Treatment Wetlands in Natural Swimming Ponds

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Natural swimming ponds using treatment wetlands (TWs) as an element of treatment of swimming water are an ecologically beneficial alternative to conventional pools. Unlike conventional swimming pools, in natural swimming ponds, the water treatment avoids the use of chemical methods and is based on the phenomenon of water self-purification and the rhizofiltration capacity of repository macrophytes in TWs of the regeneration zone, as well as on typical physical filtering processes (e.g., straining, sedimentation, or flotation), physicochemical filtration (physical and chemical adsorption, mainly of phosphorus), and biological filtration (nitrification and denitrification).

Keywords: swimming ponds ; wetland system ; nature pool ; filtration chamber

1. Structure and Function of a Natural Swimming Pond as a Treatment Wetlands (TWs) Application

The simplest construction of a natural swimming pond is shown in **Figure 1**.

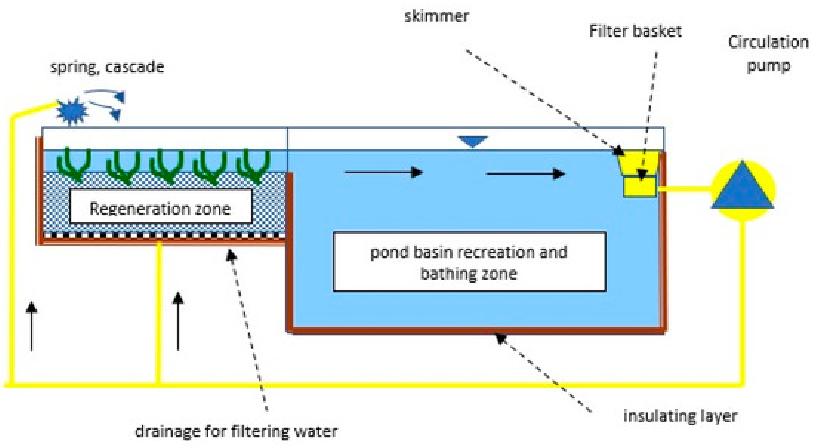

Figure 1. Major components of a natural swimming pond.

The simplest model of a natural swimming pond consists of a pond basin filled with water, lined with highly durable hydro-insulating polyvinyl chloride (PCV), a geomembrane (EPDM), or other impermeable materials (clay or bentonite mats). The use of an impermeable liner is meant to hold water and reduce contamination originating in the soil [1]. The finish of the basin varies, comprising stone slabs, 10–15 cm of fine and coarse gravel, stones, or even swimming pool tiles, depending on the design.

In functional terms, a natural swimming pond is divided into two zones: the shallow regeneration zone, functioning as a treatment wetland (TW), planted with aquatic vegetation, which helps to heat the water quickly and to successfully filter the water and sediment; and the deep recreation and bathing zone, which is intended for use [2][3][4].

The regeneration zone consists of a substrate composed of appropriate minerals (the filter), with a drain in the lower part that distributes the filtered water and appropriately selected plants growing in the upper part. The entirety is filled with water, which shares its surface with the bathing part of the pond. The circulation pump and filter are protected by a surface skimmer with a sieve that collects floating impurities, from which the pump draws water and pumps it to the drain under the filter. Some of this water can be pumped sideways over the filter where it sprinkles it, providing additional oxygenation. The water flows upwards from the drain to the surface and flows on to the bathing zone. The filter bed layer with plants functions as a plant filter, which traps organic biogenic substances and makes it a TW solution, as a planted vertical flow filter and FWS wetland.

The efficiency of plants in this filtration process is directly proportional to their biomass (ability to accumulate biogenic elements) and phenology (period of immobilization of biogenic elements). The plant biomass accumulates in the edge zone and can be removed by mowing, although the accumulation of plant biomass in the humification process in the form of fen peat has no negative effect on water quality [5]. The phytosanitary role of the regeneration zone is very important as well. The removal of microbial pathogens is based here on complex mechanisms—physical (sedimentation, adsorption, and filtration), chemical (oxidation, UV radiation, exposure to plant biocides, unfavourable water chemistry, or adsorption to organic matter and biofilm), and biological (predation, biological decomposition, antibiosis, or natural death)—often acting in combination [6][7][8]. The effectiveness of these mechanisms, therefore, depends on the synergistic effect of natural (environmental) and technical (design and operational) features, which act on different pathogenic microbes in different ways [9][10]. Similarly, TWs in the regeneration zone, depending on their construction, may take part in the removal of micropollutants, including substances originating in synthetic products and human activity, which are present in very low concentrations in the environment (parts per billion (ppb) and lower). They include pharmaceuticals and personal care products (PPCPs), pesticides, industrial chemicals, endocrine-disrupting chemicals (EDCs) (including hormones), and nanomaterials [6][11][12]. The mechanisms involved in the removal of micropollutants from an inflowing TW include microbial transformation, uptake, and metabolism by plants; adsorption onto biofilms or the substrate; volatilization; abiotic degradation, including hydrolysis or photocatalytic oxidation; and other advanced reduction or oxidation reactions [13].

It is worth noting that macrophytes of the regeneration zone, depending on their species composition and life form, are also able to accumulate heavy metals, forming a biogeochemical barrier [14]. This is particularly important when filtration of pond water involves the use of components containing copper or silver (electrodes or UV filters), which can lead to the biomagnification of these elements in the food webs of the pond [15] and pose a long-term risk for the effectiveness of TWs [16]. Plant and animal periphyton communities and bacterial biofilms are also extremely important in this zone. They grow on plants themselves as well as the porous substrate they are found in (lava, sand, or gravel) and supplement filtration in this zone, improving its efficiency, particularly in the removal of the phosphorus fraction [17].

The bathing and recreation zone is much deeper than the regeneration zone, and its depth varies. Bottom sediment accumulates here and must be removed regularly. Sometimes, if the slope of the bottom is adequate and bottom outflow is used, the sediment can be transported to the sewage system or a sediment well [2][18].

The bathing zone and TW (regeneration) zone can be separated, either completely, using wood or stone, or through a succession of changes in the ground level. These zones can also be located in completely different parts of the recreational area, in accordance with the assumptions of the landscape architect [19].

The most important assumption for the functioning of this type of pond is the complete abandonment of the use of the chemicals used in many places for water treatment. This means that the water treatment is based on self-purification of the water. This is a positive physical and biochemical phenomenon of varying intensity levels, involving the sedimentation of suspended solids and mineralization of organic compounds, followed by the uptake of the material by plants and its incorporation into their own structure [20][21][22]. Therefore, it is the basis of the functioning of TWs. In this process, the physical, chemical, and biological factors are interdependent. The physical factors include the shape of the pond basin, water density and temperature, water flow rate (usually technologically induced by a pump), and water flow turbulence (in the case of a pond combined with a waterfall). The chemical factors include the contents of CO_2 and O_2. The biological factors include plants and animals living in the pond, which take up organic pollutants, break them down into simple compounds, and secrete them in this form into the water [5][20][22].

Most of the mechanical treatment takes place in the porous layer of the substrate filling the regeneration zone, to which water from the pond is pumped from above by the circulation pump [23]. Processes such as straining, sedimentation, flotation, and filtration take place within the bed [24][25]. The end result of the filtration process, therefore, depends on the quality of the water entering the filter, the type of filter material, the grain size and height of the bed layer, the type of filter, and the flow rate through the bed. Biological water treatment technologies exploit the activity of living organisms in an artificially created environment within the biological beds of a filtration chamber (separate or part of a modular system) or accompany mechanical filtration in a water treatment system. The purification processes taking place here are identical to those in a natural water body, i.e., transformations of nitrogen compounds by nitrifying and denitrifying microorganisms on a biological bed [26].

A mixed community of microorganisms (nitrifying and denitrifying) with high purifying capacity is formed along the path of the water flow through the filtration material, forming a biofilm [27]. Organic compounds entering the biological membrane by diffusion are retained there and then mineralized by biochemical decomposition. Oxygen access in the bed is ensured by a natural air draught through the structures of the filter media [28]. An element commonly used to stabilize the most important parameters of the water of natural ponds, which is crucial to the proper functioning of biological filters, is CO_2 dispensers. They monitor the pH of the water and keep it at an appropriate level, applying carbon dioxide as needed to raise the carbonate hardness (KH) of the water, which performs the functions of a buffer. The artificial enrichment of the water with CO_2 is aimed at increasing its free reserves, which also ensures stable conditions for the development of aquatic repository plants. In this case, unwanted algae are less likely to take over the pond [29].

Bacteria, fungi, protozoa, algae, macrophytes, and animals take part in the aerobic decomposition of organic matter, in accordance with the functionality of the food web of the pond [20], and form the basis of the functioning of TWs [6]. Bacteria can utilize organic matter in the form of dissolved matter—even at very small concentrations—directly in cellular respiration, or in the form of particulate matter, secreting exoenzymes that decompose particles of matter into more easily absorbed forms [30]. Fungi, as heterotrophic organisms, play a similar role to that of bacteria. They take part in the biological decomposition (aerobic and anaerobic) of organic matter of plant and animal origins. They introduce some elements (taken up from decomposition of dead organic matter) into circulation in nature [31]. Protozoa in the aquatic environment utilize biomass accumulated in bacteria and fungi and take up organic substances in colloid form, and their species composition and abundance are closely correlated to the abundance of bacteria [20][32]. Algae (flagellates, cyanobacteria, diatoms, Zygnematophyceae, and green algae) take up carbon compounds and organic nitrogen from dissolved organic compounds. They also transform fatty acids, amino acids, urea, and peptones. They produce various photosynthetic pigments, with algae containing chlorophyll and producing oxygen as a result of CO_2 assimilation playing a particularly important role. They are food for many animals, protozoa, rotifers, molluscs, flatworms, roundworms, and larvae of aquatic insects. Their metabolism often involves the secretion of strong toxins that synergize in the water. This is particularly important in the case of a sharp increase in the biomass of algae making up the phytoplankton, causing algal bloom—a dangerous phenomenon often resulting in the intoxication of water bodies [5][20][33]. It is determined by high contents of biogenic substances, i.e., phosphorus and nitrogen fractions, causing excessive eutrophication of the water body [14][20][34].

Higher aquatic plants, both emergent and submerged (e.g., water hyacinth, common reed, rushes, or irises), function as filters. They take up vast amounts of mineral salts from the water. Of particular importance are repository plants, i.e., those that retain large amounts of nutrients in their tissues, especially phosphorus. In this way they compete with phytoplankton and filamentous algae, which makes them a factor stabilizing the ecosystem of the natural swimming pond. Well-developed populations of watermilfoil and pondweed species limit the occurrence of algal bloom threatening the ecosystem of natural ponds [6]. The intensity of the water purification process is also influenced by the effect of the rhizosphere used to remove or detoxify contaminants (rhizodegradation). This is a set of phenomena occurring in the root zone of macrophytes, manifested as increased quantity and activity of soil organisms, which facilitates the transfer of nutrients from the soil to plants.

Nutrient uptake by plants is determined by biophysicochemical processes taking place between plant root systems and the soil. These involve the secretion of carbon dioxide and organic acids by the roots, and also the supply of dying tissues, which increases the solubility of various soil substances and results in the development of soil microbes [5]. Aquatic plants additionally help to maintain oxygenating conditions around their root zones; this is particularly important on flooded filters, which are permanently filled with water [6]. Bacteria living in the vicinity of roots play the main role in the decomposition of organic compounds, and plant root secretions influence the species composition of the rhizosphere. Rhizofiltration as an element of phytoremediation is, therefore, one of the most effective means of water self-purification in the natural conditions of open water bodies [5][35]. Plants on filters also shade and cool the water. Shade minimizes the spread of filamentous algae in shallow water, because filamentous algae compete with aquatic plants not only for nutrients but for light as well. Their metabolic activity associated with photosynthesis also leads to a temporary increase in the concentration of oxygen in a given area, which enables the aerobic decomposition of organic matter and limits the metabolic intoxication of the water body (anaerobic decomposition entails the formation of compounds harmful to ecosystems, such as indole, skatole, and mercaptans). Macrophytes also provide mechanical protection for shore areas, which prevents turbidity caused by sediment stirred up by water movement. They are also habitats for a large number of aquatic invertebrates and amphibians. Helophytes with strong root or rhizome growth, e.g., of the genus *Carex*, *Juncus*, *Schoenoplectus*, *Bolboschoenus,* or *Cyperus*, are often used in such zones [6]. Submerged macrophytes are also habitats for the development of many species of zooplankton (protozoa, rotifers, microscopic crustaceans, and insect larvae), which through trophic relationships act as biological regulators of the abundance of phytoplankton (algae and cyanobacteria). This relationship is exploited for the application of natural methods of aquatic ecosystem regulation based on biomanipulation (effect on the abundance of a specific element in the food chain).

In the case of natural swimming ponds, the aim of biological regulation is to find a quantitative biocoenotic balance between the phytoplankton and the zooplankton grazing on it based on the functional traits of food webs. It should be noted, however, that a greater abundance of zooplankton does not always cause a reduction in the amount of phytoplankton. This may be due to the various feeding characteristics of zooplankton, including their moderate consumption, which stimulates the development of phytoplankton; the selective grazing of edible forms of phytoplankton, allowing inedible forms to replicate; the metabolic secretion of phosphorus and nitrogen; or the accumulation of biogenic compounds by some forms of phytoplankton when they pass through the digestive tracts of consumers. The use of zooplankton to limit the amount of phytoplankton is, therefore, very difficult to regulate, and at the same time demonstrates the vast complexity of the various relationships in aquatic ecosystems [20][36].

The conditions of plant life in natural swimming ponds are very similar to those in natural sites. The choice of suitable plants is, therefore, based on the Ellenberg indicator, defining the preferences of individual plant species with regard to the most important environmental factors [37], determined by the design specifications of the pond. Therefore, it should be remembered that well-chosen, often native plant species in the regeneration zone based on TW solutions (**Figure 2**) help to keep the biophysicochemical parameters of the water at appropriate levels; eliminate or inactivate excess biogenic substances; limit the excessive development of harmful algae and cyanobacteria; destroy dangerous bacteria of the genera *Salmonella*, *Escherichia coli*, *Enterococcus,* and *Pseudomonas aeruginosa*; remove toxic compounds, nitrates, heavy metals, phenols, and cyanides from the water; protect the edges of the water body; and create optimal conditions for the development of aquatic fauna [38].

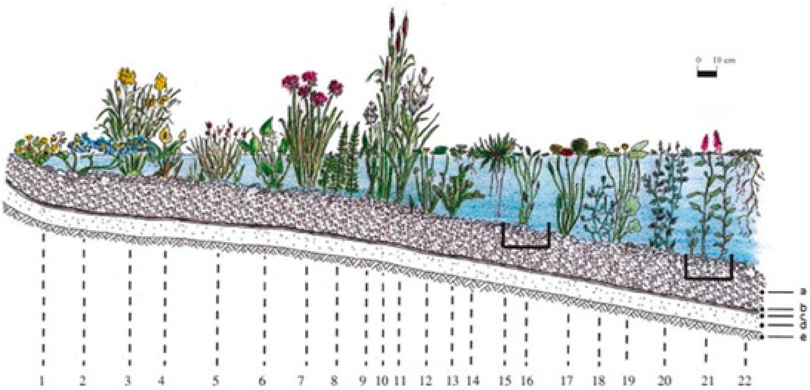

Figure 2. Regeneration zone of a swimming pond with examples of macrophytes ([5], modified): 1—*Caltha palustris*; 2—*Myosotis palustris*; 3—*Iris pseudoacorus*; 4—*Calla palustris*; 5—*Juncus* sp.; 6—*Alisma plantago—aquatica*; 7—*Butomus umbellatus*; 8—*Hippuris vulgaris*; 9—*Sagittaria sagittifolia*; 10—*Typha angustifolia*; 11—*Sparganium erectum*; 12—*Nymphoides peltata*; 13—*Ceratophyllum demersum*; 14—*Hydrocharis morus-ranae*; 15—*Stratiotes aloides*; 16—*Aponogeton distachyos* *; 17—*Nymphaea alba*; 18—*Elodea canadensis*; 19—*Nuphar lutea*; 20—*Potamogeton natans*; 21—*Pontaderia cordata* *; 22—*Trapa natans*. Note: * alien species requiring storage in winter (other species are native); a—gravel; b—PCV film; c—geotextile, d—sand, e—natural ground.

The phenomenon of water self-purification taking place in the regeneration zone of a pond with TW functions sometimes must be supported by the use of filtration systems complementing biological processes. The solutions applied here include cascades and fountains, water pumps, aerators, and carbon dioxide dispensers, or a combination of physical mechanical, mineral, and biological filtrations chambers, which maintain appropriate water quality in swimming ponds.

Therefore, bathing ponds function as quasi-natural systems based on natural processes linking the issues of the biotope and biocoenosis in the pond ecosystem. Therefore, there are no systemated methods to improve the efficiency of such a system. Ad hoc remedial actions are associated with the permanent monitoring of the biological state of the phytocenosis of the regeneration zone and the organoleptic and physicochemical parameters of the bathing water. In the absence of water treatment effects, it is recommended to replace plant species, change the proportions of individual subzones, and supplement natural water treatment methods with various technological solutions (filtration). The effectiveness of their operation is determined on the basis of the quality indices of the treated water before and after the filtration process, and on the basis of the rate of growth of bed pressure losses and the bed’s absorptive capacity. The entire biotechnological system of the water purification process is, therefore, adjusted in terms of efficiency to the needs of the investment and is subject to ongoing control, maintenance, and modification.

2. Modifications of Solutions for the Construction and Operation of Swimming Ponds

There are several criteria for classifying quasi-natural swimming ponds. In terms of the intensity of their use for bathing, the following types are distinguished:

- Extensive ponds, usually with 30% of the area designated for free swimming and 70% as a plant (regeneration) zone. Water circulation between these zones takes place owing to natural physical processes, namely different wind strengths and differences in temperature between the warmed shallow zones and the deeper, colder part of the pond. Ponds of this type are fully reminiscent of a natural environment;
- Intensive ponds, where the regeneration zone can be much smaller in relation to the recreation zone, as water circulation is forced by a pump and sometimes by more complicated water filtration systems. These include the use of various types of filters in various functional combinations, in some cases with additional equipment [39].

On the basis of the type of water treatment technology used, five types of natural swimming ponds are distinguished.

Type 1—Technology-free ponds, the simplest type, with no additional technology, natural water circulation, a recommended size of at least 120 m^2, and a minimum 7:3 ratio of regeneration zone to recreation zone (**Figure 3**).

Figure 3. Diagram of the operation of an extensive swimming pond (type 1).

Type 2—Hydro-botanical ponds, without filter beds. In this case the water flow is forced by circulation pumps, which draw water from one part of the pond using a skimmer and pump it to the opposite part, where a shallow layer of water is overgrown with plants. In addition, a pipeline is installed for the suction of water from the lowest point of the bottom of the recreation zone to remove sediment from the bottom. The recommended size for these ponds is at least 120 m^2, with a minimum 1:1 ratio of the regeneration zone to bathing zone (**Figure 4** and **Figure 5**).

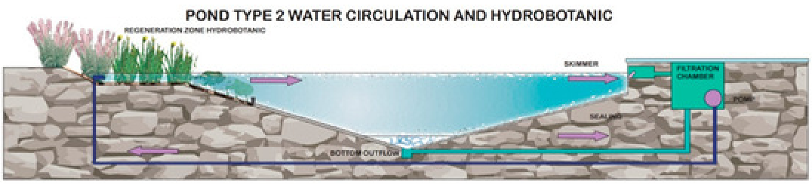

Figure 4. Diagram of the operation of a hydro-botanical swimming pond (type 2).

Figure 5. A hydro-botanical swimming pond (photo by W. Walczak).

Type 3—Hydro-botanical ponds with a filter filled with a mineral medium and other filtration systems. The pond is equipped like a type 2 pond with an additional filter filled with a mineral medium and planted plants. Owing to the use of filtration with a slow water flow (3–5 m^3/m^2/day), the regeneration zone can be smaller. In this way, natural water self-purification processes are intensified, maintaining the high efficiency of the system in the long term. To maintain adequate water quality, additional devices are used as needed, such as pool robots, bottom drains, surface skimmers, or carbon dioxide dispensers. The area should be at least 80 m^2, with a minimum 2:3 ratio of the regeneration zone to bathing zone (**Figure 6**).

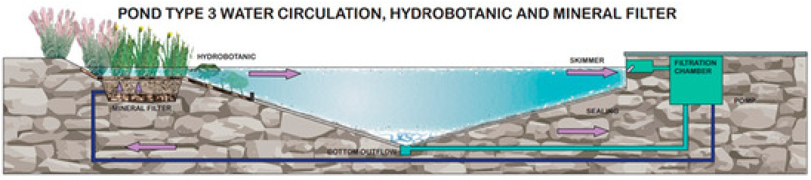

Figure 6. Diagram of the operation of a hydro-botanical swimming pond with a mineral filter (type 3).

Type 4—A pond type with rapid water flow in a filter with a mineral medium. These ponds can look similar to traditional pools, with a completely or partly separated regeneration part. They have a separate filter installed with a suitably chosen medium and a high flow rate (from 15 m^3/day). The role of the regeneration zone is still important, although less so than in the pond types described above. The conservation and care processes are often automated, and the recommended pond size is from 50 m^2 (**Figure 7** and **Figure 8**).

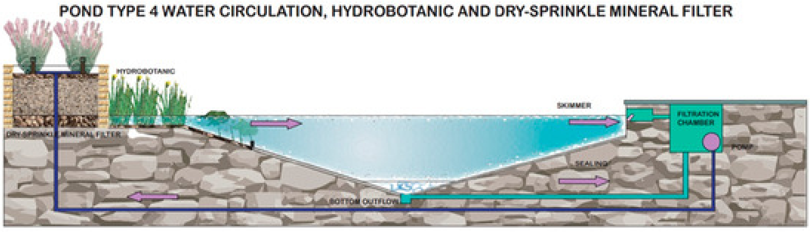

Figure 7. Diagram of the operation of a hydro-botanical swimming pond with accelerated mineral filtration (type 4).

Figure 8. Swimming pond with a regeneration zone and accelerated mineral filtration (photo by W. Walczak).

Type 5—A pond type with advanced technology, including combined water purification technologies. These are technologically complicated and require considerable financial outlays. The regeneration zone is entirely separate from the bathing zone and makes up only 25% of the area of the pond, or in some cases there is no regeneration zone at all. Therefore, plants do not play a major role in water filtration, but an increased number of other water treatment devices compensate for the absence of plants. The water is treated technologically using drum filters, modular filters, and bioreactors. This requires a large amount of energy, and the conservation and care processes are fully automated (**Figure 9**) [29].

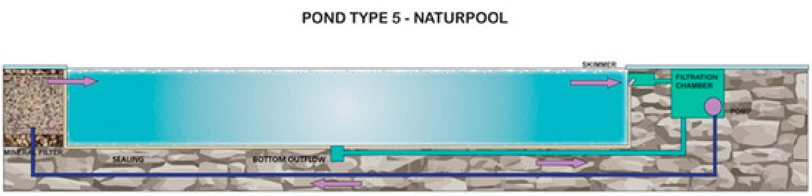

Figure 9. Diagram of the operation of a swimming pond with no regeneration zone (type 5).

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