnion below the lake. This method, called "the Olszewski method", is considered the first method of reclamation of lakes that was put into practice [Lossow 1998].

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OVERWIEV OF METHODS MOST COMMONLY APPLIED IN RECLAMATION OF WATER RESERVOIRS

Seepage trenches and filter basins

[Hino 1994]

Seepage trenches and filter basins are used in order to remove phosphorus, organic substances and bacteria from water, and are efficient when the amount of water is small. They are used in small catchments (of influent rate $Q < 100$ dm$^3 \cdot$ s^{-1}) where storm water does not cause overflows. Biogenic substances are removed from water in the course of seepage through the layers of natural or artificial soil. Higher efficiency of purification is achieved in a soil of high adsorption capacity, e.g. sandy silt, whereas quartz sands have a low adsorption capacity and low efficiency of purification. If the adsorption capacity of natural soil is insufficient, seepage filter basins with an artificial seepage layer are built. The filter must be filled with fine particulate materials which contain a high portion of aluminium and iron oxides for phosphate adsorption. The permeability of the filters should be chosen in such a way that the water could flow through them instead of passing them by. The filter bed should be covered with coarse material so as to prevent algal and microbial growth.

Pre-reservoirs

[Benndorf and Pütz 1987, Prochal 1987, Żbikowski and Żelazo 1993, Hino 1994]

Pre-reservoirs have been used for a short time. They are separate, shallower parts of the main reservoir, located in its upper part, or they are built right in front of the reservoir as separate water areas.

Reservoirs of this kind are used in areas that are subject to a high impact of surface washings. They are small and have a retention time of a few days. Their functioning is based on the development of microorganisms that fix phosphorus in their biomass. During the sedimentation of the biomass, the phosphorus remains in the sediment provided that there are aerobic conditions at the bottom of the basin. In Central Europe, in summer 70–90% orthophosphates are eliminated, while in winter the efficiency decreases to 0–30% (with light and temperature being the limiting factors). On the average, on a yearly basis 50–60% orthophosphates are eliminated. Nitrogen is fixed into the biomass (denitrification) or escapes into the atmosphere in gaseous form, particularly at a high pH value which increases as CO_2 is taken up in the process of photosynthesis.

The improvement in water quality is a result of biochemical and physicochemical processes.

The first step is biochemical transformation from soluble form to particulate matter (phytoplankton), the second step is sedimentation of the phytoplankton and the remaining matter in the pre-reservoir or in a shallow, narrow part of the main reservoir. The sedimentation process is more efficient if natural flocculants are present, thus the geochemical conditions may significantly influence the efficiency of nutrient removal. The main process at this stage is acquisition of orthophosphates by algae; chemical fixation is undesirable. This is why the pH in the reservoir should remain between 6.0 and 8.0. At pH < 6.0, the orthophosphates react with Fe, Al and Mn, and at pH > 8.0, with Ca. The sedimentation process is also supported by the appropriate structure of the plankton which should consist of species of high setting velocity, with the exception of unwanted blue-green algae. The mass development of zooplankton, in particular *Daphnia* and plankton-feeding crustaceans, should not take place as it devastates the population of phytoplankton and eventually leads to the remineralisation of biogenic substances. Appropriate proportions of species can be maintained by means of adopting an optimal, not too long residence time, which enables the quick development of phytoplankton and eliminates the zooplankton, crustaceans and slow-growing blue-green algae. It is recommended that the residence time is between 5 and 11 days, which ensures the highest efficiency of purification (see Table 1). The best results of nutrients removal in reservoirs are achieved between May and September.

Table 1. Mean annual percentage of eliminated orthophosphates as dependent on long-period average residence time of water in pre-reservoir [Prochal 1987]
Tabela 1. Procentowe średnie roczne ilości eliminowanego ortofosforanu w zależności od średniego z wielolecia czasu przebywania wody w zbiorniku wstępnym [Prochal 1987]

Residence time, days Czas przebywania, dni	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
Mean annual elimination, % Średnia roczna eliminacja, %	15	25	33	41	45	50	53	55	56	57	58	59	60

The pre-reservoir should contain only small fish which feed on zooplankton, but not predatory fish.

The depth of the reservoir should be chosen in such a way that the domination of photoautotrophic organisms would be ensured: the light should freely penetrate the layer of water. The degree of acquisition of orthophosphates by algae decreases with depth, so the recommended average depth of the reservoir should range from 3 to 5 m and should not exceed the euphotic zone.

The pre-reservoir should consist of two parts. The first part should be closed by a scarp, ca. 3 m high (w), with a rectangular crown situated at the depth h_0 from the water table. The distance from the scarp to the inlet should be equal to the sedimentation route of the particles of the river load which flows into the reservoir. Below the scarp, at ca. 6–7.5w distance, a surface barrier is built, which reaches to ca. 0.5 m over the bottom.

A properly formed water inlet to the reservoir – with the use of wings set at an angle of 90–120° – provides an even distribution of the inflowing water.

Knowing the average annual load of orthophosphates in the reservoir and their acceptable level, it is possible to calculate the required percentage of their elimination. Next, the required residence time t_p is found in Table 1 and multiplied by the mean annual flow Q_{sr}, giving the net capacity of the pre-reservoir. The result is added to the estimated capacity of bottom sediments V_{os} that will accrue within 5 years (assuming a five-year cycle of purification of the reservoir). In order not to introduce a high amount of pollution with high water, the capacity of the reservoir should ensure that the flood flow Q_{50} is stopped for 0.5 day. While passing the flood through pre-reservoirs, part of the water should be directed to the diversion channel, in order to avoid severance of the bottom sediments and moving them with the water to the main reservoir. Thus, the total capacity V is expressed as [Prochal 1987]:

$$V\,[\mathrm{m^3}] = Q_{sr}\,[\mathrm{m^3 \cdot s^{-1}}] \cdot t_p\,[\mathrm{d}] \cdot 86400\,[\mathrm{s}] + V_{os} \geq Q_{50}\,[\mathrm{m^3 \cdot s^{-1}}] \cdot 0.5\,[\mathrm{d}] \cdot 86400\,[\mathrm{s}] + V_{os}\,[\mathrm{m^3}]$$

Regular removal of bottom sediments from pre-reservoirs prevents the nutrients from re-entering the cycle. Every 5–10 years (in winter), the reservoir should be thoroughly cleaned and then refilled. While cleaning the pre-reservoir, the water is let directly into the main reservoir through the diversion channel, which is also used to channel flood flows.

Biofilters

[Mioduszewski 1999]

Biofilters are shallow reservoirs (0.3–0.6 m) in which plants, particularly reed, grow luxuriantly on the whole surface. The recommended flow velocity should not exceed $0.15\ \mathrm{m \cdot s^{-1}}$. Nitrogen elimination in such reservoir is ca. $1\ \mathrm{g \cdot N \cdot m^{-2}}$ per year. In order to improve purification, it is recommended to cut down the plants regularly in winter.

Biomanipulation

[Bendorf et al. 1984, Shapiro and Wright 1984, Jørgensen and Johansen 1989, DeMelo et al. 1992, Kajak 1998, Perrow and Davy 2002, O'Sullivan and Reynolds 2005, SWCSMH 2006]

Biomanipulation means stocking, limiting fish crop, as well as removing plants. This is manipulating living organisms in order to induce specific changes in the ecosystem. Most commonly, the aim is to maintain the phytoplankton biomass at a low level, even at a high nutrient concentration. This increases water transparency, which may cause growth of underwater plants, limiting the reversion of nutrients from the sediment and removing them from circulation. The most modern method of biomanipulation is to change the quantitative proportions of fish in order to impact zooplankton and phytoplankton.

Introducing carnivorous species of fish into the reservoir leads to a reduction in the population of zooplankton-feeding fish. The increase in the population of zooplankton leads to a decrease in the concentration of phytoplankton. The results are a visible reduction in the mass of phytoplankton, higher water transparency, decrease in the amount of bacteria, and higher concentration of dissolved oxygen, although the long-term effect at a constant inflow of nutrients is questionable.

It is easy to achieve a reduction in the number of plankton-feeding fish, such as bleak, pope, young bream, roach, chub, young perch, by introducing carnivorous fish, i.e. pike, pike perch, adult perch, by means of stocking but also by limiting fish crop. However, carnivorous fish are the most attractive for anglers and poachers. Maintaining a constant level of stock is only possible in small reservoirs, without inflows or outflows, with constant supervision of fish crop.

Biostructures
[Eko Tech 1995, Lossow and Gawrońska 2000]

These are three-dimensional spatial barriers immersed in the water. Biostructures, which are used only in Poland, are very controversial. It is assumed that they function as biological filters which improve water quality by enabling the development of peryphytone of rich species composition. In fact, they often function as islands, crowded by water birds, as a hatchery of dipterous larvae and oligochaetes. If not removed in winter, they re-supply nutrients to the reservoir.

Removal of water from hypolimnion
[OECD 1982, Hino 1994, Kajak 1998]

This method was first applied by Przemysław Olszewski to Lake Kortowskie in Olsztyn. Such a treatment is only possible in flow-through reservoirs. It consists in removing contaminated deep water through a siphon instead of removing superficial water (Fig.). The treatment is cheaper and easier than the removal of bottom sediments. Its serious disadvantage, however, is the possibility of contaminating the outflow from the reservoir with nutrients and other substances, and the likelihood of damaging the stability of bottom sediments that remain balanced with the contaminated deep water, which leads to the secondary pollution of the reservoir. The advantage of this method is its low cost, without energy expenditure.

The method can be recommended for small, deep reservoirs whose topography enables the use of a siphon. In dam reservoirs, the water of hypolimnion may be drained through bottom sluices.

Removal of sediment by dredging
[Peterson 1981, Hino 1994, Kajak 1998, Lossow 1998, SWCSMH 2006]

Dredging may only be used for small, shallow reservoirs. The most important problem is purification and storage of the removed material. Particular attention must be paid to the possibility of occurrence of heavy metals in the sediments.

The most famous example of applying this method is Lake Trummen (ca. 100 ha in area) in Sweden. After cutting off the inflow of sewage to the lake, in 1970 and 1971 a nearly 1-meter deep layer of bottom sediment was removed from it with the use of a hydraulic dredger with a cutter. The nutrient-rich sediment was transported to sediment basins and used as fertiliser after being drained off. Filtered, clear water was pumped through a batcher of aluminium sulphate, filtered again, and finally, free from nutrients, it flowed back into the lake. In this operation 600 000 m^3 of sediment and 300 000 m^3 of water were removed, together with 50 Mg of phosphorus (90%) and 450 Mg of nitrogen, which resulted in a decrease in the mean biomass content from 75 to 10 mg per dm^3, elimination of algal blooms, increase in water transparency from 0.2 to 0.8 m, restoration of the recreation function of the lake, and a 70% growth in the lake capacity.

When the concentration of nutrients in sediment is high, the removal of a 10 cm layer of sediment allows one to withdraw from the ecosystem the same amount of nitrogen and phosphorus as may be removed from an 8-meter deep layer of water of the hypolimnion.

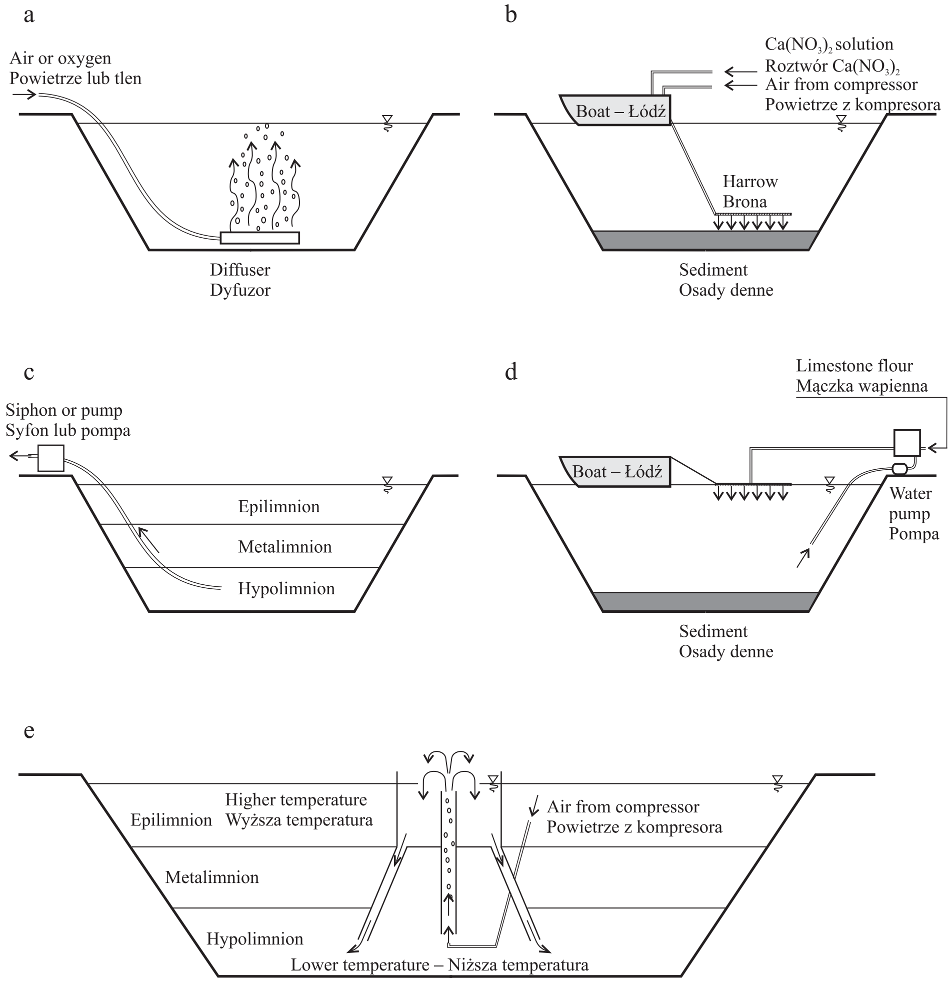

Fig. Schemes of some reclamation methods: a – hypolimnetic aeration with artificial destratification, b – sediment oxidation (nitrate treatment), c – removal of water from hypolimnion, d – lime treatment, e – hypolimnetic aeration without disturbing the temperature (based on: Kajak [1998], Perrow and Davy [2002])

Rys. Schematy wybranych metod rekultywacji: a – napowietrzanie wód hypolimnionu z zaburzeniem uwarstwienia termicznego, b – utlenianie osadów dennych (traktowanie azotanami), c – usuwanie wód hypolimnionu, d – wapnowanie, e – napowietrzanie wód hypolimnionu z zachowaniem uwarstwienia termicznego (według: Kajak [1998], Perrow i Davy [2002])

Apart from being cost-consuming, this method causes numerous technical problems. It cannot be applied in locations where there is no nearby space available for depositing and draining off sediments. The nutrients should be prevented from re-entering the basin while removing, transporting and depositing the sediments.

Sediment oxidation

[Björk 1985, Barroin 1991, Kajak 1998, Szyper and Gołdyn 2000, Perrow and Davy 2002]

The basis is the oxidation of reduced compounds in the superficial layers of bottom sediments (Fig.). Hydrogen peroxide solution or liquid oxygen may be used for the oxidation of sediments, although the efficiency of such methods is low. Good results may be achieved by using calcium nitrate solution, which is distributed over the bottom with the use of a machine similar to a harrow. Such a treatment is only possible in small shallow reservoirs in order to reduce internal supply. The method is commonly named Riplox, after the name of its creator – Ripl. During the reclamation of Lake Lillesjon (over 4.2 ha in area), 13 Mg of iron chloride ($FeCl_3$) were introduced into the sediments in order to fix phosphorus with iron and to remove H_2S. To neutralise the sediments, 5 Mg of $Ca(OH)_2$ were added (sample reactions are provided for the method involving the chemical precipitation of phosphorus), and to oxidise the inorganic and organic matter (FeS), 12 Mg of $Ca(NO_3)_2$ were used:

$$5CH_2O + 4NO_3^- + 4H^+ \rightarrow 2N_2 + 5CO_2 + 7H_2O \text{ organic matter oxidation}$$

$$5S^{2-} + 8NO_3^- + 3H^+ + H_2O \rightarrow 5SO_4^{2-} + 4N_2 + 5OH^- \text{ inorganic matter oxidation}$$

[Perrow and Davy 2002]

Introducing nitrate to the sediments caused their oxidation, removal of sulphides, and evaporation of nitrogen in gaseous form into the atmosphere (stimulated denitrification). Water transparency increased from 2.3 to 4.2 m, and the concentration of phosphorus fell from over 3 to 0.04 $mg \cdot dm^{-3}$.

Sediment covering

[Olem and Flock 1990, Hino 1994, Kajak 1998, SWCSMH 2006]

This method is used to isolate sediments and prevent internal supply, or to limit the growth of macrophytes when they pose an obstacle for boats. Macrophytes require light, and thus they are unable to grow below a barrier. The synthetic material used for covering the sediments should be heavy and resistant to floating. Sand and gravel may not be used for providing extra load as they constitute a good substrate for macrophytes. The sheeting should be permeable to gases. Black polyethylene (0.1 mm) is often used, mainly to suppress the growth of macrophytes. Unfortunately, it is impermeable to gases and after perforation may be easily grown through by macrophytes. It is also very sensitive to light. Typar, and Fiberglass PVC (Aquascreen) are recommended as they are gas-permeable and easy to use. Aquascreen is extremely heavy and floating-resistant. The layers whose only role is to protect from internal supply may be built from bentonite or other clay materials. The method is expensive and applicable to small reservoirs and lake bays of low water flow.

Hypolimnetic aeration with artificial destratification
[Steel 1975, Vandermeulen 1992, Hino 1994, Kajak 1998, SWCSMH 2006]

This method consists in supplying air bubbles to deep water (Fig.). The air bubbles partly dissolve and partly escape to the atmosphere, causing the water masses to dislocate. This leads to the oxygenation of water, the precipitation of phosphorus from bottom sediments as a result of the chemical reaction with iron, as well as to a change in the composition of the algal population, and a decrease in the number of algae and in their growth rate, resulting from keeping them in a dark, deeper layer of the reservoir. Since oxygenation may cause temperature inversion, the warm water coming in contact with the sediment may lead to an increase in the intensity of internal supply. This process is time-consuming and requires a constant supply of electric power. In flow-through reservoirs, aeration combined with a cutoff of external pollution sources results in improved water quality after several years. The method may be applied in reservoirs with a constant depth, which limits its usage in dam reservoirs.

Hypolimnetic aeration without disturbing the temperature
[Fast and Lorenzen 1976, Olem and Flock 1990, Kajak 1998, SWCSMH 2006]

Pumped deep-water is aerated or oxygenated in a separate tank (container), then the water is pumped back into deep-water layers (Fig.). This method has all the advantages of the method described above, yet, as it allows one to maintain thermal stratification, there is no threat of increased internal supply. The method may be applied if the depth of hypolimnion exceeds 10 m, and the proportion of epilimnion to hypolimnion capacity is lower than 2. It is widely and successfully applied throughout the world. In Poland, the lack of positive effects results from using inappropriate equipment and insufficient supervision.

Elimination of phosphorus from tributaries by means of precipitation, flocculation and filtration
[Bernhardt and Schell 1982, Hino 1994]

This method, often called the Wahnbach system, was used for the reclamation of the Wahnbach reservoir. It may be used in reservoirs which have one or two tributaries. The method involves the elimination of phosphorus from the whole capacity of flowing water by means of precipitation, flocculation and filtration. It requires building a plant similar to a water-treatment plant, which only uses physicochemical and chemical purification processes. It is very efficient, but at the same time extremely time- and labour-consuming. The system enables a reduction in the concentration of phosphorus to 5 $\mu g \cdot dm^{-3}$. In contrast with biological methods, the phosphorus elimination amounts to ca. 99%, regardless of temperature and light.

Lime treatment
[Murphy et al. 1988, Babin et al. 1989, Perrow and Davy 2002, SWCSMH 2006]

This method consists in adding calcium hydroxide or calcium carbonate to the reservoir and in precipitating phosphate into hydroxyapatite, an insoluble Ca-PO_4 complex (Fig.).

Dosage has to be repeated through several years, otherwise phosphorus and calcium will dissolve and will not create apatite.

The reaction which takes place when adding calcium carbonate is as follows [Perrow and Davy 2002]:

$$10CaCO_3 + 6HPO_4^{2-} + 2H_2O \rightarrow Ca_{10}(PO_4)_6(OH)_2 + 10HCO_3^-$$

Other methods for phosphorus precipitation: aluminium treatment and iron addition

[OECD 1982, Olem and Flock 1990, Szyper and Gołdyn 2000, Perrow and Davy 2002, SWCSMH 2006]

Apart from calcium, also aluminium and iron may, in specific conditions, create insoluble compounds with phosphorus. In the water body, phosphorus precipitates in reaction with iron salt, calcium hydroxide and aluminium sulphate.

Sample reactions which take place during the formation of iron phosphate with the use of iron chloride are shown below [Perrow and Davy 2002]:

1.	Hydrolysis	$FeCl_3 + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ + 3Cl^-$
2.	Dewatering	$Fe(OH)_3 \rightarrow FeO(OH) + H_2O$
3a.	Formation of iron phosphate	$FeO(OH) + H_3PO_4 \rightarrow FePO_4 + 2H_2O$
3b.	Adsorption to iron oxide-hydroxide	$FeO(OH) + PO_4^{3-} \rightarrow FeO(OH) \sim PO_4^{3-}(aq)$

As a result of the reactions, hydrogen sulphide is also eliminated:

$$2FeO(OH) + 3H_2S \rightarrow 2FeS + S^0 + 4H_20$$

In order to neutralise the low alkalinity resulting from the reactions, compounds which contain calcium hydroxide or calcium carbonate are added at the same time:

$$6H^+ + 3CaCO_3 \rightarrow 3CO_2 + 3H_2O + 3Ca^{2+}$$

As a result of using iron chloride, phosphorus is bound in two ways: part of the phosphorus is bound and iron sulphate precipitates, the other part drowns with the flocs as a result of flocculation, and is also withdrawn from circulation. The mechanism is similar if aluminium sulphate is used, but the flocculation of organic particles is more efficient, as flocs of the ($Al(OH)_3$) complex create traps for algae and other particulate matter.

The added compounds are distributed in a solid state on ice, sprinkled on the surface of water, or served in the form of solution. Aluminium is used most commonly, as phosphorus binds with it firmly, regardless of the conditions. The emerging salt is stable even at a very low level of dissolved oxygen. During the serving, phosphorus is initially withdrawn from the water body, then the emerging flocs sink and settle on the bottom, covering it with a ca. 5 cm deep layer, reacting with the phosphorus aggregated in the sediment. So, both the phosphorus withdrawn from the water body and the phosphorus which previously accumulated in the sediment are inactivated. The method is particularly efficient in stratified lakes and may be successfully used in small reservoirs and ponds. However, if they are exposed to waving and the resulting re-suspension of nutrients from the sediment, the method may be less efficient. It is not recommended for large reservoirs. Aluminium salt dissolves in acid and alkaline water, demonstrating toxic qualities, iron salt may be used in shallow, non-stratified or oxygenated reservoirs. In anaerobic conditions, iron is subject to reduction and phosphorus is released. Calcium hydroxide causes an excessive increase in pH values, which limits its applicability to acid lakes or deep aerated reservoirs.

Some of the less often applied methods are: harvesting of macrophytes [Cooke et al. 1986, Kajak 1998, SWCSMH 2006], crop of fish and seston [Kajak 1998], addition of algicides [Kajak 1998, SWCSMH 2006], dilution of waters and flushing reservoirs [Welch 1981, Kajak 1998, Lossow 1998, Perrow and Davy 2002, SWCSMH 2006], restoration by circular canalisation [OECD 1982, Lossow 1998, SWCSMH 2006].

The evaluation of the efficiency of selected methods, shown in Table 2, would be very helpful in selecting the appropriate method.

Table 2. Evaluation of efficiency for selected methods of reclamation of water reservoirs [SWCSMH 2006]
Tabela 2. Ocena skuteczności wybranych metod rekultywacji jezior i zbiorników wodnych [SWCSMH 2006]

Method – Metoda	Effectiveness Efektywność	Longevity Efekt długoterminowy	Confidence Pewność	Applicability Łatwość zastosowania	Potential negative impacts Potencjalne skutki ujemne	Capital cost Koszty inwestycji	O & M cost Koszty utrzymania
Aluminium treatment to precipitate and inactivate phosphorus Strącanie fosforu związkami glinu	E	G	G	E	F-G	G	G
Dredging of whole lake Usuwanie osadów dennych – bagrowanie całego zbiornika	P	E	E	P	F-G	P	E
Dredging of lake inlet areas Usuwanie osadów dennych – bagrowanie zatok zbiornika	E	E	E	E	G	P	E
Dilution Rozcieńczanie wód	F	F	F	P	F	P	P
Flushing/Artificial circulation Przepłukiwanie/Napowietrzanie wód hypolimnionu z zaburzeniem uwarstwienia termicznego	F	F	P	F	F	P	F-P
Hypolimnetic aeration Napowietrzanie wód hypolimnionu z zachowaniem uwarstwienia termicznego	F	F	F	F	F	P	F-P

Table 2 cont. – Tabela 2 cd.

Method – Metoda	Effectiveness Efektywność	Longevity Efekt długoterminowy	Confidence Pewność	Applicability Łatwość zastosowania	Potential negative impacts Potencjalne skutki ujemne	Capital cost Koszty inwestycji	O & M cost Koszty utrzymania
Sediment oxidation Utlenianie osadów dennych	G	G	P	F	G	F	G
Addition of algicides Zastosowanie algicydów	G	P	E	F	P	G	P
Food chain manipulation Biomanipulacja	G	U	P	F	U	E	E
Hypolimnetic withdrawal Usuwanie wód hypolimnionu	G	G	G	G	F-P	G	E
Water level drawdown to remove weeds Obniżanie poziomu piętrzenia w celu eliminacji makrofitów	F	F	F	P	F-P	F	G
Weed harvesting Wykaszanie makrofitów	G	P	G	G	F	F	P
Biological controls to reduce weeds Bilogiczne metody ograniczania rozwoju makrofitów	G	G	F	G	F-P	G	G
Addition of herbicides Zastosowanie herbicydów	G	P	G	F	P	G	P

E – excellent − bardzo dobry, G – good − dobry, F – fair − zadowalający, P – poor − słaby, U – unknown − nieznany

EXAMPLES OF APPLICATION OF RECLAMATION METHODS TO LAKES AND WATER RESERVOIRS IN POLAND AND ABROAD

Water reservoirs in Poland and other countries have been reclaimed for several decades. During those years, numerous new methods were developed, and the old ones were modified. They were applied to many reservoirs in the world (Table 3).

Polish experience with the reclamation of lakes, however, was not good as the effectiveness of the actions taken was rather low (Table 4). Most of the lakes were reclaimed by means of the hypolimnetic aeration method without disturbing the temperature, which proved unsuccessful. Some optimistic aspect here might be the research results concerning Lake Wolsztyńskie [Sprawozdanie… 2005], as well as Lake Długie and Lake Głęboczek where positive results were observed after applying the phosphorus precipitation method with PAX coagulants (based on aluminium) and/or PiX (based on trivalent iron) [Gawrońska and Lossow 2003]. However, the latter method, applied after 2000, still requires further research in order to evaluate long-term reclamation trends.

Some works of Danish and Dutch researchers [Søndergaard et al. 2007] present the experiments in Denmark and the Netherlands related to the reclamation of lakes. Most of those lakes are reclaimed with the use of the biomanipulation method. Long-term research shows that the Secchi depth increased by more than 50% in 14 of 20 lakes, Chla (chlorophyll a) decreased in 8 of 21 lakes, total nitrogen remained unchanged in 16 lakes and decreased in 5 lakes, and total phosphorus remained unchanged in 15 lakes, decreased in 5 lakes, and increased in 1 lake out of 21 lakes.

Table 3. Some examples of reclamation of lakes and water reservoirs in the world [SWCSMH 2006]
Tabela 3. Wybrane przykłady rekultywacji jezior i zbiorników wodnych na świecie [SWCSMH 2006]

Name of reservoir/lake Nazwa zbiornika/jeziora	Method − Metoda
Arbuckle & Ham's Lakes (Oklahoma, USA), Larson & Mirror Lakes (Wisconsin, USA), Klopeiner See, Kraiger See, Piburger See, Worthersee, Ossiacher See, Millstädter See, Weieusee (Austria)	Aeration/Destratification Napowietrzanie wód hypolimnionu
Bautzen reservoir (Germany), Lake Trummen, Lake Bysjön, Lilla Stockelidsvatten (Sweden)	Biomanipulation Biomanipulacja
Cox Hollow Lake, Marion Millpond (Wisconsin, USA)	Covering bottom sediments Przykrywanie osadów dennych
Green & Moses Lakes (Washington, USA), Snake Lake (Wisconsin, USA)	Dilution/Flushing Rozcieńczanie/Przepłukiwanie
Laguna Lake (Philippines), Lake Sallie (Minnesota, USA)	Harvesting of macrophytes Wykaszanie makrofitów
Precambrian lake (Canada)	Hypolimnetic injection of nutrient effluents Iniekcja biogenów do hypolimnionu
Lake Apopka (Florida, USA)	Lake drawdown Obniżanie poziomu piętrzenia

Table 3 cont. – Tabela 3 cd.

Name of reservoir/lake Nazwa zbiornika/jeziora	Method − Metoda
Beerenplaat (Netherlands), East Twin & West Twin Lakes (Ohio, USA), Horseshoe Lake (Wisconsin, USA), Medical Lake (Washington, USA), Stony Lake (Michigan, USA), Lake Jabel, Suesser See, Talsperre, Haltern, Tegeler See, Wahnbachtalsperre (Germany)	Nutrient inactivation Inaktywacja biogenów
Beverinsee (Germany), Lilly Lake (Wisconsin, USA), Lake Herman (South Dakota, USA), Lake Trehörningen, Lake Trummen (Sweden), Steinmetz Lake (New York, USA), Lake Stubenberg (Austria)	Sediment removal (dredging) Usuwanie osadów dennych (bagrowanie)
Wahnbach reservoir (Germany)	Phosphorus removal at river mouth (pre-reservoirs) Eliminacja fosforu z dopływów (zbiorniki wstępne)
Lake Fuschl, Lake Ossiacher, Worthersee, Ossiacher See, Millstadter See, Weiensee (Austria), Lake Gjersjoen (Norway), Kerspetalsperre, Schliersee, Tegernsee, Stechlinsee (Germany), Lower Madison Lakes, Lake Waubesa, Lake Wegonsa (Wisconsin, USA), Lake McIlwaine (Zimbabwe), Lake Minnetonka (Minnesota, USA), Lake Norrviken (Sweden), Lake Sammamish, Lake Washington (Washington, USA), Lake Vesijarn (Finland)	Wastewater diversion/Seepage trenches Kanalizacja opaskowa/Zbiorniki infiltracyjne
Lake Asvalltjarn, Lake Boren, Lake Ekoln, Görväln Bay, Lake Ringsjön, Stockholm Archipelago, Lake Vättern (Sweden), Lake Burrinjuck (Australia), Lake Constance, Greifensee (Germany), Finger Lakes, Lower St. Regis (New York, USA), Gravenhurst Bay, Kootenay Lake, Little Otter Lake (Canada), Haley Pond (USA), Lake Mjösa (Norway), Saginaw Bay (Michigan, USA), Shagawa Lake (Minnesota, USA), Walensee, Zurichsee (Switzerland)	Wastewater treatment for phosphorus removal (including phosphate detergent restrictions) Oczyszczanie ścieków w celu usunięcia fosforu (z ograniczeniem związków fosforu w detergentach)
Lake Balaton (Austria & Hungary), North American Great Lakes (USA & Canada)	Multiple control measures Metody złożone

Table 4. Some examples of reclamation of Polish lakes with evaluation of efficiency of measures [Lossow 1994]
Tabela 4. Wybrane przykłady rekultywacji jezior w Polsce z określeniem skuteczności podjętych działań [Lossow 1994]

Name of lake Nazwa jeziora	Method used Zastosowana metoda	Results Rezultaty
Lake Mutek near Reszel Jezioro Mutek k. Reszla	Artificial circulation Napowietrzanie wód hypolimnionu z zaburzeniem uwarstwienia termicznego	No effect Brak efektów
Lake Długie in Olsztyn Jezioro Długie w Olsztynie		Positive effect was noticed Zanotowano pozytywne efekty
Lake Starodworskie in Olsztyn Jezioro Starodworskie w Olsztynie		
Lake Miłki near Giżycko Jezioro Miłki k. Giżycka	Hypolimnetic aeration Napowietrzanie wód hypolimnionu z zachowaniem uwarstwienia termicznego	No effect Brak efektów
Lake Kierskie in Poznań Jezioro Kierskie w Poznaniu		
Lake Jaroszewskie near Sieraków Jezioro Jaroszewskie k. Sierakowa		
Lake Zamkowe near Wałcz Jezioro Zamkowe k. Wałcza		
Lake Lidzbarskie near Lidzbark Welski Jezioro Lidzbarskie k. Lidzbarka Welskiego		
Lake Klasztorne Małe in Kartuzy Jezioro Klasztorne Małe w Kartuzach		
Lake Starodworskie in Olsztyn Jezioro Starodworskie w Olsztynie		Positive effects stopped after aeration was discontinued Pozytywne efekty ustąpiły po zaprzestaniu napowietrzania
Lake Kortowskie in Olsztyn Jezioro Kortowskie w Olsztynie	Hypolimnetic withdrawal Usuwanie wód hypolimnionu	Positive effect was noticed Zanotowano pozytywne efekty
Lake Rudnickie Wielkie in Grudziądz Jezioro Rudnickie Wielkie w Grudziądzu		
Lake Mogileńskie in Mogilno Jezioro Mogileńskie w Mogilnie	Sediment removal Usunięcie osadów dennych	

CONCLUSION

Numerous lakes and water reservoirs in the USA, Europe and Scandinavia [Perrow and Davy 2002, O'Sullivan and Reynolds 2005] have undergone successful reclamation. One has to remember though that reclamation is an ultimate, difficult, risky and cost-consuming solution and the reclamation activities should be preceded by a number of protective activities in the catchment area. Conclusions must be drawn from the experience gained, and, first of all, technical reclamation should be applied very carefully as an ultimate solution.

In Poland, a growth in the number of reclaimed lakes and water reservoirs took place only in the 1980s. Unfortunately, in most cases no positive effects were achieved, mostly as a result of design errors, the use of inappropriate equipment and the lack of due supervision and maintenance [Kajak 1998]. Spectacular and cost-consuming reclamation measures were often adopted without previously limiting the inflow of nutrients to the reservoir or implementing protective measures in the catchment area. Unfortunately, most projects of technical reclamation (mainly of lakes), described in Polish literature, failed to improve water quality. The most often applied methods were those connected with water aeration [Lossow 1994].

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METODY REKULTYWACJI ZBIORNIKÓW WODNYCH

Streszczenie. W artykule omówiono najczęściej stosowane metody rekultywacji zbiorników wodnych. Dokonano przeglądu najważniejszych publikacji naukowych z ostatnich lat, przedstawiono rys historyczny podjętego problemu oraz podano przykłady zastosowania poszczególnych metod w praktyce. Szczegółowo scharakteryzowano metody rekultywacji zbiorników wodnych, biorąc pod uwagę ogólne założenia, możliwości zastosowania, efektywność i koszty. Rekultywację należy traktować jako rozwiązanie ostateczne, stosowane wówczas, gdy wcześniejsze działania ochronne w zlewni nie przyniosły pożądanego skutku. W przypadku niektórych silnie zeutrofizowanych zbiorników jej przeprowadzenie jest niezbędne w celu uzyskania poprawy jakości wody. Działania rekultywacyjne powinny zawsze być poprzedzone szczegółowym interdyscyplinarnym rozpoznaniem zlewni oraz samego zbiornika.

Słowa kluczowe: rekultywacja zbiorników wodnych, ochrona wód powierzchniowych

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