Supplementary Material

Suplementary S1. Processes Driving Water Purification, Characteristics of Designated Types of Wetland Buffer Zones (WBZs), and the Scope of Work Needed to Create Each WBZ Type

Water purification by WBZs results from the removal and capture of nutrients present in waters moving from land to stream (or from an upper course of a river to its lower course). Specific nutrients include the available forms of nitrogen (N), that is, nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+), and forms of phosphorous (P) such as phosphate (PO_4^{3-}) and particulate P. These forms of N and P commonly originate from the runoff and leaching of synthetic and organic fertilizers applied to agricultural land. In addition, WBZs may also help in removing other pollutants, such as herbicides and pesticides, heavy metals, and biologically active compounds [70–73]. Several different processes of nutrient removal and capture by WBZs can be distinguished, however, their single importance in WBZ type described below is often poorly investigated.

(1) **Nitrogen removal via bacterial processes**, including nitrification and denitrification, have been comprehensively investigated [74,75]. Nitrification is the process of NH_4^+ oxidation to NO_3^- and NO_2^-, whereas denitrification is responsible for the reduction of NO_3^- to NO_2^- and further to nitrous oxide and molecular N_2, which leaves the system to the atmosphere. While nitrification requires an oxic environment, denitrification occurs both under anoxic and oxic conditions. Gradients of oxic and anoxic zones within WBZs allow for both processes to occur together, that is, effective simultaneous removal of NH_4^+ and NO_3^-/NO_2^-. Microbial processes are an important mechanism of N removal in both through-flow and flooded wetlands [76].

(2) **Nutrients capture by vegetation**. This process is important for both N and P and additionally also for other nutrients, especially potassium (K) that may sometimes lead to K-limitation and limiting of the nutrient capture function due to inhibited primary production [77]. Plants uptake nutrients from incoming waters and build them in their below- and above-ground tissues. This biomass can be further transferred to the next trophic level through herbivory (refer to point 6) or partly decomposed, returning nutrients to the system via detritus pathways (refer to point 7). Part of the biomass will decompose within the same season that it was produced, whereas another fraction remains alive for a number of seasons (e.g., roots and woody tissues). Part of the biomass may also be removed from the cycle for a longer period of time through being buried in organic sediments, particularly as peat, which can be stored for thousands of years. In riverine wetlands, peat is primarily produced from the roots of plants. Aboveground biomass can also be harvested manually and removed from the system (refer to point 3).

(3) **Nutrient removal through biomass harvest**. Aboveground biomass has been traditionally harvested in riverine wetlands for use as hay and litter in animal husbandries. During the last decades, the concept of paludiculture has emerged and gained importance as a means to commercially cultivate peatlands under wet conditions (though typically after re-wetting). This minimises carbon loss from the peat while keeping an economically productive status on formerly reclaimed (drained) peatlands [78]. Wetland agriculture can enhance the water purification function by removing nutrients from the system completely, while offering entry to circular economy to produce fodder, energy and building materials, or agricultural substrates from wetland plants.

(4) **Precipitation of PO_4^{3-} ions in the soil**. Phosphates make insoluble compounds with calcium and complexes with iron hydroxides, which may lead to P immobilization in riparian areas. However, these processes, especially with regard to iron, are redox-dependent, and thus increasing wetness and altering redox conditions can enhance the re-mobilization of P. WBZ soils with iron to P ratios above 10:1 are considered low-risk for rewetting, as PO_4^{3-} released from the soil would be resorbed to iron hydroxides at the soil surface (redox interface) [23]. A redox-stable and thus long-term Fe-P form is the precipitation of vivianite ($Fe_3(PO_4)_2{\cdot}8H2O$), which is

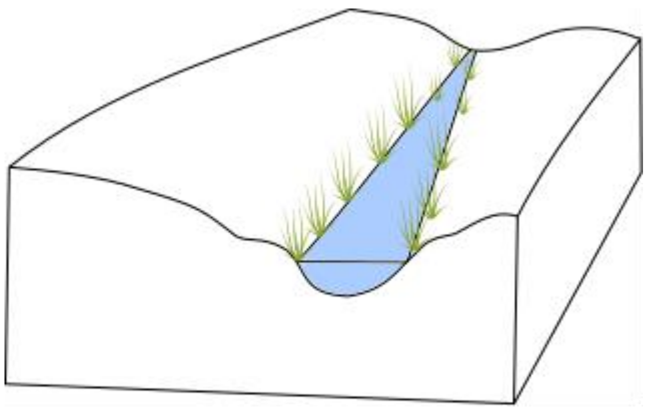
formed under anoxic conditions at high concentrations of ferrous iron and phosphate supported at increasing pH [23,79].

(5) **Physical sorption of PO_4^{3-} to mineral particles**. Orthophosphate ions adsorb to mineral particles present in soil or suspended in water, which contributes significantly to P removal from water. This suspended, particulate P, adsorbed to mineral particles may be deposited on river floodplains during flooding events, deposited in new sediment layers in low energy environments, or become incorporated in local biological cycles and partly removed with biomass harvest [80].

(6) **Deposition by flooding.** Temporal inundation with river water can deposit particulate P (orthophosphate ions adsorbed on mineral particles), organic matter carried by river water that decomposes after drop of water, as well as dissolved nutrients brought by flood water, which are captured by vegetation on the floodplain.

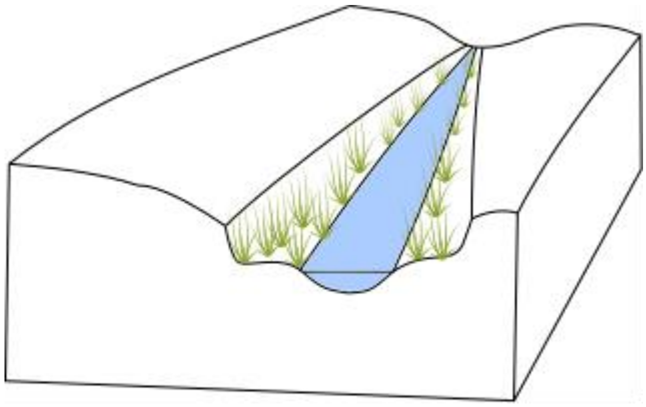
(7) **New autochthones sediment formation**. If permanently inundated conditions are created, a novel "shallow lake type" ecosystem may be created and a fine mud layer would form over the surface of the degraded peat. This accumulates through the sedimentation of fresh and decomposed organic matter. It can act as a sink but also a potential source for remobilisation of nutrients [81].

For a WBZ to act as a nutrient sink, it is necessary to have hydrological connectivity to incoming waters, thus allowing for biological, chemical, and physical processes to take place, lowering the nutrient content in water leaving the WBZ system. Nutrient removal describes the processes facilitating the export of specific nutrients from incoming waters, often through chemical changes to the nutrients, whereas nutrient capture is the process of retaining or uptaking nutrients dissolved in transfer water and storing it in the soil or biomass within the WBZ. Water transfer within each individual wetland will have a different character, depending on the type of WBZ involved and its particular eco-hydrological circumstances, for instance, seasonal influence or vegetation characteristics. The following WBZ types are differentiated in this work:



(I) **Wetland banks**—a narrow strip of "wet land" along the river achieved by raising the river water level. Higher water level in the river results in inundation of land in its proximity—the width of the rewetted zone should typically extend for at least several metres. This type of WBZ is difficult to set up along rivers that are deeply incised below the surrounding land; therefore, the method is more applicable to rivers flowing through organic soils, where channels are less inclined due to smaller eroding capacity of the stream. Because the inundated zone is not large, the risk of P remobilisation is not high, and thus in principle this WBZ type can be implemented both in organic and mineral soils. Vegetation harvesting can enhance nutrient removal but the potential of wet agriculture is usually limited by a relatively small area of rewetted land.

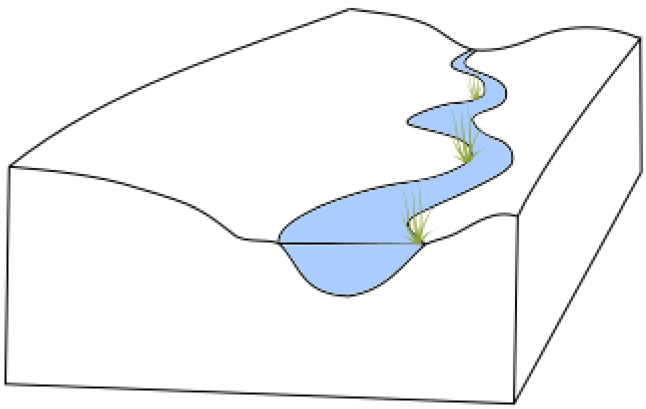
The scope of work needed: Planned works for this WBZ type were limited to small hydraulic structures in the channel (e.g., wooden trunks, stones). Numbers of structures required and included in budget calculations was established separately for each case with relation to water surface slope (approximately 1 structure per 0.5 m of slope).



(II) **Two stage channel**—a regulated channel is modified to form a two-stage profile, with adding space for wetlands on the upper terrace. Typical hydrological and geomorphological settings: this type of WBZ is especially beneficial if an intensive groundwater seepage occurs within the channel, because upper-level terrace retains nutrients arriving with groundwater even in the drier season when the river water is restricted to a part of the narrower low-flow channel. Further, this type of WBZ is recommended along heavily modified rivers when no re-meandering is possible (e.g., due to geomorphological settings or existence of infrastructure). Application of this technique in ditches and rivers cutting through organic soils should, however, be done with caution—while on one hand the removal of degraded peat or moorsh layer may prevent it from re-mobilising phosphorus, on the other hand one should take into account the loss of organic carbon with removed layer and potential enhancement of greenhouse gas emissions. Vegetation harvesting on the upper terrace can enhance nutrient removal but the potential of wet agriculture is limited by the relatively small area available.

The scope of work needed: Estimated costs include costs of preparatory works, that is, the removal of current vegetation (on the basis of field surveys and Google Earth maps, it was assumed that on average 20 trees will be removed per 1 km of watercourse, whereas 30% of the belt area would require removal of bushes), earthworks (excavating the floodplains and levelling of the excavated soil), bank strengthening, construction works aiming to raise water level in the channel (wooden trunks, stones or threshold with water overflow, up to 0.5 m high; type and number of structures needed was calculated on the case by case basis, taking into account average water surface slope (approximately one structure per every 0.5 m of slope)), and rebuilding of existing infrastructure (mainly road culverts; number calculated on a case-by-case basis). Furthermore, it was assumed that implementation of this kind of WBZ would require land purchase in a 2 m-wide belt each side of the stream.

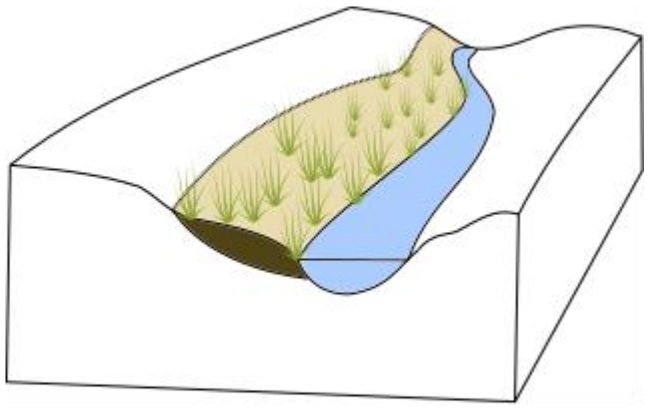
Calculations were based on a standardized profile of a two stage channel, uniform for all WBZs of this type. They were based on size of the stream planned for WBZ development and actual field conditions in the surrounding valley. The main assumptions regarding profile included a symmetrical channel (i.e., floodplain terraces on both sides of low waters channel), slope of banks of 1:1, width of main channel bottom at 0.5 m, and width of floodplain at each side of the main channel at 1.25 m.



(III) **Meandering channel**—a section of naturally meandering or re-meandered river can act as a WBZ towards the lower section of the river or another river of higher order. When working with rivers flowing through organic soils, care should be taken for conservation of carbon stocks when excavating new channels in peat. In the proximity of the river, wet agriculture has limited potential due to typically difficult access and variable relief; however, flooding of adjacent areas, which often results from re-meandering, can create good conditions for wet agriculture.

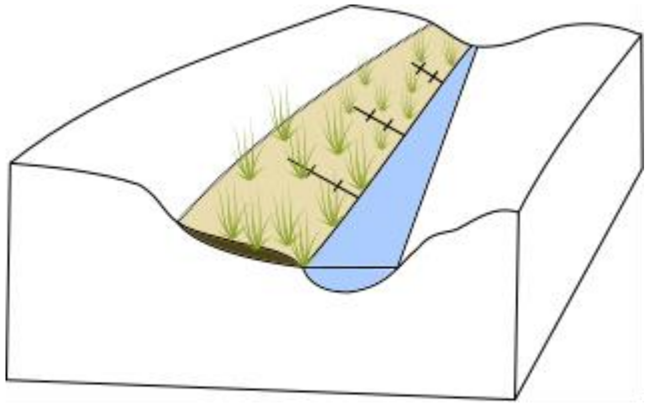
The scope of work needed: Three sites were selected for placement of this WBZ type within sub-catchments studied. Extent of works and associated costs were calculated separately for each case, as standardization attempts failed. For two sites, costs included removal of trees and bushes, dredging the meandering channel, construction of dammings directing the water to newly built meandering channel sections, and building new culverts necessary after the change of channel course. For the third WBZ, which assumed the use of an existing, old river bed, planned earthworks included both the building of sections of a new channel and deepening the old, unused channel section. Construction works, in this case, included building a structure sourcing the old channel section and road culverts. In all three cases, costs also included land purchase for the areas covered by the project.

(IV) **Fen**—peat-accumulating wetland, typically developing in groundwater discharge sites, usually dominated by sedges but sometimes also reedbeds, shrubs, and trees; undrained fens should be distinguished from rewetted fens that have previously been drained (and usually utilised agriculturally), in effect forming a layer of heavily mineralised peat (so-called moorsh soil). They are defined into two separate categories. This WBZ category differs from WBZ type 5.1. (floodplains with organic soil) in that here the water level is constantly high, whereas on the floodplains it strongly drops below the ground surface in the period between floods.



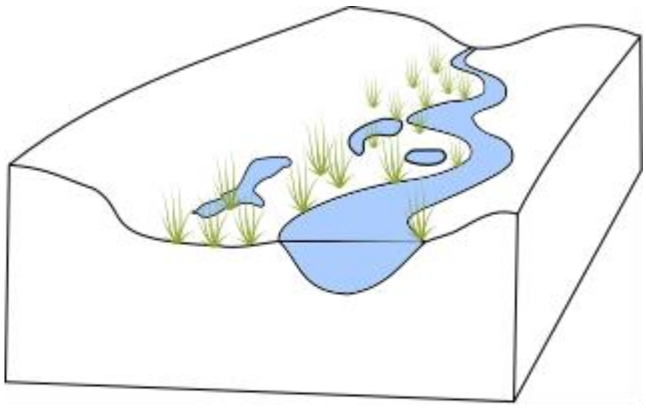
(IVa)**Undrained fen**—groundwater-fed peatland that lacks a heavily mineralized peat layer, typically covered by peat-forming plant communities (sedges, brown mosses). Existing active fens should be preserved, whereas restoration of once-drained fens is difficult due to compaction of peat, but can be attempted by the removal of the degraded, upper peat layer. This measure should be considered in areas with an intensive groundwater seepage; usually high water level in the river should be ensured by rising river water level. Fens are potentially suitable sites to implement wet agriculture (paludiculture) and have been commonly used as hay meadows. However, species-rich and naturally resilient fens may vanish due to mowing and driving with machinery, therefore passive conservation should have priority in such sites.

Costs of maintaining existing undrained fens were assumed as being zero, because neither construction works nor special payments are needed in comparison to the current status.



(IVb) **Rewetted fen**—fens that have been drained and, as an effect of that, the upper part of their peat deposit that mineralized and turned into 'moorsh' soil can be treated as WBZ only after rewetting, which reduces their carbon and nitrous oxide emissions and re-establishes conditions for denitrification. Only sites with water levels close to peat surface (or above) for most of the year can be classified here. After rewetting of a drained fen, phosphorus bound to iron in the soil may re-mobilize from the soil due to lowered redox potential; therefore, this WBZ type is recommended especially where content of phosphate ions bound to iron hydroxides in the soil is low. Rewetted peatlands are recommended sites for wet agriculture, called in this case "paludiculture" as a means of simultaneous nutrient removal (particularly counteracting P remobilisation) and soil-carbon conservation.

The scope of work needed: Budgeting necessary costs of these polygonal WBZ was based on the analysis of individual field conditions for each site planned for development, including density of existing drainage network. Building of one new weir per 200 ha of area planned for re-wetting was assumed. Width of structures was established case by case, in relation to the width of the stream.



(V) **Floodplains**—areas periodically flooded by river water with strongly alternating water levels; due to different geochemical processes and prospects of wet agriculture operating in floodplains with mineral and organic soil, we distinguished these two categories.

(Va) **Floodplains with organic soils**—distinguished as a separate category because, in addition to sedimentation during peak flow, they may also act as more effective denitrification areas than floodplains with sandy soils, whereas on the other hand P remobilisation from organic sediments due to internal eutrophication may counteract nutrient sink function. Floodplains on organic soil may be either natural wetlands, commonly with a shallow layer of muddy peat or degraded fens, with the after-effects of former drainage and subsidence on peatlands. The latter type will change from groundwater through-flow mires to surface water flooded wetlands with a change in river water levels. Input of sulphide-rich water from the river may lead to internal eutrophication and phosphorus mobilisation to surface waters; phosphorus bound to iron in the soil may also re-mobilize during flooding due to lowered redox potential, and therefore establishment of flooding regime on former fens should only be done in sites where these risks are assessed as low. Floodplains on organic soil may be suitable sites for wet agriculture; however, periods of low water level may cause degradation of organic soils and loss of carbon. Vegetation harvest may particularly counteract P remobilisation from the soil, because vigorously growing plants may rapidly take up free phosphate ions.

No WBZs belonging to this type were proposed in the analysed sub-catchments.

(Vb) **Floodplains with mineral soils**—most floodplains, with muddy or sandy soils and low organic matter contents can be regarded as effective P removal sites through sedimentation and removal of both N and P via uptake by vegetation. Maintaining a high water level in the river is usually necessary in order to enhance flooding. Ox-bows and back swamps present on floodplains facilitate nutrient removal. Floodplains are excellent areas for promoting wet agriculture due to the high potential for nutrient removal with biomass and an easy to mineral ground during low water level periods. They have been traditionally used as pastures or hay-meadows.

The scope of work needed: Costs included only construction of weirs with shutters, enabling flooding of areas in the stream valley. Width of weirs was established, case by case, in relation to the width of the stream.