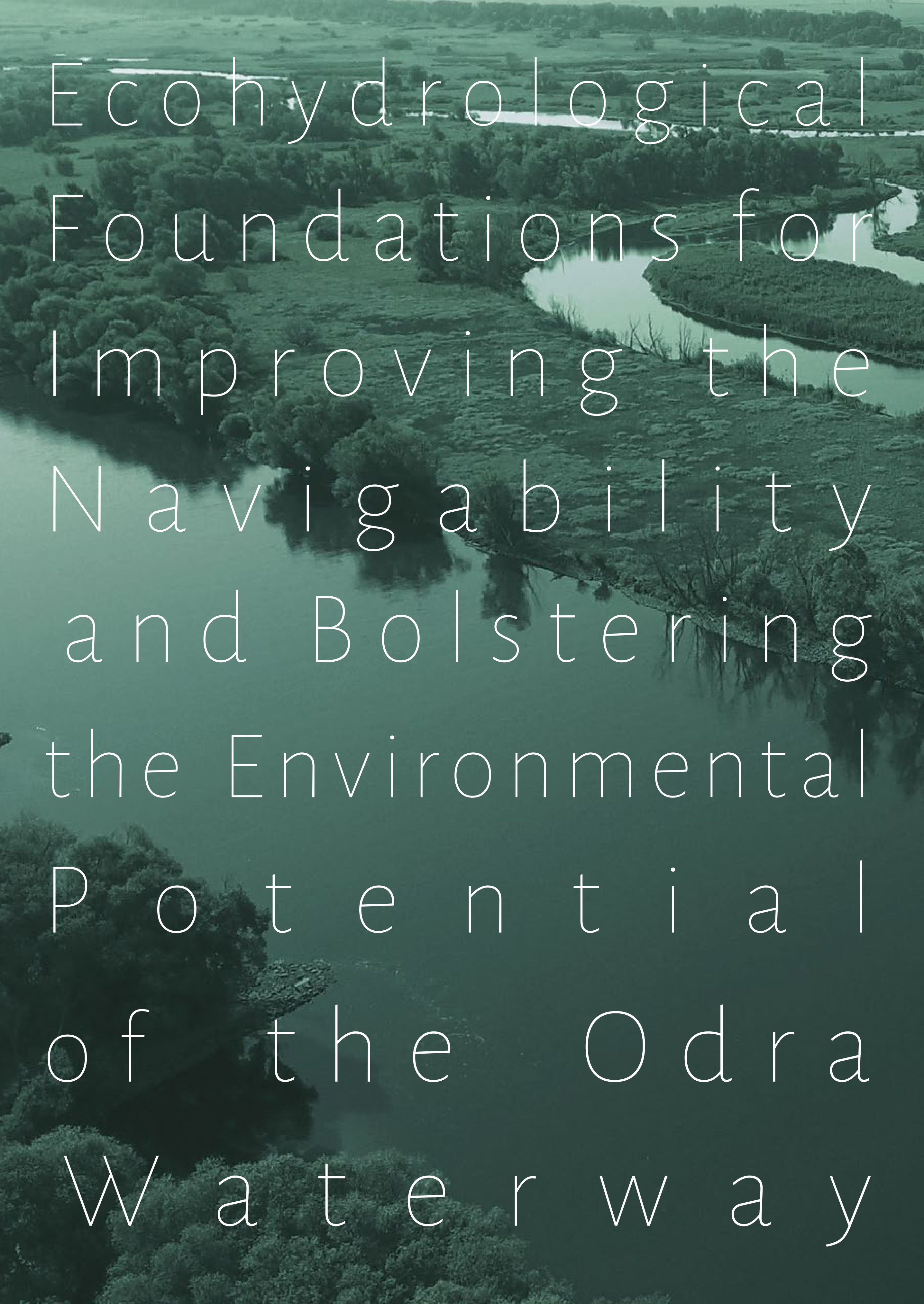
Ecohydrological Foundations for Improving the Navigability and Bolstering the Environmental Potential of the Odra Waterway



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Maciej Zalewski
Paweł Jarosiewicz

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Maciej Zalewski European Regional Centre for Ecohydrology, Polish Academy of Sciences
Paweł Jarosiewicz UNESCO Chair on Ecohydrology and Applied Ecology,
University of Łódź, Poland

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INTRODUCTION

The economic development of a seaport largely hinges on the quality of its sea and land access. Once the Odra Waterway – running along the Odra (or Oder) River – successfully meets the criteria of an international navigation route along its entire length, this will represent a key factor bolstering the competitiveness of the seaports in Szczecin and Świnoujście. It will also create conditions more conducive to sustainable economic growth in areas situated along the Waterway. Under the "Main Assumptions for Plans to Develop Inland Waterways in Poland in 2016-2020 for the 2030 Perspective", adopted by Resolution No. 79 of the Polish Council of Ministers on 14 June 2016, the Odra Waterway is slated to meet the parameters of class Va navigability. This will be achieved by means of the Odra Waterway Development Program, an initiative which will also fulfill the terms laid out in the European Agreement on Main Inland Waterways of International Importance (the AGN agreement), ratified by Poland in 2017. The main investment task envisaged for the development of the Odra Waterway is the construction of regulatory barriers – weirs – along the free-flowing Odra River to ensure the needed transit depth along the navigation route in low-flow periods by damming the river in the river channel. The conceptual work in that regard rests with the Odra Waterway Bureau, set up at the Szczecin and Świnoujście Seaports Authority. It is informed by one overarching principle: consideration for the natural environment. The intended goal for the Odra Waterway Development Program is not only to provide the infrastructure for environmentally friendly inland water transport which is consistent with the European Union's conception of sustainable transport development, but also to propose solutions and measures conducive to the environment, to help preserve biodiversity, to reduce water pollution and mitigate the consequences of climate change. The completion of the Program based on the aforementioned assumptions will help attain the Global Sustainable Development Goals adopted by the United Nations General Assembly in 2015, in terms of both economic growth and consideration for the natural environment.

Jacek Cichocki, PhD Eng. –
Vice President for Development
Szczecin and Świnoujście Seaports Authority

In modern ecological terminology, the ecosystem of the Odra (Oder) River may be dubbed a novel ecosystem, i.e. one that has been profoundly transformed by human activity. Notwithstanding the unquestionable role that natural, meandering rivers combined with valleys rich in natural assets play in adapting to climate change and increasing biodiversity, in the case of the Odra River no return to the status that preceded the first attempts at regulation is possible, not least for socio-economic reasons. On the other hand, the ongoing climate crisis, which in the future will produce longer drought periods and only slightly increased precipitation in the winter-spring season, forces us to seek novel forms of water retention nationally, ranging from increasing the soil retention capacity in agricultural areas, to enhancing landscape complexity, river renaturation, and incorporating blue and green infrastructure into the urban fabric, all the way to reservoir and channel retention. Faced with changes on the global scale, a "conservational" approach to environmental protection more and more frequently leads to clashes with the expectations of the public, yet with no guarantee being given that the richness of the natural life will be preserved. Sustainable economic growth should be pursued in a way that preserves biodiversity, ensures adaptation of river basins to climate change and takes care to protect the cultural heritage in river valleys. Ecohydrology is a transdisciplinary science that integrates knowledge about hydrological and ecological processes in order to design methods and systemic solutions for the sustainable management of water resources. Not only does it offer innovative solutions, it also provides strategies for their implementation and integration in a holistic, catchment-level approach. When completed, the Odra Waterway will shape the river continuum, affecting the ecological processes of self-purification, fish migration and many others. For this reason, the introduction of nature-friendly ecohydrological solutions to mitigate the negative impact and enhance the environmental potential of the river and its valley is of cardinal importance. In ecohydrology, this strategy is known as the "WBRS+C approach", whereby water, biodiversity, resilience, ecosystem services, cultural heritage and education are taken as the main prerequisites for achieving lasting and sustainable development. Importantly, investing in the Odra Waterway also means investing in order to retard the pace of runoff in low groundwater periods. It is a matter of primary importance for the function of water-dependent ecosystems and the nearby farming areas because slower runoff fosters habitat restitution and enhances biodiversity, particularly in river valleys.

Professor Maciej Zalewski –
Director European Regional Centre
for Ecohydrology,
Polish Academy of Sciences


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THE ODRA WATERWAY AND RIVER ECOSYSTEM FUNCTION

The pace of change in river ecosystems is dictated not only by climate and geomorphological conditions, but also by biological evolution and ecological succession. Ever since the dawn of civilization, humans have refashioned hydrological and ecological processes, thereby influencing the flows of energy in land and water ecosystems. Unfortunately, this has typically been done with no consideration being given to the interrelationships that affect how ecosystems function. In consequence, this has more and more frequently led to grave consequences in the form of catastrophic droughts, floods, mass-scale expansion of undesirable organisms or invasions of alien species. In many areas of the globe, Poland being no exception, it has resulted in the degradation of natural systems, impaired the function of many ecosystems and caused biodiversity loss. And yet, until recently most decisions concerning water resources management were made with no scientific or natural-life context taken into account, with the focus being on isolated issues and short-term solutions. Engineering measures aimed at regulating the river channel in the in the Odra valley have been undertaken since the Middle Ages, while the history of well-documented human interventions dates back to as early as the 18th century. Nowadays, the Odra is a profoundly human-altered river, particularly in its middle and upper sections. Such a situation is reflected in environmental evaluation reports, which in many cases classify the water condition of the Odra as less than good.

River ecosystems represent intricate complexes of mutual relationships where even the tiniest disruptions may have unpredictable consequences. Any human intervention in a river system should therefore take as its frame of reference the available knowledge about the fundamental processes comprising the river continuum, while factoring in the impact of the entire basin on the dynamic of the water resources and the circulation of elements. The basic assumption should be to regard the river as an open ecosystem whose qualitative and quantitative features are regulated by the structure, forms of use and ecohydrological processes on the whole-catchment level. That is why it is so crucial for investment projects such as expanding or constructing a navigable waterway to take into account the river's surroundings (the river basin) in addition to the river channel itself.

The continuity of the processes which determine how a river and its valley function as a plant and animal habitat is key for the protection and conservation of its environmental assets. If these components are to function smoothly, the river needs to enable the transport of mineral and organic matter (river sediments), which is for instance essential to ensuring an optimal trophic structure of the river ecosystem. This process is visible in the segregation of particles transported by the river current, ranging from gravel beds predominant in upper sections to deposits of fine-grained sediments prevalent in lower river sections. In addition to the river's trophic structure, such transport helps diversify the estuary zone and significantly ensures the proper functioning of saline water ecosystems. A river also provides multiple habitats, whose richness helps enhance biodiversity and increase productivity, including in ecosystems adjacent to the flowing waters. Wetlands, oxbow lakes, still-water pools and riparian buffer zones are also important factors for preserving biodiversity, water retention and purification.

A natural feature of rivers is the temporal variability of flow intensity, with intermittent periods of flooding and of low flows which threaten the very existence of water organisms (hydrobionts). As regards periodic floodwaters, the important role played by the availability of floodplains able to receive them should be particularly emphasized. The flooding process facilitates water purification and fertilization of the river valley; it also fosters the movement of matter and even genetic material between the river system and the various ecosystems of the valley, which in turn helps maintain the populations of many hydrobionts in good condition. In fact, the genetic diversity of all such populations can be preserved only if migration along and across the river continuum is possible.

The Odra Waterway Development Program is aimed at improving the navigability of Poland's second largest river. Importantly, as this document has been prepared, attention has been focused not only on fulfilling the main technical requirement, which is to adapt the Odra Waterway to the parameters of navigability class Va, but also on many other aspects of sustainable development policy such as environmental protection and adaptation to climate change. The Program will be drafted to be compliant with the statutory requirements relating to environmental protection and to respect protected ecosystems and those with valuable natural assets, while taking into account the possibilities for enhancing the environmental potential of the Odra and its valley with a view to offsetting the anticipated negative impacts. The draft will undergo a strategic environmental impact assessment.

It has been ascertained that the reconstruction of the river channel to create a class Va waterway using traditional methods will disrupt the Odra's biocenosis, mostly due to the modification of the river's hydromorphology, which will include:

- restricting the longitudinal and transversal continuity of the Odra's channel and valley;
- altering the transport of mineral and organic matter along the river continuum and its periodic accumulation;
- changing the characteristics and spatial distribution of hydraulic processes in the river channel and inundation areas;
- reducing the river's length by straightening it in those locations where the curve radius prevents watercraft from maneuvering, which will increase runoff and reduce both the surface area and the diversity of habitats;
- at a later stage of operation, disruption of the bank line by watercraft due to the instability of habitat conditions as a result of wave generation and propeller operation, as well as their direct impact on water organisms;
- increasing the speed at which water heats up, as a result of periodic backwater formation and the associated excessive growth of plankton organisms in the stagnation areas.
- These phenomena will influence biocenotic diversity by means of:

- changes in the composition of fish and invertebrate assemblies due to the restricted migration of diadromous species (migrating between saline and fresh waters) and potamodromous species (migrating within fresh waters);
- reducing the number of species susceptible to anthropopressure;
- increasing hydrobiont mortality caused by periodic drainage due to unnatural wave intensity and direct propeller impact (mostly in the case of sessile and poorly swimming organisms, e.g. fish at early development stages);
- increasing the threat posed by invasive species.

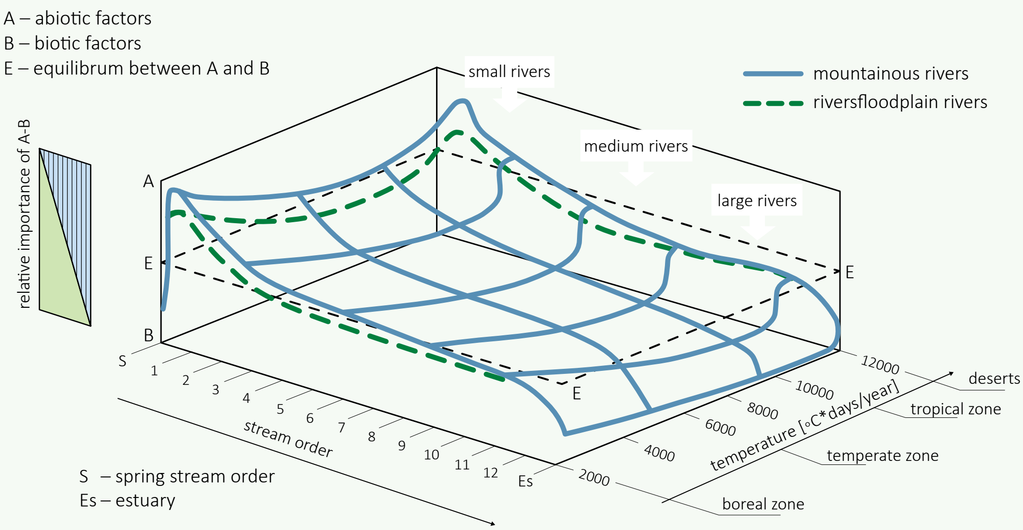
Given such clearly defined environmental risks, which nowadays provoke a notable share of ecological and social debates, relevant measures aimed at alleviating the negative effects of the investment project need to be put in place.

ECOHYDROLOGY

Ecohydrology is a subdiscipline of hydrology which strives to integrate knowledge from various areas (particularly ecology and hydrology) in order to explain and hierarchize the processes taking place in water and water-dependent ecosystems. Understanding the interactions between these processes both at molecular and landscape levels serves as the basis for proposing innovative, low-cost methods and systemic solutions, the implementation of which can enhance the environmental potential of ecosystems, predominantly with regard to water resources.

The potential of ecohydrology for resolving contemporary issues related to water resources management has been recognized by the United Nations. The year 1996 saw the launch of the UNESCO International Hydrological Program, which opened up a platform for collaboration among specialists in ecology, geomorphology, hydrology and hydro-engineering and laid the foundation for a new approach to water management (Zalewski 1997). Ecohydrology is currently one of the six pillars of the UNESCO IHP and can boast of a network of research areas and demonstration sites across the globe where various innovative solutions have been tried (for more information see: http://ecohydrology-ihp.org/demosites).

The scientific foundations of ecohydrology are directly derived from the abiotic-biotic regulatory concept (ABRC) (Zalewski & Naiman 1985; Zalewski 1986). The ABRC model was devised in response to recognition that the river continuum concept (Vannote et al. 1980) cannot serve as a model to be extrapolated to other ecosystems, since every river is different in its abiotic and biotic aspects and plays a different role for mankind. Quantification of ecological processes and deduction on their basis should start at the most fundamental level, that of the laws of physics and hydraulics, because it is basic transformations at the physical level that are crucial for life in the water environment. In such a context, abiotic factors are superior to biotic ones because they determine physiological processes which are only partly subject to compensatory adaptations. Only when abiotic factors such as the availability of water, temperature, flow dynamics become stable and predictable, can the biotic factors be manifested and reveal the interactions between organisms themselves and between their envi-



Stream order determines the hydrodynamics and energy expenditure of organisms. Temperature determines the metabolic rate, growth rate, and bioproductivity under unlimited trophic conditions. Bioproductivity and biodiversity depend on the relation between energy obtained from food to the energy expenditure described by the above parameters (modified from Zalewski & Naiman 1985).

Fig. 1. A model of how the hierarchy of abiotic and biotic factors changes along the river continuum and temperature gradient

ronment, thus shaping the species structure of the environment (Fig. 1).

The dynamic development of ecohydrology has led to the formulation of the principles of sustainable water resources management intended to respect all the recipients and employ strategic thinking. In ecohydrology, environmental potential is defined using five parameters summarized as the "WBRS+C" approach (***W****ater,* ***B****iodiversity,* ***R****esilience, ecosystem* ***S****ervices,* ***C****ultural heritage*) (Zalewski 2014). The accessibility of water determines the capacity of the land ecosystems in a given basin to accumulate carbon, which translates into increased biological production and biodiversity as well as carbon footprint reduction (https://www.carbonfootprint.com). Water and biodiversity provide the basis for ecosystem services such as food production, recreation, tourism, etc. For this reason, apart from developing mechanisms of adaptation to climate change, scientists must also face the challenge of enhancing the environment's capacity to flexibly respond to different forms of human pressure. Relevant measures to be undertaken need to be in line with society's needs and preserve the cultural heritage in a given region.

Comprehensive adaptation to climate change requires above all water to be retained within the basin's area through such measures as improving soil water retention, enhancing agricultural landscape complexity and increasing the acre-

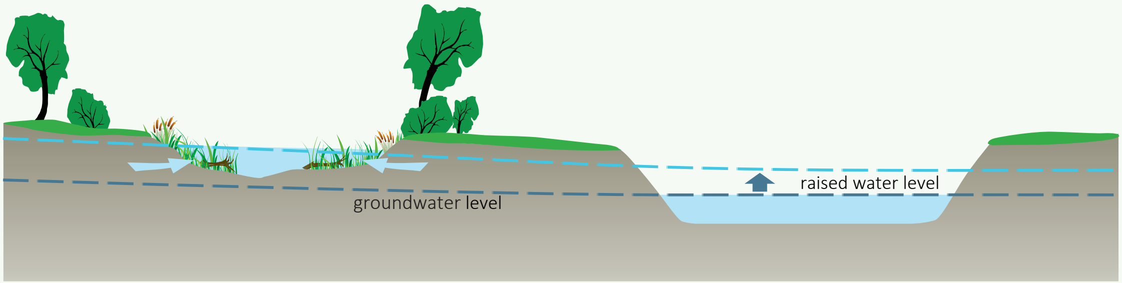


Fig 2. Wetland restitution

age of blue-green areas in cities. In the face of imminent climate change, however, water runoff from the landscape, a process of crucial importance for the productivity of ecosystems and replenishment of groundwater resources, should concurrently be retarded by increasing the area of water ecosystems and water-dependent ecosystems. Constructing weirs in order to dam a waterway, despite its frequently negative impact on the structure and ecological processes in a river, may nevertheless help improve water retention in the river channel, raise the subterranean water level and increase groundwater replenishment. Periodic, well-considered river damming, which takes into account the ecological processes and ensures ecosystem services for society at large, may constitute a major factor in comprehensive adaptation to climate change (Fig. 2).

Raising the water level helps increase water retention in the river channel, replenish groundwater resources and support the functioning of land ecosystems and wetlands in the river valley. It can serve as an example of measures facilitating adaptation to climate change which makes it possible to preserve biodiversity reservoirs within the river valley and in the adjoining areas.

The Odra Waterway project will clearly help boost the availability of ecosystem services such as tourism or recreation; similarly, it will increase the share of low-emission transport. The growing awareness among society of health issues and the role of active lifestyles, combined with the unquestionable merits of a large river and its valley, may significantly improve the pro-ecological perceptions of the public and sustain the project outcomes. The completion of the Odra Waterway will also open up economic growth opportunities for areas directly neighboring on the river.

What should also be borne in mind is that river valleys, along with the ecological services they generate, represent a significant feature of cultural heritage. They have been vital for human presence throughout the history of mankind, ensuring the fulfillment of basic needs and facilitating the development of civilization. Long-term losses and benefits should always be factored in as a priority consideration in analyzing the effects of any investment projects likely to affect water systems.

The adoption of the principles of ecohydrology for the Odra Waterway Development Program means that:

1. innovative ecohydrological solutions will be devised to compensate for the impact of nav-

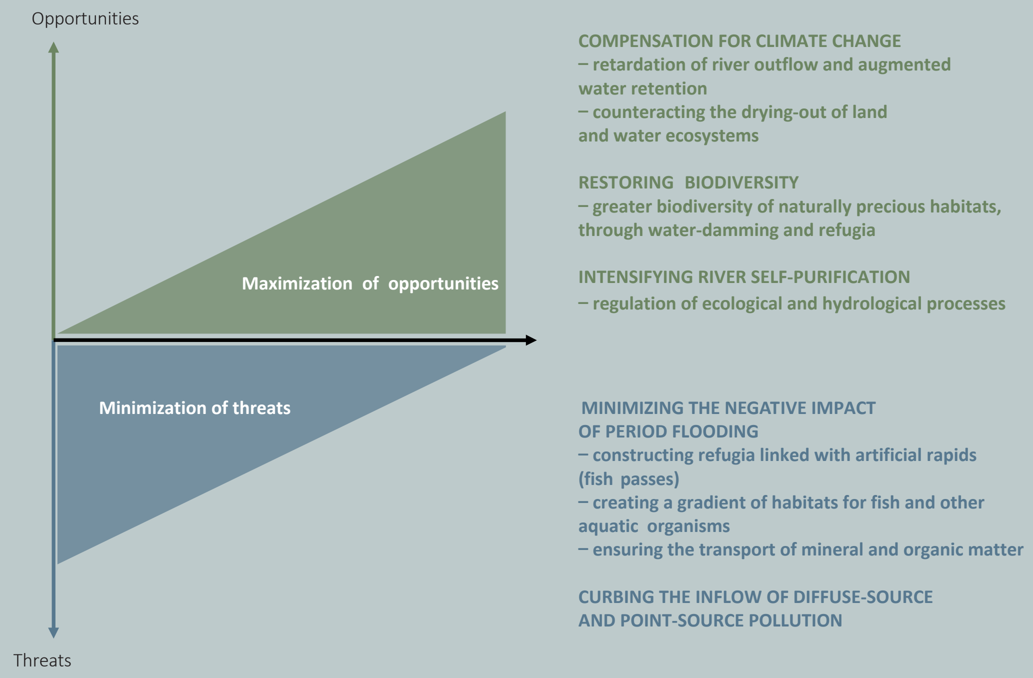


Fig. 3. Elimination of threats and maximization of opportunities as priorities for ecosystem solutions in terms of river valley management (modified from Zalewski et al. 1997)

igation on the river's ecosystem;
2. water retention in the catchment area will be increased to adapt to climate change;
3. water quality will be improved by reducing the inflow of diffuse-source and point-source pollutants in those parts of the catchment area that neighbor on the waterway, as a component of the Water Framework Directive of the European Union and its implementation.

These aspects may be summed up as a two-element strategy: to maximize the opportunities and to minimize the threats (Fig. 3).

NATURE-BASED ECOHYDROLOGICAL SOLUTIONS AIMED AT INCREASING THE ENVIRONMENTAL POTENTIAL OF THE ODRA WATERWAY

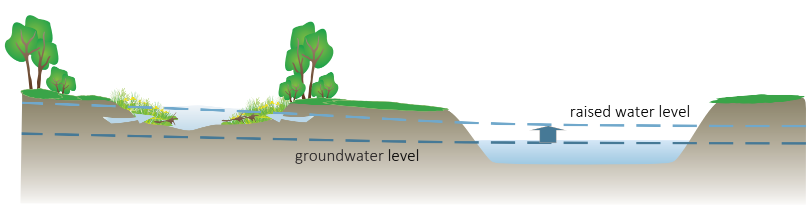
The negative effects of the investment project planned as part of the Odra Waterway Development Program need to be mitigated or offset by nature-based solutions (NBS) if a significant impact cannot be prevented (World Water Development Report 2018). NBS are solutions that draw on an understanding of evolutionary processes occurring in water and water-dependent ecosystems. To ensure their lasting and effective operation in a given river basin, NBS should be implemented in a systemic way which takes multiple variable factors into account (Fig. 4 shows a systemic, ecohydrology-based approach to the execution of the Odra Waterway project).

Ecohydrology provides a relevant frame of reference for implementing such solutions thanks to the following three principal assumptions:

1. Water is the essential factor driving the evolution of the biogeosphere, since all ecological processes, and thereby the entire ecosystem structure (e.g. carbon content, ratio of biomass to organic matter), rely on it.
2. The water cycle provides a framework for quantitative analysis (quantification) of both hydrological and biological processes across the entire basin.
3. Understanding the correlation between abiotic (hydrological, physiochemical conditions) and biotic factors (live organisms) in the entire basin helps regulate the whole spectrum of ecological processes, encompassing the molecular level up to the landscape level, and ultimately enhance the ecological potential of the environment and its resilience to stress.

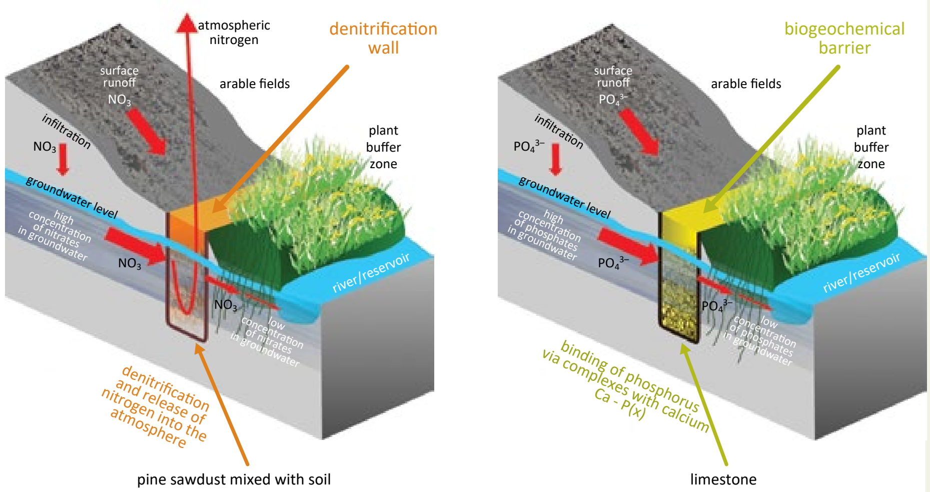
Management of organic and mineral matter transport
a) Deposition of sediment accumulated upstream of a weir in order to transport it downstream.
b) Siphon that removes silt deposit to a lock in certain conditions.
c) Regulation of the weir opening in order to force the transport of sediment.

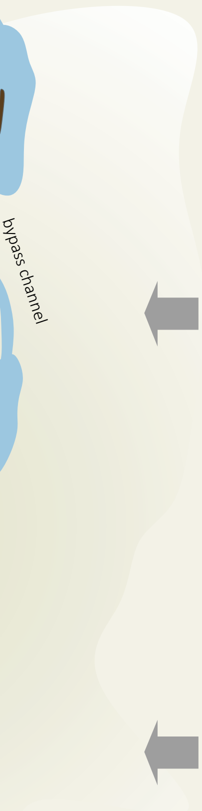
Wetland restoration
The increase in water level as a result of periodic damming promotes the functioning of wetlands and water-dependent ecosystems in the river valley and adjacent areas.



Creating stable habitats for aquatic organisms through
a) Adaptation of existing river spurs to make them biodiversity refugia.
b) Creating new areas based on the understanding of ecohydrological processes.
c) Preservation of river habitats formed as a result of natural ecological succession result.

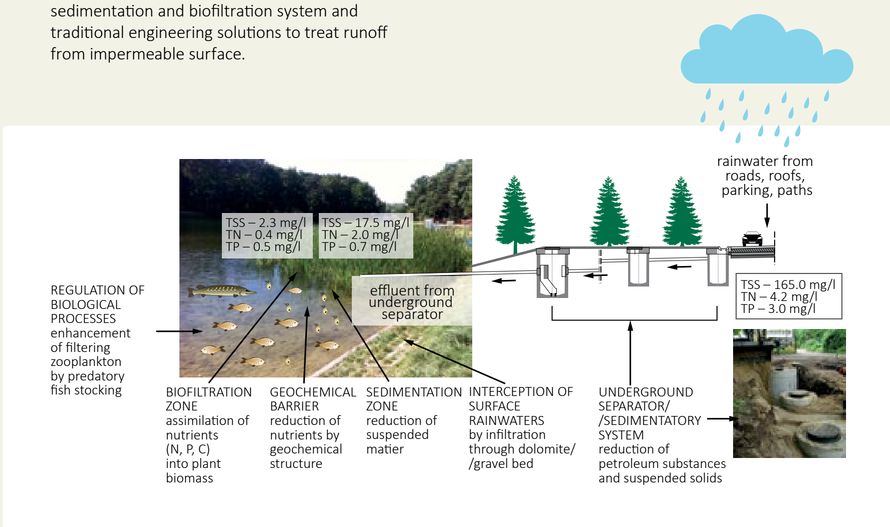
Water quality management
Enhanced Riparian Buffer Zones - an ecohydrological tool for reducing nitrogen, phosphorus and pesticides in an agricultural catchment.



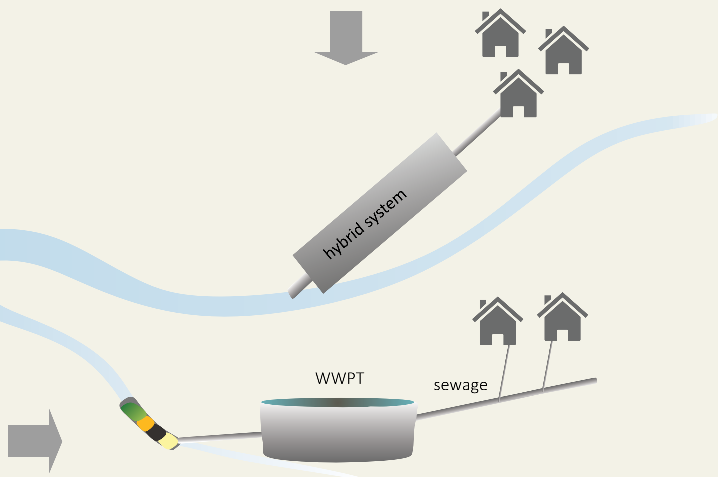


Water quality management
A hybrid ecohydrological system for purification of rainwater that integrates sequentional sedimentation and biofiltration system and traditional engineering solutions to treat runoff from impermeable surface.

Preserving river continuity
Weirs will be equipped with an ecological bypass for migrating organisms. Special habitats for rheophilic fish will be created and supplied with spawning grounds and refugia.



The network of refugia
In order to increase resistance to eutrophication and ensure appropriate habitat conditions for aquatic organisms, reservoirs imitating natural oxbows will be created, with continuous exchange of water.



Water quality management
Hybrid Sequentional Biofiltration System for small wastewater treatment plants is an ecohydrological solution that allows not only to reduce loads of point source pollution but also to protect river in case of emergency.

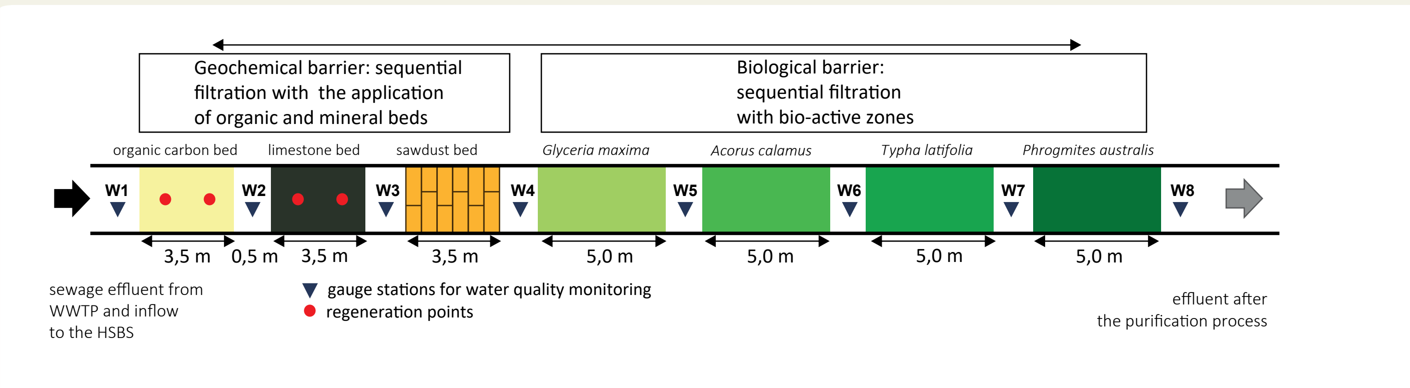


Fig. 4 Systemic, ecohydrology-based approach to the execution of the Odra Waterway project

REGULATION OF PROCESSES INVOLVED IN THE TRANSPORT OF ORGANIC AND MINERAL SEDIMENTS

As regards the construction of weirs – understood herein as man-made structures stretching across a river, consisting of a barrier damming the river water, possibly also including an associated lock and hydropower installation – the main resulting change in the stream morphology is the increased cross-section area, which in effect reduces the average current speed, mostly in low-flow periods. In consequence, fine-grained organic matter accumulates near the damming structure, whereas the coarse-grained fraction builds up in the initial section of the emerging backwater. In the case of the transversal structures planned on the Odra for navigation purposes, this problem may be manifested during low-flow periods. After some time, the accumulation of organic matter near the damming structure may lead to the generation of anoxic conditions, the release of additional pollutant amounts and creation of toxic blue-green algae blooms. In contrast, a decrease in organic and mineral matter can be observed downstream of the damming structures, which may disrupt the function of the river ecosystem, typically manifested in the form of biocenosis depletion.

Moreover, the change of a lotic environment into a lentic one increases the risk of accelerated eutrophication due to the altered circulation speed of biogenic compounds. In the case of rivers, this involves not so much circulation as the spiral movement of biogenic compounds, because concurrently with their transfer between the individual energy levels they are also transported downstream – giving rise to a spiral type of motion. In those ecosystems where the spiral is long, e.g. due to poor sunlight access to the stream, primary production is low and the assimilation of biogenic compounds by living organisms is poor, the rate of self-purification is low and pollutants are transported downstream at a faster rate. In contrast, in naturally diverse ecosystems with high biodiversity, the circulation of biogenic compounds is more efficient, which accelerates the self-purification process.

The design of a weir should facilitate the transport of suspended load and periodically facilitate the transport of bed load. Opening of the dam barrier in floodwater periods will foster the transport of bed load. Experience shows that whenever a transversal structure is located on a stream and founded on the river bed, the transport of mineral and organic matter will inevitably be disrupted. For this reason, measures need to be taken to curb the disruption caused by such hydro-engineering structures in the river's ecosystem and also to undertake compensatory activities. As regards the latter, numeric modelling of the transported load is required for each transversal structure. This will help identify precise areas where the accumulation of organic matter may be the strongest, and, at a later stage, to apply tailor-made solutions to mitigate the negative effects. One should not overlook the fact that the construction of sequential weirs damming a river will prevent the negative consequences of excessive erosion downstream of the hydro-engineering structure, the lowering of water levels and the draining of neighboring areas.

Importantly, minimizing the negative effects of damming structures should take account of more functions than just sediment transport. Rather, sustainable environmental management means compensating for the energy costs of every investment project undertaken. A common solution applied in the case of transversal structures is hydropower generation using the potential energy of the river water. Furnishing every weir on the Odra with a small hydropower facility, located for instance at the weir head, could help offset the energy costs of the investment projects being implemented under the Odra Waterway Development Program. Other ecological costs, however, should also be analyzed, including the sum of various impacts, cost-effectiveness and potential economic viability, alongside the measures used to minimize the negative impact of the hydropower plant on migrating fish species.

The transport of mineral and organic matter in the river channel should be regulated mainly by controlling the closures of the damming structure. If, however, numerical modeling indicates that such a solution will be insufficient and silt will accumulate in the pockets upstream of the structure, thereby increasing the risk that anoxic conditions will appear or there will be a substantial release of biogenic substances, the application

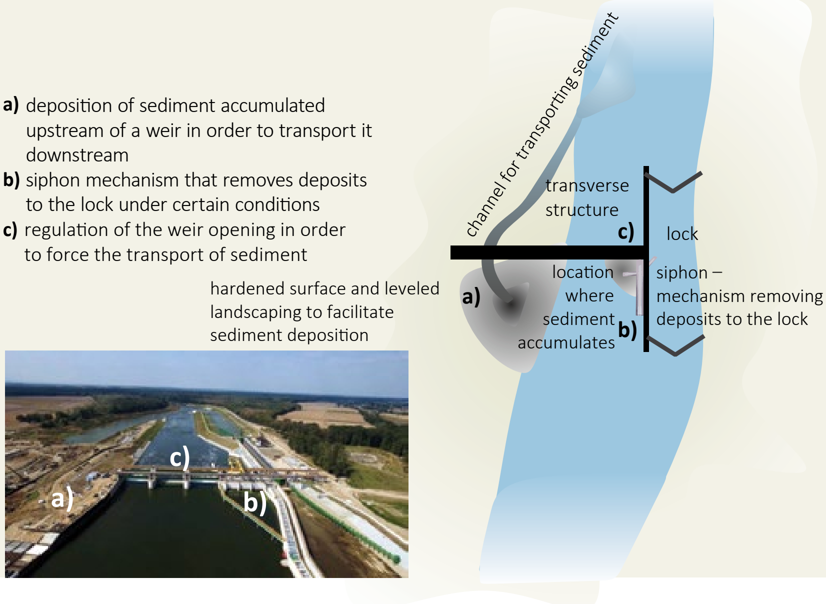


Fig. 5 Managing organic and mineral matter transport

of systems enabling active or passive transport of accumulated wash load in the form of a siphon whose outlet will be located downstream the weir structure should be considered (Fig. 5). The energy output required by sediment transport ought to be offset by water or solar power generation.

RIVER VALLEY RETENTION

Flow variability can significantly affect ecosystem productivity in the river valley and thereby in the river itself, which is a heterotrophic system. Inundation areas offer favorable conditions for sustaining high biodiversity and genetic reserves for many species living both in water and on land. Periodic inflow of water to habitats situated in floodplains has a positive effect on natural processes, habitat diversity (including the emergence of areas for reproduction and early life stages of fish and other organisms, transport of organic and mineral matter between the water and land environment); it also boosts circulation of such elements as carbon, nitrogen and phosphorus. Moreover, inundation areas mitigate the risk of flooding by slowing down the runoff and flattening out the flood wave. For this reason, restoration of inundation areas should come as a priority in all hydro-engineering projects carried out in river valleys. Such areas may be used for intercepting river sediment and can minimize if not offset the influence of human activity, e.g. by restoring habitats lost due to flood embankments. Redirecting floodwater to natural or artificially created floodplain areas (polders) is a factor that considerably reduces water pollution, but also facilitates flood prevention and increases water retention.

Complete restoration of a natural river system, encompassing periodic flooding of the floodplain, is not possible at the present stage of human civilization. However, there exist solutions which may be applied to alleviate human impact on river systems, and enable at least their partial functioning in accordance with the rhythm developed during river evolution. In the case of large rivers, building embankments is the most common flood protection mechanism in addition to constructing storage reservoirs. One measure that is favorable for increasing the environmental potential is positioning the embankment as far away from the river channel as possible; during times of flooding, this enables water to spill over a larger area, which in turn reduces the flow velocity and decreases the flood wave. It also means better water retention in the valley and greater purification potential. Construction of retention basins (polders) and dry storage reservoirs is a solution that directly affects floodwater retention. Designing spillways and culverts to enable short-duration flooding of selected parts of the valley beyond the embankment is also beneficial for the functioning of the river valley. Other significant measures include restoration of oxbow lakes and wetland areas by ensuring their periodic or permanent connectivity with the river waters.

Retention basins and reservoirs should be designed in different shapes so as to ensure the presence of both areas that dry out and ones that remain continually wet. The canals which supply and discharge water ought to meander and be made of natural materials. Such design of artificial inundation areas helps vary the current velocity, extend the flow time, increase the effectiveness of self-purification, and also create diverse habitats for plants and animals. The dry parts of these areas, which are flooded only when the water level is the highest, may serve for longer periods as pastures or hay-growing meadows. For this reason, polders and dry reservoirs should always fulfill the following three functions:

- flood protection;
- enhancing biodiversity by the restoration of areas operating as floodplains;
- utilitarian role for the local communities.

Oxbow lakes should remain connected with the river channel as this halts the process of succession which, over time, has a negative effect on how they function as habitats for organisms living in the river. Additionally, oxbow lakes provide a much richer food base, offering macrofauna density even fifteen times higher than in the river itself (Obolewski 2006).

Oxbow lakes are natural mainstays of biodiversity, comprising numerous habitats. Unfortunately, insufficient flow can mean that during periods of higher temperatures or icing, oxygen deficits may appear which threaten the life of the hydrobionts inhabiting them. Restoring old oxbow lakes, creating new ones, as well as building reservoirs imitating natural oxbow lakes requires forcing of water flow by ensuring that there exists a connection between them and the river stream. In order to maintain high biodiversity, oxbow lakes should be as varied as possible in terms of habitats and substrates. In that regard, the growth of plant assemblages typical of such

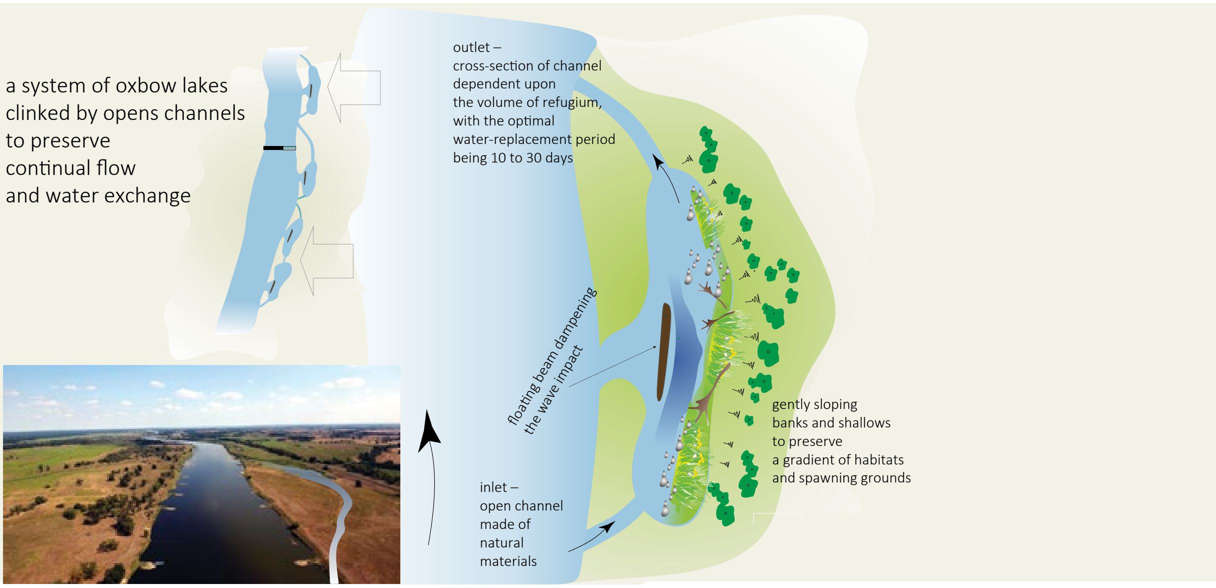


Fig. 6. System of refugia

water bodies and the presence of large woody debris are of crucial importance. For safety reasons, tree trunks and stumps need to be stably anchored in the riparian zone, to reduce the risk of their being washed out into the fairway. Moreover, to maintain stable conditions for the development of the littoral zone, oxbow lakes ought to be secured by a breakwater, for example in the form of a floating beam affixed to the river bottom or the riverbank or long dams made of stones and gravel. It is recommended that such refugia should have hollows at least 1.5 meter in depth and, if possible, a varying depth where the oxbow lake meets the river channel. The banks should be gently sloped to ensure an appropriate habitat gradient to diversify aquatic plants (macrophytes) in the riparian zone. The cross-sections of the inlet and outlet canals should be designed in such a way as to ensure a 10- to 30-day water exchange period (Fig. 6).

The morphology of the river channel is of primary importance because oxbow lakes form an environment with frequent oxygen deficits at advanced stages of ecological succession, when large amounts of organic matter are accumulated. In contrast, at early succession stages and when the exchange of water is frequent, they are mainstays of biodiversity, serving particularly as refugia for fish in winter. Therefore, restitution of river biodiversity ought to ensure the conditions for frequent water exchange (Mrozińska et al. 2018).

HABITAT RESTITUTION AND MAINTAINING MIGRATION CORRIDORS

Engineering structures, river-training measures and deepening the river channel are methods intended to modify the hydromorphology of a given watercourse, and thereby to alter their habitat and trophic conditions (Cowx & Welcomme 1998; Welcomme 2001). In consequence, this reduces the survival rate of specialized species and decreases their share in the species assemblage while also increasing the share of tolerant species, a phenomenon which is usually observed in the case of fish. Engineering works which intervene in the river channel impair its function as an ecological corridor by severing or disrupting the continuity of the river continuum. This is especially true in that a migration barrier may be formed not only by physical transversal structures, but also by modifications of the substratum, depth and speed of the current that affect the behavior of organisms (Kemp 2015; Schinegger et al. 2016; Zajicek et al. 2018). On the other hand, individual components of engineering structures such as escarpments or structural supports (rock fill, submerged parts of the structure), may serve as living and reproduction habitats for certain fish species and other hydrobionts. For this reason, the final impact assessment of a given investment project must always be made on a case by case basis, with regard to specific hydro-engineering works.

Analyses of typical threats involved in the modernization and extension of waterways indicate that the most negative effects are generated by transversal stream structures (Kemp 2015; Zajicek et al. 2018). In addition to its most discernible impact, which is the severance of migration routes, the establishment of a zone of decelerated flow or stagnating water changes the abiotic conditions, which leads, among other things, to the disruption of the circulation of matter, a rapid increase in temperature and, in some cases, alterations in other physiochemical parameters of the water, such as clarity, dissolved oxygen concentration or pH. Modification of habitat conditions entails changes within species assemblages, which comprise not only the backwater area upstream of a structure but also the adjacent sections of the watercourse (Kruk 2007; Gouskov et al. 2016; Kaczkowski et al. 2019). One major consequence of decelerated flow is the transition from the heterotrophic system, as is constituted by a free-flowing river, to autotrophy in stagnation areas. In autotrophic systems, the prevalent portion of energy and matter used by the individual trophic levels is bound and generated from low-energy compounds, dissolved in incoming water or deposited in the sediment. The intensity of this process is correlated with the retention time and temperature, which are derivatives of the number, size and particular application of the specific damming structures. This correlation has far-reaching consequences for the functioning of the entire trophic network because it entails the dominance of other primary producers (plants) and lower-level consumers (invertebrates) than is the case in the lotic sections of the stream, and ultimately has a bearing on top consumers (fish). In areas of decelerated flow, a competitive advantage is gained by plankton assemblages (phyto- and zooplankton), which are not an optimal food base for the typically fluvial macrobenthos (i.e. organisms living at the bottom) or for rheophilic fish species, adapted to large-particle, energy-rich matter supplied from the land adjacent to the watercourse (Allan 1998). Another effect of the accumulation of bed load and rolled load sediment, as well as mineral debris, i.e. stones, gravel or sand upstream of the dam is the disappearance of the stone and gravel substratum needed for the reproduction of fish from the so-called lithophile group (Ward & Stanford 1995; Tockner et al. 1999; Wolter et al. 2016). The most easily visible consequences of such changes include the receding of reophile species and species with narrow ranges of ecological tolerance, and the dominance of eurytopic species (having a broad tolerance range) and limnophilic species (which prefer stagnant water), which also means increased competition for environmental resources for those species which are confined to rivers (Kruk 2007; Gouskov et al. 2016; Kaczkowski et al. 2019).

The impacts associated with river training and deepening of the river channel mostly comprise structural changes within the riparian zone. River straightening, bank reinforcement and construction of spurs all destroy the natural microhabitat variety in the riparian zone (Schinegger et al. 2016; Zajicek et al. 2018). The riverside shallows and side-arms serve as habitats for most aquatic plants, invertebrates and fish in early life stages. The riparian zone also plays an important role in enhancing river productivity and self-purification capacity (Zalewski & Naiman 1985; Schiemer & Zalewski 1992).

Another type of impact on fish life is related to the use of inland waterways for navigation, mainly to the phenomena generated by the movement of watercraft, propeller operation and bow waves. Small organisms, including fish in early life stages, which are characterized by little or no swimming ability (aquatic plants, sessile invertebrates, spawn) are the most susceptible to these types of impact. The bow wave which is generated at 10 to 12 km/h, the average speed of European lighters, causes an aggregate drawdown of water from parts off riverside habitats lasting for a total of about 2 minutes (Husig et al. 2000). This type of impact has been best described for fish: in their early life stages, with a total length under 47 mm, fish can withstand such force of current for not longer than 20 seconds, and fish having under 147 mm in length become exhausted to a life-threatening degree if they have to withstand such force for over an hour (averaged values for the main taxonomic categories of freshwater fish) (Larinier et al. 2002; Wolter & Arlinghaus 2003).

Direct impacts, i.e. those which lead to death or cause injuries and which are associated with the waterway infrastructure, are basically limited to the stages of construction or modernization of the fairway. Construction works which involve the need to occupy a specific site for the infrastructure under construction lead to the destruction of habitats and organisms with limited mobility. It can be said, therefore, that the extent of the threat posed to the environment is mostly associated with the scale of the project at hand and the use of good professional building practices, which include professional environmental supervision and technologies which are the least detrimental to the natural environment.

When analyzing individual variants of waterway extension and modernization, it should be borne in mind that planning a large number of weirs poses a serious threat to the fish community, especially in a situation when, in low-flow periods, the water dammed at a given weir may stretch back to the previous weir immediately upstream. Such a situation can reduce chances of survival for diadromous or rheophilic (current-loving) migrating species even if such mitigating measures as fish-passes are put in place.

Despite the above-mentioned threats, the negative impact of the Odra Waterway Development Program on the continuity of the river channel may be mitigated through a concurrent use of fish passes and a varied network of refugia, i.e. places where hydrobiont species may survive periods of unfavorable environmental conditions (Bojarski et al. 2005; Nawrocki et al. 2016).

As stipulated in the terms governing water use, applicable to the regions of the Lower and Central Odra River, all migration facilities must fulfill the requirements for the sturgeon, for which species the watercourse viability is required up to the confluence point of the Nysa Kłodzka River. Currently, two types of fish passes are being developed as part of hydro-engineering construction activity: technical and ecological, i.e. passes whose structure emulates the conditions prevalent in the natural river. One set of guidelines for designing nature-based (ecological) fish passes can be found in a study by Nawrocki et al. (2016). Nonetheless, on all such occasions, consultations with ichthyology specialists are necessary; after analyzing the local conditions, they may suggest the specific locations and manner in which the fish bypasses ought to be constructed.

Fig. 7 shows the concept of a proposed bypass, which imitates a mountain or a valley stream and may be home to many rheophilic fish species. Such a bypass should be meandering, structured as a sequence of riffles and pools. Its banks ought to be covered with natural vegetation, and its reinforcements ought to be made of such materials as fascine proper (fences, bunches), fascine and

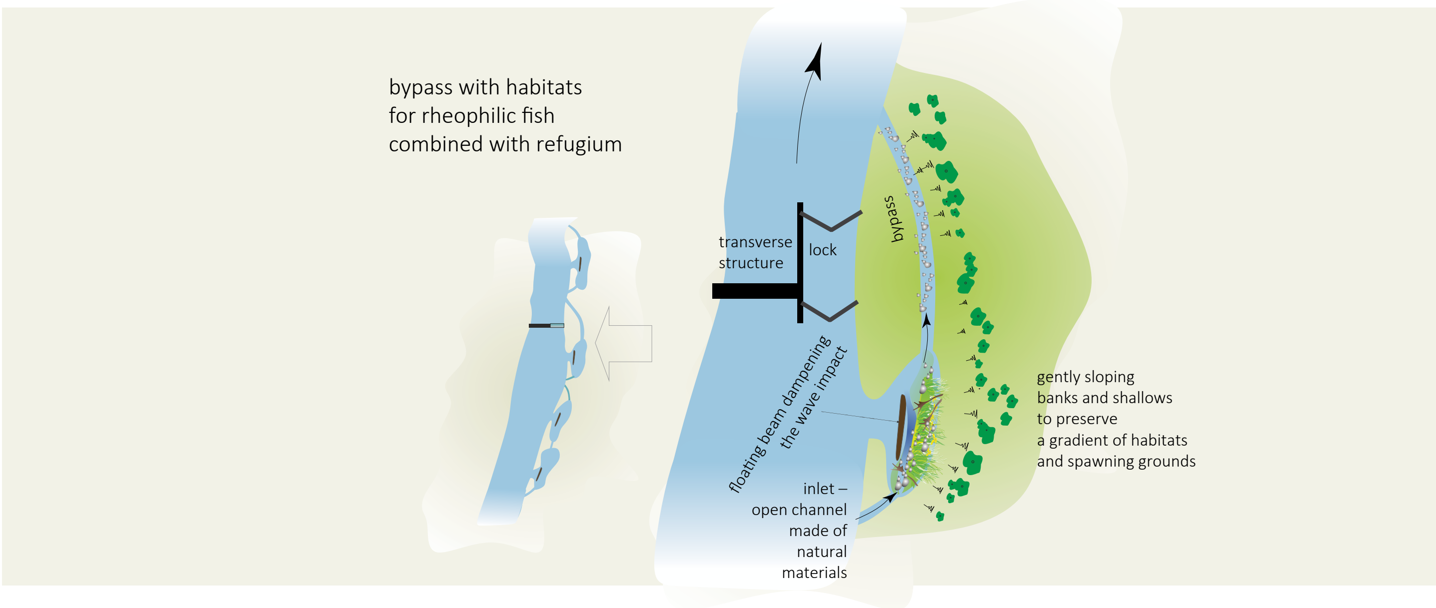


Fig. 7. Maintaining river continuity

earth material, broken stone, or as mixed structures, e.g. fascine and stone, timber and stone, etc. (Żelazo & Popek 2002; Mioduszewski 2014; Biedroń 2018).

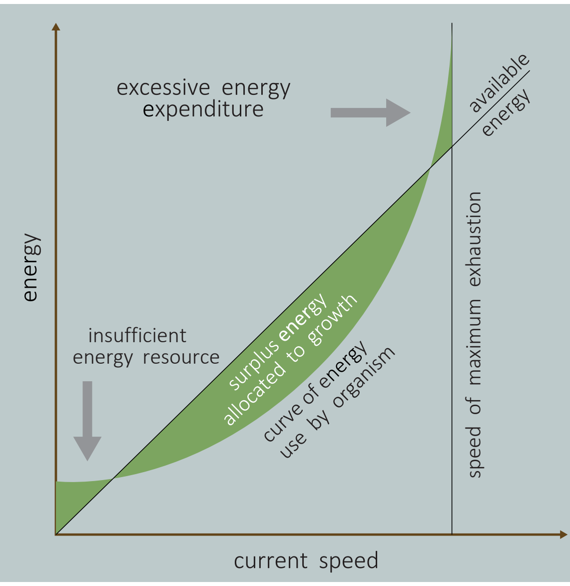
The bypass connects to a resting area with a habitat gradient. The created habitats comprise stone, gravel and plant areas, as well as spots with large woody debris such as tree trunks or wooden beams. Smaller resting areas, where fish can discontinue migration and rest, ought to be situated in the bypass, and their number and size adapted to the local conditions.

In order to mitigate the negative impacts of river navigation, above all, old habitats ought to be restored and new ones created, to provide protective functions for aquatic organisms. If they are already absent, such habitats need to be recreated based on the understanding of natural processes. To this end, ecohydrology proposes mitigating and compensating measures which mainly focus on river spurs. Natural elements such as large woody debris, large-size boulders or tree stumps (including root systems) should be used as much as possible in the construction of new or modernized river training facilities (Prus et al. 2017). All the elements of woody and mineral debris should be secured to prevent them from being transported to the main channel due to the threat they may pose to the fairway operation. Additionally, gentle sloping (shallows) should be maintained in the riparian zones, where vegetation is emerging, and the plant life ought to be diversified by constructing stone and gravel embankments. Similarly, the riparian zone ought to include wooden beams, to serve as riverbank reinforcements on the one hand and as underwater shelters on the other (Prus et al. 2017). To sustain riparian vegetation, construction of nature-based breakwater structures is recommended, for example in the forms of beams anchored to the river bottom or the riverbank, or palisades which will protect the riverbank against waves but which will also permit the movement of hydrobionts (De Roo & Troch 2013).

Ecotones – buffer zones between the water and land environment – are crucial elements for the functioning of a water ecosystem. As the complexity of the ecotone structure increases, so decreases the velocity of the flowing water, which has a bearing on many aspects of the biology of the river channel. The biomass of the wash load in a given unit of time is proportional to the flow velocity, whereas the amount of energy fish need to expend on swimming increases exponentially with the velocity of water. Above a certain speed, fish will expend more energy on swimming than they can absorb from the environment (Fig. 8, Bachman 1982), and the balance of energy costs and benefits which is optimal for fish will change as the fish size increases (Webb et al. 1984). Species of varying sizes and in different life stages (Krauze 2002) occupy habitats with different flow velocities and different morphologies, thus preventing habitat competition. To make optimal use of a river ecosystem, its organisms need diversified habitats with varying flow velocities; these are offered by complex ecotones. In riparian environments of little complexity and with high flow velocity, high energy costs tend to restrict the occurrence of species (Thorpe 1986).

Fish, as opportunistic organisms, frequently migrate up and downstream in search of optimal habitat and feeding conditions. Fish in large rivers use environmental diversity to their advantage, such as oxbow lakes which, as more stable, "current-free" habitats, provide refuge in periods of abiotic stress such as winter or flood (Bouvet et al. 1985; Schiemer & Spindler 1989). Oxbow lakes may also act as genetic refugia for populations living in water bodies under strong anthropopressure (Bouvet & Pattee 1991). Fish spawning and the critical stage of larval development both take place near riverbanks, in the ecotone, since it is a shallow habitat with a varied structure and rich in diverse food sources (Benke et al. 1984). Accordingly, inter- and intra-species interactions in ecotones, such as competition or predator pressure, can assume complex forms.

The presence of various habitats, arising from the depth gradient, the current velocity, the nature of the substratum and the presence of hide-



The lower portion of the graph represents rivers with slow current and impoverished ecotone zones, whereas the upper portion reperents fast-flowing currents with little habitat diversity, in which the energy expenditure is larger than the energy obtained from rich drift. This type of analysis are performed in the field of ecohydraulics (modified from Bachman 1982) and should be taken into consideration for plans to revitalize rivers.

Fig. 8. The relationship between energy consumption and river current speed, for fish feeding on river drift.

aways, is the single most important direct consequence of the existence of complex ecotones. It can be said, therefore, that these zones offer optimal conditions for the concurrent presence of large numbers of fish from different species and in different life stages. They also mitigate the impact of catastrophic events on fish by providing hideaways, areas for feeding, reproduction and breeding of offspring (Schiemer & Zalewski 1992). Water-undermined riverbanks with exposed tree trunks, branches overhanging the river channel and falling into the water all ensure constant access to organic matter, thereby maintaining high invertebrate biomass, whereas access to sunlight regulates the presence of aquatic plants. The overall high biological diversity in ecotones improves the stability and productivity of fish assemblies, while the increased trophic state of the environment, within certain bounds, also enhances their biodiversity.

New refugia for fish and other aquatic organisms need to be designed, e.g. through the adaptation of the existing spurs or creation of artificial oxbow lakes (Fig. 9). Additionally, if the existing spurs which have undergone natural succession show favorable features, they should be maintained. Such favorable features include still-water pools and local shallows, mixed bed substrate in the form of stone and gravel bars and sandbars, as well as the presence of water and land plants. To protect riparian vegetation, nature-based solutions are recommended in order to suppress wave impact.

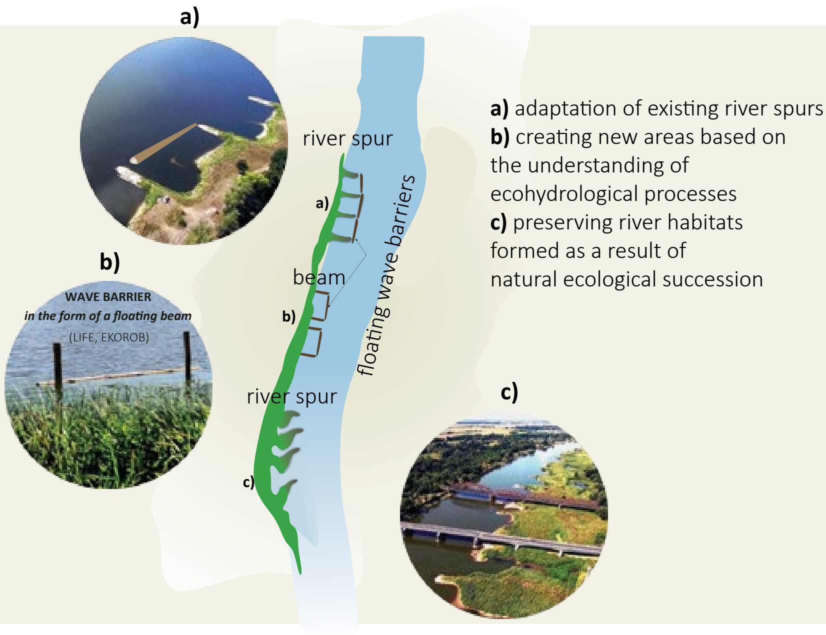


Fig 9. Creating stable habitats for aquatic organisms

APPLYING ECOHYDROLOGICAL BIOTECHNOLOGY METHODS TO REDUCE POLLUTION IN THE ODRA RIVER BASIN

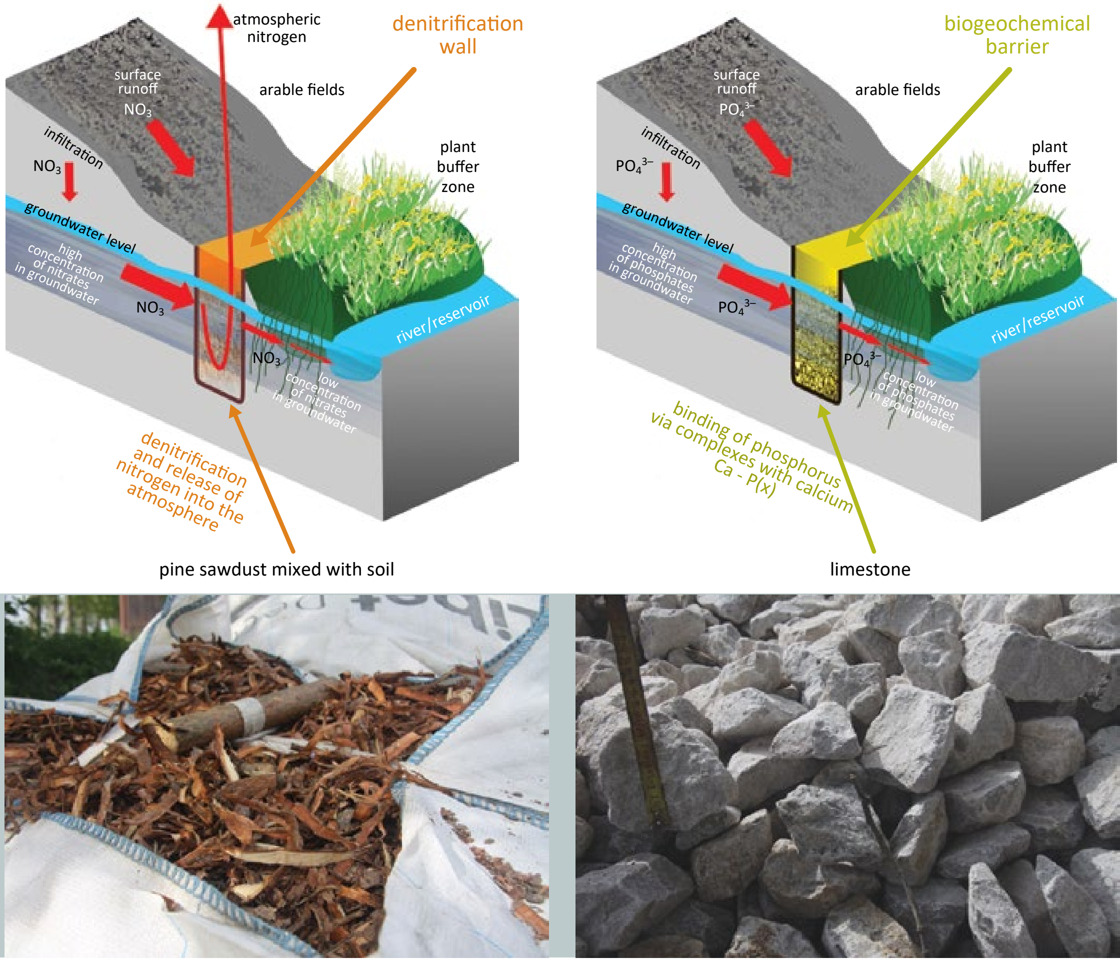
As a measure to offset the negative impact of the investment project aimed at improving the navigability of the Odra River, ecohydrological biotechnologies can be applied to reduce the load of pollutants originating from the river basin, in particular diffuse-source pollutants transported with surface runoff or shallow subsurface water towards small watercourses, drainage ditches and rivers. In addition to reducing the existing threats, the proposed solutions help increase the resilience of the entire ecosystem to extreme phenomena. In reality, all the tributaries of the Odra and its direct basin should be protected against the negative impact of pollutants if long-term and tangible effects are to be achieved.

APPLYING BUFFER ZONES AND HIGHLY-EFFECTIVE ECOTONES TO REDUCE THE TRANSFER OF DIFFUSE-SOURCE POLLUTANTS

Buffer zones at the intersection of land and water are among the most popular nature-based solutions. They assume the form of riparian, permanent vegetation such as herbaceous plants, rushes, willows, coppices, and also meadows put to extensive agricultural use. Ecotones situated between arable land and watercourses protect water ecosystems against the direct impact of farming activity, e.g. by reducing the movement of fertilizer components in the environment (Doskkey et al. 2010; Parn et al. 2012). Buffer zones help reduce the amount of pollutants transported via surface runoff and decrease the permeation of harmful substances present in shallow ground water into surface waters and the groundwater system.

In view of the above, proper management of buffer zones in river valleys is one of the most effective strategies aimed at ensuring a good quality of surface waters and groundwater. It is particularly recommended for buffer zones to be applied along small streams exposed to strong agricultural pressure, owing to high pollutant concentration in surface waters and groundwater in relation to the stream flow. In the case of both natural and artificial water bodies, restoration of buffer zones along their banks and shorelines can be regarded as the basic measure to protect the waters against pollutants from the catchment area used for agriculture. However, it should be borne in mind that certain boundary conditions need to be fulfilled:

1. Optimal buffer zones should be at least 10 meter wide. A 10-meter zone will not only guarantee a considerable degree of biogenic removal, but will also provide a sufficiently wide vegetation belt serving as a migration corridor for animals. Such a belt is typically quite narrow in relation to the adjacent field, therefore not excluding an excessively large area from agricultural production.
2. The effectiveness of buffer zones is determined by their continuous presence along the bank or shoreline. Continuous and narrow zones are more effective than zones which are wide but occur only along certain sections of the bank of a watercourse or shoreline of a water body. Special attention should be devoted to various kinds of per-



Left: a vegetated buffer zone reinforced with a denitrification wall intended to reduce nitrate pollution. Right: a vegetated buffer zone rinforced with a barrier of limestone or highly absorbent BioKer intended to reduce phosphorous pollution (modified from Izydorczyk et al. 2015).

Fig. 10. Enhanced ecotone zones as a tool for curbing dispersed pollution of agricultural origin

manent or temporary gaps such as furrows or depressions, which represent privileged runoff pathways and have the potential to significantly prevent the intended impact of the buffer zone.

3. Buffer zones need to be mowed every year. Mowing helps maintain them in early succession stages, when they have the greatest capacity to store organic matter. Such capacity wanes over time and a state of equilibrium evolves between accumulation and discharge. When the zone is saturated with organic matter, phosphorus and nitrogen may be released into water from the ecotone. Mowing is recommended along with the trimming of shoots and pruning of branches in late summer, and removing them later from the buffer zone before the nitrogen and phosphorus released during biomass decomposition penetrate into the soil and water (Izydorczyk et al. 2015).

Enhanced ecotones (Fig. 10) are among ecohydrological biotechnologies recommended in areas of heavy pollution of groundwater with biogenic compounds (Izydorczyk et al. 2015). These are riparian plant buffer zones, whose effectiveness has been increased by the installation of a denitrification barrier and/or a geochemical barrier, and which serve as a major tool in reducing the transport of biogenic substances from arable land to streams and water bodies. They can be used in intensely farmed areas, i.e.:

- in areas of heavy groundwater pollution;
- when the area is insufficient for a wide plant buffer zone to be put in place;
- in areas with shallow groundwater level near escarpments in those watercourses where water seepage can be observed (Izydorczyk et al. 2015).

APPLYING ORGANIC MANURE PLATES TO REDUCE CONCENTRATED POLLUTANTS

Organic manure plates offer an alternative to concrete-lined manure plates. Their function is to protect topsoil and water against the migration of nitrogen compounds (nitrates, nitrites and ammonia) from manure piles in farms which lack appropriate infrastructure to store organic fertilizers. Research shows that storing manure in a single location may lead to a considerable contamination of water, many times over the limit allowed under the Nitrates Directive (Bednarek & Zalewski 2007). Due to the shortage of organic carbon (humus) in the soil profile, natural denitrification processes need to be supported in areas of higher pollution with nitrogen compounds, nitrates in particular. Research has shown nitrate reduction following the use of organic manure plates ranging from 60% to as much as 90% (Bednarek et al. 2014). Denitrification bacteria which commonly occur in the soil reduce nitrates to nitrogen gas, using carbon compounds as electron acceptors in their growth. The key is to create optimal solutions for the functioning of microorganisms capable of transforming nitrogen and for enriching their population to accelerate the activation of newly constructed deposits and to increase resilience to environmental stress (e.g. hydrological drought or a significant pollutant load).

COMPENSATION BY REDUCING POLLUTANTS FROM STORMWATER INSTALLATIONS: SEQUENTIAL SEDIMENTATION-BIOFILTRATION SYSTEMS

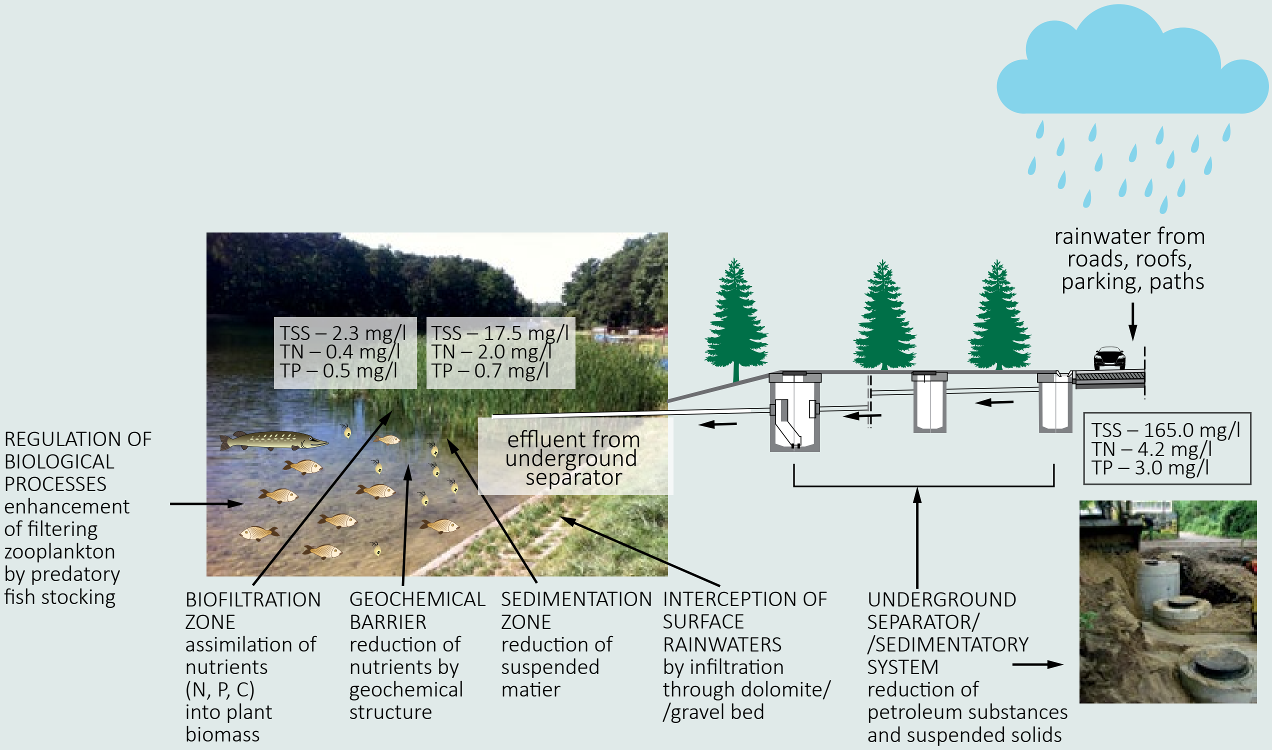
A sequential sedimentation-biofiltration system (SSBS) may be installed at the confluence point of a stream, canal or stormwater runoff, and may be modified depending on the size and type of inflow as well as the morphology and hydrological characteristics of the stream. The efficacy of such a system at reducing the inflow of organic substances is around 60%. If loaded with precipitation runoff from roads, the SSBS may be augmented with standard treatment facilities such as separators or settling tanks. Such facilities are not visible, being situated in the existing underground rainwater sewer pipes, have no adverse impact on landscape assets (hybrid systems, Fig. 11), and are much more effective (up to 90%) in removing pollutants.

In turn, the use of aquatic plants in a SSBS, and similarly in hybrid systems, apart from ensuring the reduction of inflowing biogenic substances, can also have a positive impact on other aspects of the functioning of a water body, such as providing habitats (hideaways, feeding and reproduction areas) for various bird, fish and invertebrate species.

The research and implementation work that has been carried out to date in the field of ecohydrology has gained increasing recognition – such as from the European Commission, as tangibly manifested in the granting of the LIFE program's "Best of the Best" award to the project entitled "Ecohydrological rehabilitation of recreational reservoirs Arturówek (Łódź) as a model approach to rehabilitation of urban reservoirs" LIFE08 ENV/PL/000517EH-REK, selected from the projects which were completed in 2016 and 2017.

The biotechnological structures employed in an SSBS have two components: the sedimentation zone and the biological zone, divided by a filtration geochemical barrier in the form of a gabion partition.

Thanks to its relatively large area, the sedimentation (upper) component of an SSBS facilitates effective interception of suspended matter transported to the receiving reservoir. Its size is adjusted to the amount of inflowing water from the stream or pipe during precipitation. Insufficient area of the sedimentation zone carries the risk of the gabion partition and/or vegetation growing in the other parts of the system becoming damaged by rainwater. The bottom of the sedimentation component is typically strengthened



Hybrid ecological system for the purification of rainwater from recreational areas (the project LIFE08 ENV/PL/000517, www.arturowek.pl

Fig. 11. A hybrid system created as a consequence of sequential sedimentation-biofiltration system (SSSB) with rainwater purification solutions

with open-work reinforced concrete slabs placed on geoxtile fabrics laid out on a filtering, gravel layer or on sand gravel. Such a structure, with a reinforced exit, allows easy removal of accumulated silt during the normal operation of the sedimentation tank. In sedimentation-biofiltration systems which operate as separate retention tanks, hydro-engineering solutions may be used to regulate the level of inflowing water; this enables temporary rainwater retention by its damming and then slow runoff during precipitation-free periods. For collecting rainwater from hard-surface areas (streets, pavements, parking lots, etc.), the SSBS should be connected to an underground network of separators and sedimentation tanks used for preliminary water treatment, mainly to remove suspended matter (sand, earth, leaves, tree branches and other fine organic matter) and oil-derived substances.

The gabion partition separating the sedimentation component from the biological component is filled with sorption material; it functions as a geochemical barrier which halts the suspended matter reaching the first part of the settlement tank and purifies the water flowing into the next zone in the process of chemical adsorption of chemicals. Ideally, the sorption material ought to be replaced once the sorption capacity is exhausted, and then reused. This is possible with BioKer, a special light ceramic aggregate which may be used again in the SSBS after regeneration (Jarosiewicz & Zalewski 2017). This invention has won prizes including the gold medal at Concours Lépine, an international innovation fair held in Paris in 2018.

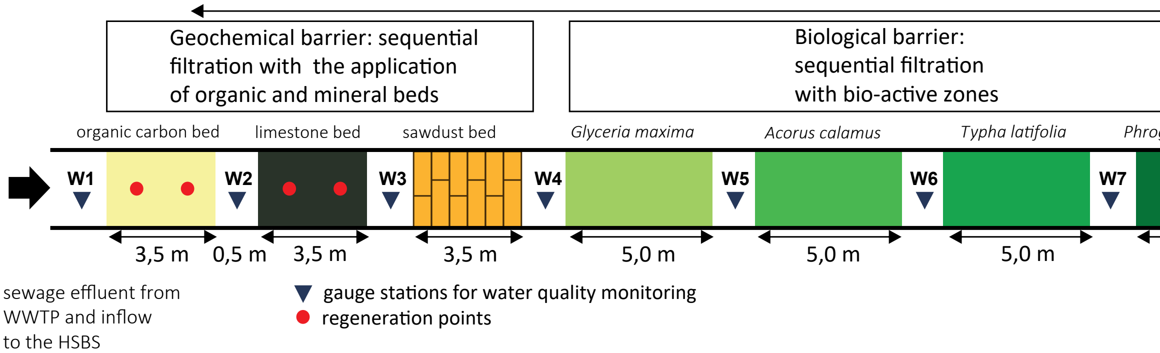
The biological (lower) component of an SSBS is the zone situated below the gabion partition, covered with native aquatic plants (e.g. narrowleaf or common cattails, lesser pond sedge, bottle sedge, greater pond sedge, wood clubrush, great manna grass, yellow flag, etc.), which reduces the amount of contaminants dissolved in water by their incorporation into the plant biomass (phytoremediation). It also improves the aesthetics and landscaping value of these solutions, enhances biodiversity in the natural system and provides habitats for many aquatic organisms.

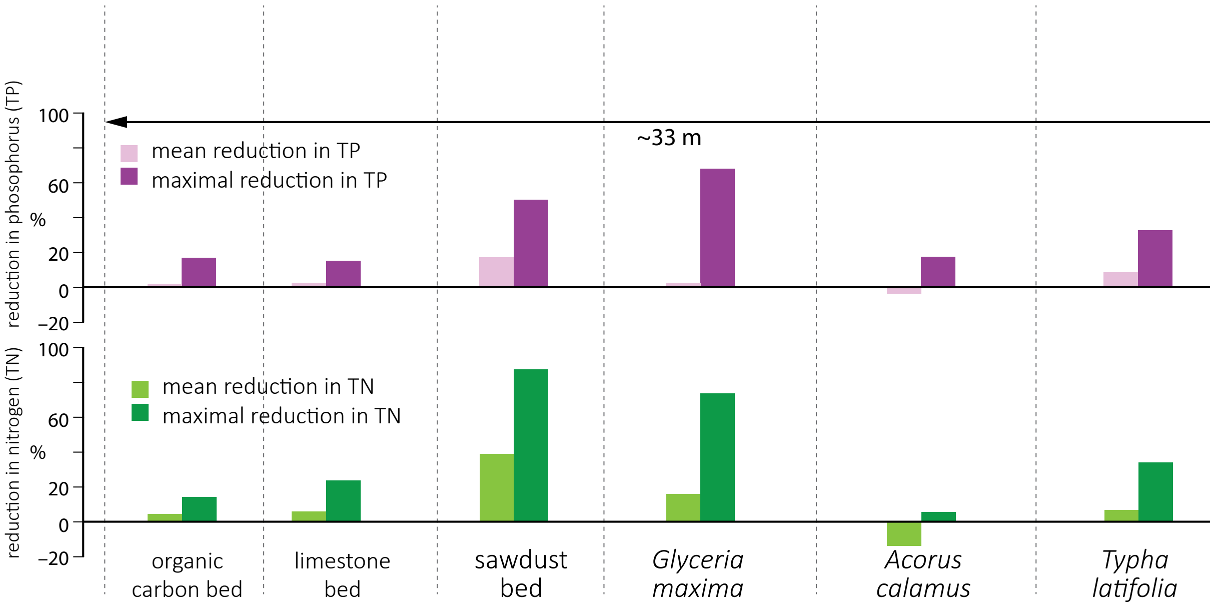
One significant element in designing solutions based on ecological (ecohydrological) biotechnologies is providing optimal conditions for the functioning of microorganisms, as they play a key role in nitrogen compound transformations, accumulation of phosphorus and metabolization of more complex compounds (pharmaceuticals, pesticide substances). In the case of nitrogen compounds, when an SSBS system is set up in order to foster the growth and endogenous activity of populations of denitrification and nitrification bacteria, zones with specially selected sources of organic carbon are applied.

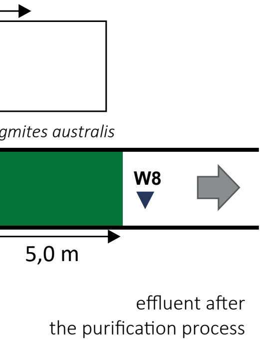
HYBRID SEQUENTIAL BIOFILTRATION SYSTEM FOR SMALL SEWAGE TREATMENT PLANTS

Municipal sewage discharged from sewage treatment plants is frequently a significant source of phosphorus and nitrogen and other, more complex contaminants such as pharmaceutical substances, hormone modulators or polychlorinated biphenyls. In many cases, small sewage treatment facilities find it more difficult to comply with the standards required for biogenic compounds concentration in discharged sewage than large plants which will often use more advanced technologies for their interception (Kiedrzyńska et al. 2012, 2014, 2017). Therefore, there is a need for additional systems, such as Hybrid Sequential Biofiltration Systems (HSBS), able to ensure extra treatment for effluents released into the environment. The role of the HSBS is to remove suspended matter, phosphorus, nitrogen, heavy metals and other contaminants from the effluent discharged from the sewage treatment facility in real operational conditions (Fig. 12).

A model HSBS can be found at a sewage treatment facility in Rozprza (Łódzkie Province, Poland). The system is an effective solution drawing on ecohydrological biotechnologies used by small waste water treatment plants – WWTPs (discharging up to 100 m^3 effluent per day) to improve the quality of the discharged effluent and to remove contaminants. The system can be tailored for larger sewage treatment plants through its extension and modification. The use of the HSBS as an element of additional treatment of effluent discharged from a treatment plant is an effective method which should be used to reduce the pollutant load discharged from point sources and to improve the quality of water in river basins. It is recommended that such extra treatment systems should be used below the outlet pipes from the sewage treatment plant not only in cases when the impact of hydro-engineering structures is in conflict with the outlet coordinates, but also as a compensatory measure. Since it is anticipated that the entire project may partly lead to the lessening of the littoral zone, which is extremely active in the process of pollutant removal, all point sources of contaminants should be additionally safeguarded using ecohydrological biotechnology methods.


Geochemical barrier: sequential filtration with the application of organic and mineral beds
Biological barrier: sequential filtration with bio-active zones
organic carbon bed
limestone bed
sawdust bed
Glyceria maxima
Acorus calamus
Typha latifolia
W1
W2
W3
W4
W5
W6
W7
3,5 m
0,5 m
3,5 m
3,5 m
5,0 m
5,0 m
5,0 m
sewage effluent from WWTP and inflow to the HSBS
gauge stations for water quality monitoring
regeneration points


reduction in phosophorus (TP)
%
100
60
20
0
−20
~33 m
mean reduction in TP
maximal reduction in TP
reduction in nitrogen (TN)
mean reduction in TN
maximal reduction in TN
organic carbon bed
limestone bed
sawdust bed
Glyceria maxima
Acorus calamus
Typha latifolia



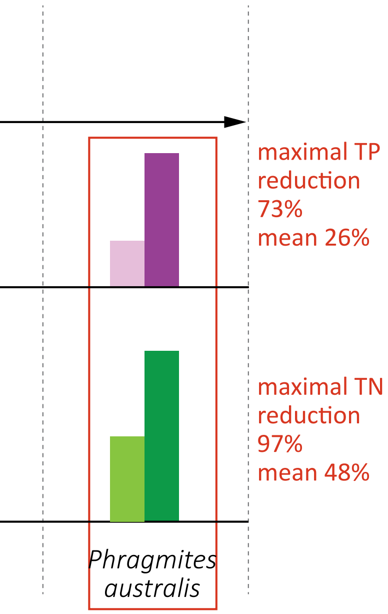


Fig. 12. The Hybrid Sequentional Biofiltration System is an innovative solution for small wastewater treatment plants (WWTPs), providing extra treatment of already treated municipal wastewater (Kiedrzyńska et al. 2017)

CONCLUDING REMARKS

As we noted in the introduction, in modern ecological terminology, the Odra River is classified as a "novel ecosystem" (Hobbs et al. 2006), i.e. one that has already been profoundly transformed by human activity and significantly modified in terms of both ecological and hydrological processes. This means that it is not a system which should be considered equivalent to a biosphere reserve, but rather a system where the natural and socioeconomic functions need to be harmonized with one another, further supplemented by a whole gamut of benefits gained by society.

Given the above assumptions, the science of ecohydrology provides a framework for enhancing the sustainable development of the river valley; it identifies the multidimensional goal of catchment management (the "WBRS+C approach", described above). Thanks to an in-depth understanding of the interactions between ecological and hydrological processes, principles can be formulated for how to implement innovative solutions aimed at minimizing negative impacts while also bolstering the environment's potential capacity to help mitigate the consequences of climate change.

In developing the Odra Waterway Development Program, a holistic perspective was adopted, whereby measures to adapt of the Odra River for use in navigation, which will help reduce carbon dioxide emissions (by promoting a low-emission form of transport), should also improve both the quality (through biotechnologies for pollutant reduction) and the quantity of the water (by boosting retention capacity), while also enhancing the biodiversity of the river and its valley so as to augment the benefits for the society. This also involves the use of the fairway for the development of tourism, while fostering more diverse habitats in the Odra River valley may bolster the attractiveness of the landscape and open up opportunities for active recreation. In turn, periodic damming, e.g. during low-flow periods, can help sustain the good condition of wetlands and small water bodies within the river valley and the neighboring ecosystems, which, in the face of the climate crisis, can provide refugia for multiple assemblages of organisms ranging from invertebrates to mammals.

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