10.A. CONSTRUCTED WETLANDS: HOW TO COMBINE SEWAGE TREATMENT WITH PHYTOTECHNOLOGY

Operation of constructed wetlands is based on a detailed understanding of ecohydrological processes in different types of natural wetland systems. In the purification of sewage/water, both abiotic and biotic processes are involved. By employing evolutionary established regulation processes (see „green feedback concept", Zalewski et al., 2003) it is possible to optimize these systems. For planning high efficiency or long-term use of wetlands, these systems need additional management such as plant harvesting, fishing, and sediment removal.

Fig. 10.1
Constructed wetland for storm water
Karls-Einbau Project Company
(photo: EKON Polska Biologia Inzynieryjna Sp. z o.o.)

WHEN TO APPLY CONSTRUCTED WETLANDS

Constructed wetland can be applied to:

- treatment of **sewage from small settlements**;
- treatment of **municipal and industrial sewage**;
- **storm water** treatment (Fig. 10.1);
- purification of outflow from a sewage treatment plant for stabilization, reduction of nutrients, reduction of microbial and other pathogens;
- treatment of **surface runoff from arable land** (Fig. 10.2); and
- for use as a clean-up process in closed water cycles for industry or for water reuse.

The key challenge for the ecohydrology concept is converting potential threats, e.g., water pollutants, into opportunities such as energy sources. This new challenge of sustainable development can be achieved by combining water purification systems with the production of biomass in constructed wetlands, which can be utilized as bioenergy for local communities and provide them with economic profits (Box 2.8).

WHAT ARE THE ADVANTAGES OF USING CONSTRUCTED WETLANDS?

- they utilize solar energy driven purification processes;
- the establishment of a constructed wetland is rather simple compared to building a sewage treatment plant (there is no need for specific building equipment);
- if available land is not a limitation, the longevity of large systems is calculated to be 50 - 100 years;
- properly designed, they are self-sustaining systems;
- because constructed wetlands are very productive systems, it is possible to combine wetlands with economic profits for local communities using proper phytotechnologies (fast gowning plants: willows, reeds, or other native species for a region); and
- combining constructed wetlands with specific phytotechnologies, like phytoextraction or rizodegradation, can solve specific water pollution problems such as heavy metals and organic compounds.

WHAT PROBLEMS CAN BE SOLVED BY CONSTRUCTED WETLANDS?

The following processes take part in constructed wetlands and solve respective environmental problems (see Guidelines Chapter 5):

- **denitrification** whereby nitrate is denitrified under anaerobic conditions in a wetland and organic matter accumulated in the wetland provides a carbon source for microorganisms converting nitrate to gaseous nitrogen - oxygen conditions can be regulated by water flow rates;
- **adsorption of ammonium and metal ions by clay minerals** - the adsorption process can be regulated by addition of various minerals during the filter design,
- **adsorption of metal ions, pesticides, and phosphorus compounds** by organic matter, and

the complexing of metal ions by humic acids and other organic polymers, which significantly reduces the toxicity of these ions - stimulation of humus-forming processes;

- **decomposition of biodegradable organic matter**, either aerobically or anaerobically, by microorganisms in the transition zone - creation of proper microhabitats;
- **removal of pathogens** that are out-competed by natural microorganisms within the transition zone; UV radiation plays an important role;
- **uptake of heavy metals and other toxic substances** by macrophytes to varying degrees of efficiency; proper selection of plants and regulation of oxygen conditions using the water regime;
- **decomposition of toxic organic compounds** through anaerobic processes in wetlands, which depends upon the biodegradability of the compounds and their retention time in a wetland;
- for regions with **eutrophication problems**, the use of additional materials with high concentrations of magnesium, calcium, iron, and/or aluminum, increases phosphorus sorption; and

Fig. 10.2
Constructed wetland for surface runoff from arable land, Japan
(photo: V. Santiago-Fandino)

- enhancement of **sedimentation** of TSS in wetlands for storm water treatment by using a sequence of different plants.

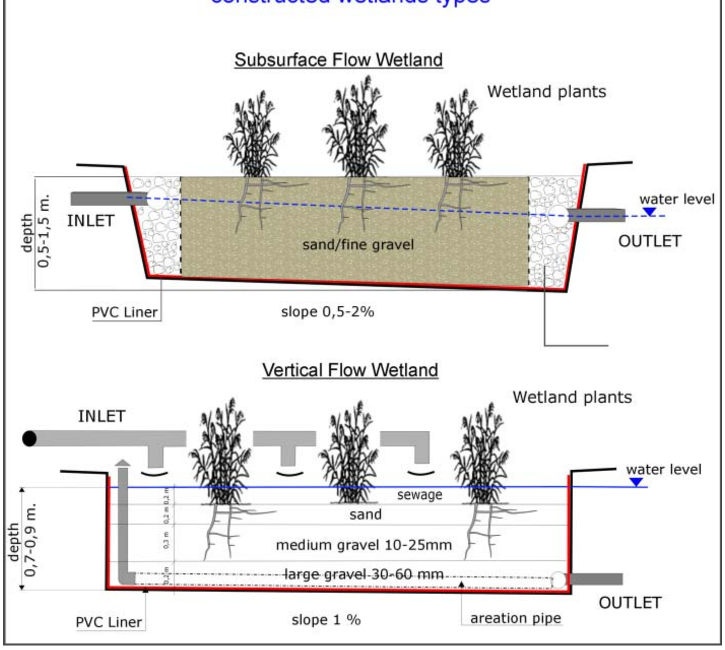
HOW TO DESIGN A WETLAND

Preliminary criteria

To **optimize the efficiency** of a constructed wetland, all possible potential processes should be carefully quantified at the design stage.

The following aspects should be taken into account: region, climate, key contaminants, main purpose, health aspects (e.g., pathogens, malaria). Examples of **typical constructed wetlands** are demonstrated in Box 10.1. In order to enhance the efficiency

BOX 10.1
The cross-section for the most popular constructed wetlands types



of purification, newly constructed systems comprise of sequential systems, with several - sometimes more then 5 - stages of purification. For example, in a typical system the following stages can be applied:

- horizontal subsurface flow;
- vertical flow; and
- stabilization pond(s).

The combination of various wetland systems increases the efficiency of BOD and nutrient removal, even up to more than 90%.

The **preliminary criteria** to be considered in order to construct a properly planned wetland should include:

- **type of outflow** to be controlled, e.g., need for preliminary treatment or use of a multi-functional system combining different types of constructions;
- **hydrogeological** characteristics of a site;
- surrounding **landscapes** provide the conditions for one of the following wetland types:
  - overland flow;
  - surface flow;
  - subsurface flow; and
  - ponds.
- **available space** and the price of land;
- **possible additional economic profits** for local communities;
- the **cost** decrease for treating sewage.

Plants to be used in wetlands

Use of native species is recommended in wetlands. For this purpose, recognition of vegetation communities in natural wetlands and land/water ecotones is recommended. The following plant types can be used:

- **emergent species**: cattails, bulrushes, reeds, rushes, papyrus, sedges, manna grass and wil-lows;
- **submerged species**: coontail or horn wart, redhead grass, widgeon grass, wild celery, Elodea, and water milfoil; and
- **floating plants**: duckweed, water meal, bog mats and water hyacinth.

Specific criteria

The following specific criteria will influence the efficacy of wetlands:

- **hydrology and size**:
  - water retention time;
  - hydraulic conductivity;
  - water depth; and
  - length to width ratio.

TABLE 10.1
Summarized design criteria for constructed wetlands

	UNIT	OVERLAND FLOW	SURFACE FLOW	SUBSURFACE FLOW	PONDS	PONDS FOR STORM WATER
Need for preliminary treatment	-	Preliminary or secondary	Preliminary or secondary	Preliminary or secondary	Preliminary or secondary	sedimentation area
Specific treatment area	Ha 1000 m^{-3} day^{-1}	6-67	0,8-12	0,25-3,5	0,2-1,5	not applicable
Specific treatment area	m^2 PE	10-25	3-25	1-10	2-5	
Hydraulic loading rate	cm day^{-1}	1-10	0,5 -12	3-40	5-20	
Detention Time	days		7-10	2 - 15	0,5 - 14	0,1-5
Average Water depth	m	<0,1	0,1-0,5	0,5-2 depth of filter	1,5 - 4	0,5-1,5
Length to width ratio	-	5:1	2:1	6:1	1:1	15:1

PE – person equivalent
Preliminary treatment – the first step in sewage treatment consists of screening and sedimentation of particulate solids.
Secondary treatment – wastewater treatment beyond initial sedimentation; the second step of treatment includes biological reduction of particulate and dissolved compound concentrations.

(Vymazal et. al, 1998; Kadlec & Knight, 1995)

- **wetland soil**:
  - organic content;
  - clay content; and
  - soil water capacity.
- **contaminant concentration**:
  - presence of heavy metals (application of specific phytotechnologies is recommended; see chapter 9.A);
  - organic compounds - phytodegradation;
  - N - denitrification;
  - BOD;
  - TSS; and
  - P - use of additional materials for sorption.

The design criteria are summarized in Table 10.1.

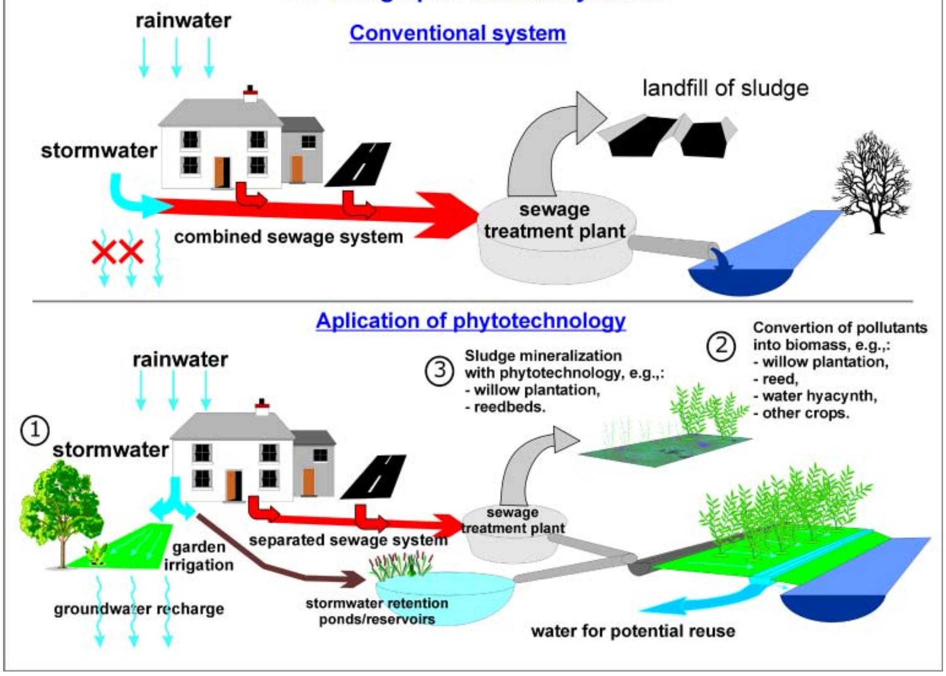
HARMONISATION OF TECHNOLOGIES AND ECOLOGICAL METHODS

There are several advantages of the harmonization of technologies with ecohydrology and phytotechnology application in sewage purification. The following can be listed among the most important ones:

- increase of the efficiency of pollutants removal (in case of nutrients it reach even more than 90%);
- decrease of investments for sewage treatment systems;
- decrease of operational costs of treatment systems;
- stabilizing hydrological cycles in a local scale;
- converting pollutants into renewable energy resources;
- decrease of waste (sludge) production; and
- creating of employment opportunities.

The example of the approach to combining technical and ecological solutions is given on the simplified schemes in the Box 10.2.

BOX 10.2
Application of phytotechnology in sewage purification systems



MAKE SURE TO CHECK THESE RESOURCES:

Guidelines: chapters 5.H-5.Q, 7.A
Mitsch & Jorgensen 2004
http://www.gpa.unep.org/documents/sewage-docs.htm
http://www.cep.unep.org/pubs/techreports/tr43en/Small%20community.htm
http://www.epa.gov/owow/wetlands/construc/content.html
http://www.waterrecycling.com/constwetlands.htm

10.B. ECOTONES: HOW TO DIMINISH NUTRIENT TRANSPORT FROM LANDSCAPES

One premise of the ecohydrological approach is the enhancement of ecosystem resilience in order to protect it from disturbance. At the landscape scale, resilience is a function of the area occupied by biogeochemical barriers that create nutrient storage. From the point of view of freshwater quality improvement, land-water ecotones are one of the most important biogeochemical barriers in a landscape. This chapter introduces basic methods related to use of natural properties of terrestrial and freshwater ecosystems toward reducing nutrient exports to fresh waters.

Fig. 10.3
An example of a natural ecotone zone (photo: K. Krauze)

HOW TO DESIGN AND CONSTRUCT A BUFFERING ZONE

Plant buffering zones may have natural or artificial origins. For ecological, economic and aesthetic reasons it is recommended to preserve or enhance natural ecotone zones rather than build artificial ones.

In some areas, however, due to lack of natural buffering zones or high pollution loads, it maybe necessary to create artificial buffering zones or to modify existing ones.

There are several factors that have to be considered before preparation of an action plan:

- the geomorphology of the area;
- hydrological dynamics, e.g., water level fluctuations, timing and the range of extreme events;
- plant species composition in natural land / water ecotones in the area;
- species - specific efficiency of nutrient removal, growth rate, decomposition;
- interactions between plant species; and
- planned use of an area (for recreation, agriculture, etc., see Box 10.4).

Geomorphology

It has been shown that incline is an important factor determining the rate of nutrient reduction in buffering zones. Muscutt (1993) demonstrated that for plant strips with a width of 4,6 m located on an incline of 11%, a 73% reduction of total phosphorus transport to a water body could be achieved. The efficiency was only 49% when the incline was 16%. Similarly for wider strips (9 m), the reduction rates were 93% with an incline of 11% and 56% with a 16% incline.

It is also highly recommended to reduce the bank slope, if possible, before building an ecotone. This will reduce the risk of bank erosion and, therefore, transport of matter into the water (Petersen et al., 1992). Moreover, the widening of a river channel will enhance the process of wetland development and help to disperse the energy of peak flows. Finally, a larger floodplain is conducive to sedimentation processes.

Species composition

It has to be underlined that artificial and modified buffering zones should reflect the natural biodiversity (use of alien species should be avoided), zonation and patchiness of vegetation in an area if they are to be efficient.

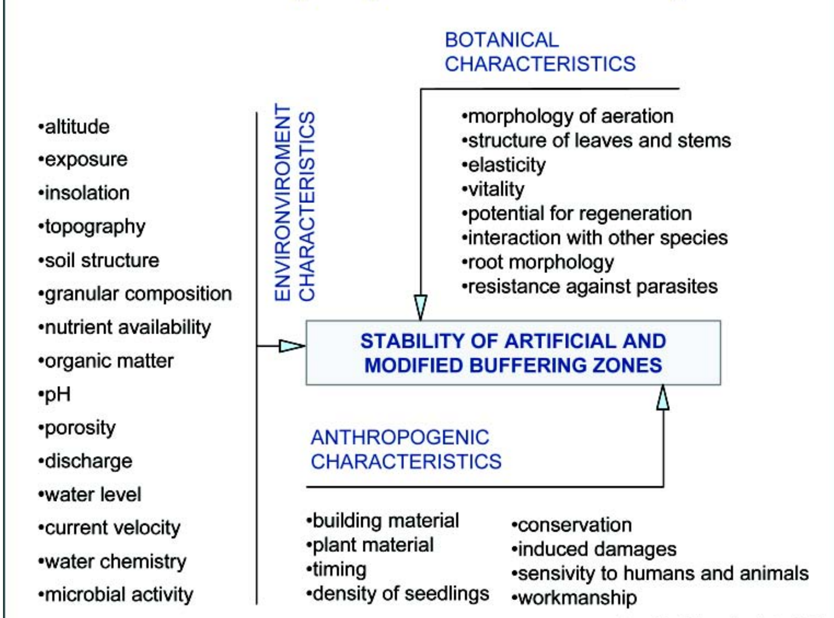
Trees

Tree species are elements of buffering zones that are able to store nutrients for longer times and do not require time-consuming conservation. They also regulate the dynamics of herbs, grasses and shrubs (Boyt et al., 1977).

They should be distributed in an irregular way and at a distance of 4-5 m from one another. To avoid linear patterns, which are unusual in nature, it is also recommended to use different tree species, with different heights and to leave some gaps between trees.

Species that strongly shade the ground should be used carefully (oaks, beech, conifers) and plan-

BOX 10.3
Factors determining stability of artificial and modified buffering zones



(modified from Lechat, 1991)

ted with other species like birch, willow, rowan tree, ash or hazel.

Shrubs

The most popular shrubs used in buffering zones are willows. Different species of willow provide a broad range of possibilities as they have species-specific adaptations to water level, nutrient concentrations, and different rates of nutrient accumulation and distribution of accumulated contaminants among plant organs.

Efficiency of nutrient uptake by willow strips maybe enhanced by cutting furrows in the ground (as it increases water retention in ecotones).

Grasses

Grasses are highly applicable in infrequently flooded areas. They are not as efficient in nutrient uptake as other plant species, but they may play important roles in reduction of bank erosion.

Grasslands require very intense care and conservation as species composition changes easily due to disturbances (increased nutrient supply, prolonged flooding, etc.).

The choice of grass species should be made on the basis of the following rules:

- the most resistant are species that form deep roots;
- to enhance biomass production it is necessary to use a diverse grass composition; and
- as grasses are used to fasten soil on banks and scarps, it is important to use them with poor, sandy soils on slopes distant from water and with fertile soils on a riverside.

TABLE 10.2
The rate of biomass increase of some wetland species

Artificial buffering zones often require careful management. It is especially important when introducing macrophytes. They efficiency in nutrient accumulation is often directly related to their high productivity. On the other side to maintain a buffering zone it is important to remove the biomass seasonally, which has to be calculated in terms of time and cost necessary for conserving an ecotone.

SPECIES	INCREASE OF BIOMASS ($kg\ ha^{-1}\ year^{-1}$)
Typha	8 000 - 61 000
Juncus	53 300
Scirpus	7 130
Phragmites	10 000 - 60 000
Hydrocotyle	30 000 - 60 000
Lemna minor	6 000 - 26 000
Salvinia	9 000 - 45 000

(modified from Reddy, DeBusk, 1987)

Macrophytes

The most popular species of macrophytes are emergent ones, like reeds. They are valuable in building biochemical barriers because they not only accumulate nutrients, which can be easily removed after plant harvesting, but some of them are able to oxygenate sediments (e.g., *Phragmites, Typha*). In this way they enhance development of microorganisms and increase oxidation process rates.

TABLE 10.3 (A)
Phosphorus and nitrogen assimilation by macrophytes

Phosphorus and nitrogen accumulation by different macrophyte species		
SPECIES	N uptake [kg ha^{-1} year^{-1}]	P uptake [kg ha^{-1} year^{-1}]
Typha	600 - 2 630	75 - 403
Juncus	800	110
Scirpus	125	18
Phragmites	225	35
Hydrocotyle	540 - 3 200	130 - 770
Lemna minor	350 - 1 200	116 - 450
Salvinia	350 - 1 700	92 - 450

(Kadlec & Knight, 1996 after Reddy & DeBusk, 1991)

There are several factors which one should consider when planning to use macrophytes in ecotone zones. The most important are:

- growth rate;
- nutrient uptake and accumulation rate;
- hydroperiod ; and
- decomposition rate (Tables 10.2-10.4).

In general

There are several components which are used in constructing wetlands along rivers and reservoir shores. The most common are:

- sedimentation ponds;
- by-passes;
- ditches for surface flow collection;
- willow zones;
- tree and shrub zones;
- floating macrophytes zones;
- submerged macrophytes zones; and
- embankments, etc.

Their sequence has to be planned according to local requirements (Box 10.4).

TABLE 10.3 (B)
Phosphorus and nitrogen assimilation by macrophytes

Percentage phosphorus and nitrogen accumulation by different macrophyte species		
SPECIES	N uptake [% of dry weight]	P uptake [% of dry weight]
Bidens sp.	no data	0,582
Mentha aquatica	no data	0,584
Typha latifolia	1,37	0,21
Typha laugustifolia	0,8-22,9	0,1-0,5
Phragmites communis	2,57	0,18
Glyceria maxima	0,4-4,6	0,1-0,8
Juncus effusus	1,24	0,27
Scirpus sp.	1,22	0,18
Acorus calamus	1,3-3,7	0,1-0,9
Schoeplecyus lacustirs	0,6-2,6	0,1-0,5
Sagittaria	no data	0,827
Nuphar luteum	no data	6,2
Lemna sp.	1,5-7,2	0,6-2,8
Ceratophyllum demestrum	1,8-4,5	0,1-0,8
Elodea candensis	1,8-7,7	0,1-1,4
Myriophylum spicantum	1,4-4,1	0,1-0,7

(Bazan, 1998; Kadlec, Knight, 1995 after Boyd, 1978; Reddy, Ozimek, 1991; DeBusk, 1987)

TROUBLESHOOTING

There is little or no influence of ecotones on the chemistry of waters

Sometimes it may happen that plant communities do not influence the chemistry of ground water passing an ecotone. One of the common reasons is the geological structure of the area. Due to the arrangement of different water permeability layers, pollution may, **instead of passing a plant root zone, go with ground water directly to the river, or reservoir.** The only way of avoiding this problem is to know the geology of the region and distribution of point and non-point sources of pollution.

Buffering zones release nutrients

There are three common reasons for this phenomenon:

1. Biogens are stored in plant biomass and soil structures. Prolonged nutrient inflow to a buffering zone may occasionally cause a decline of bio-

diversity and, therefore, reduction of biomass production. It may also lead to saturation of soil and ground structures. In these cases, an ecotone is no longer effective as a biofilter and starts to release nutrients.

For these reasons it is very important **properly plan, monitor and managebuffering zones**.

2. The ability of ecotones to reduce nutrient concentrations in water changes seasonally, and depends on species composition, species phenology, growth rate, etc. Nutrients that were accumulated during the growing season are released at its end due to an increase in litter production and decomposition. The process maybe controlled and reduced by using **plant** species, which are easy to **maintain, cut and remove**.

In temperate regions the growing season starts when water temperature reaches 7^{0}C and ends when it drops below 10^{0}C (Bernatowicz & Wolny, 1974). Reeds have the longest life cycle but submerged macrophytes are often active throughout the year.

3. Exceeding the threshold tolerance of plant species to concentrate nutrients causes plant buffering zones to degrade. The process has been well documented for submerged macrophytes, e.g., for *Elodea canadensis* and *Elodea nuttali* - the critical concentration of nitrogen in water is 4 mg L^{-1} (Ozimek et al., 1993).

Vegetative season end

Even after the end of a growing season there are still processes that may improve water quality.

It was found that the denitrification rate is low, but stable even when air temperatures drops below 5^{0}C. This is possible because the ground water temperature is usually higher, and stays stable during winter.

High efficiency of ecotones is also maintained if seasonal plant harvesting is carried out. It prevents secondary nutrient release after plants decompose and retains the whole system at an early succession stage, which is more effective for nutrient uptake. For management purposes it is better to use species that accumulate nutrients in leaves and stems instead of in roots.

TABLE 10.4
Tolerance of some typical land/water ecotone species to hydrological conditions

In land/ water ecotones water plays an especially important role. It may support plant development, but can also stop it leading to degradation of ecotone functions. Therefore, one of the factors, that has to be considered is the hydroperiod. It is defined by the time when the community is flooded and the depth of the water covering plants (Gunderson, 1989).

SPECIES	maximum tolerable water depth [m]	Time of flooding [%]
Fontinalis	0,1 - 1,5	80 -100
Elodea	0,1 - 3,0	90 -100
Myriophyllum	0,25 – 3,0	90 -100
Nuphar	0,5 – 3,0	90 -100
Hydrocotyle	<0,005 – 1,0	25 -100
Salix	0,1 – 0,5	50 -100
Sagittaria	0,2 – 0,5	50 -100
Carex	0,05 –0,25	50 -100
Scirpus	0,1 – 1,5	75 -100
Phragmites	<0,05 – 0,5	70 -100
Iris	<0,05 – 0,2	50 -100
Juncus	<0,05 – 0,25	50 -100
Typha	0,1 – 0,75	70 -100
Glyceria	<0,05 – 0,3	0 -100

(modified from Kadlec & Knight, 1996)

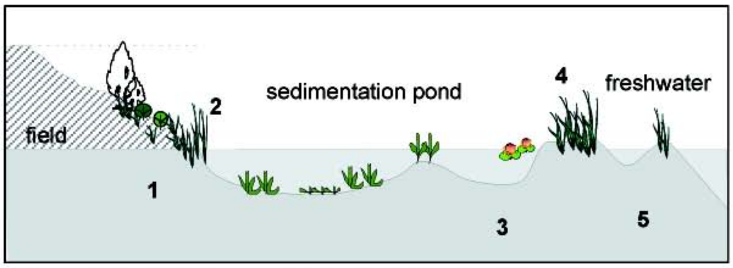
CONCLUDING REMARKS

The use of ecotones as a tool for water and environmental quality improvement is concordant with the ecohydrological approach. Buffering zones enhance natural resilience of water ecosystems against human impacts, are easily applicable, have good cost/benefit ratios, and may provide additional sources of income for local communities. It is, however, highly advised to combine protection of water resources with riparian zones and large scale landscape planning. The aim has to be a counterbalancing of the impacts of human activity at a catchment scale. According to Mander & Palang (1996) this has to be hierarchically organized, and include:

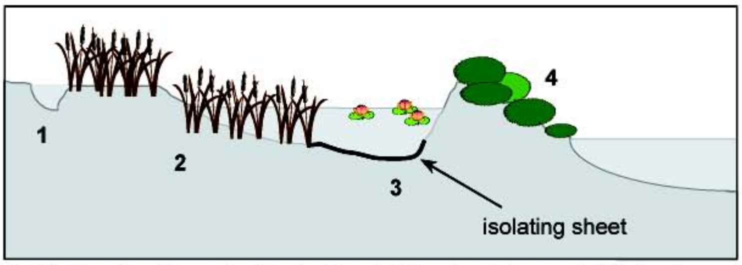
- core areas;
- buffer zones of core areas and corridors; and
- natural development areas to support recovery of the resources.

BOX 10.4
Proposed structure of ectones

PROPOSED STRUCTURE OF ECTONES AIMED AT PROTECTING RESERVOIRS

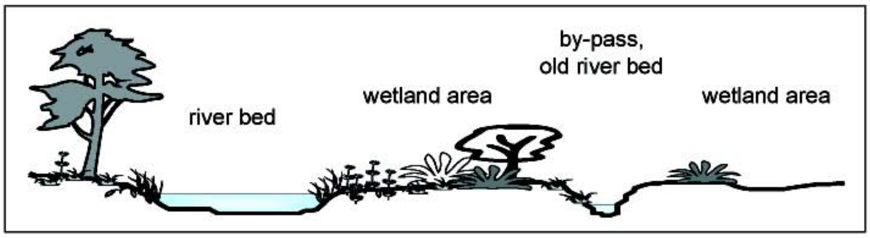


1. trees, shrubs *(Salix, Quercus, Betula, Alnus);* **2.** rushes *(Phragmites, Typha, Saggitaria, Scirpus, Hydrocotyle);* **3.** sedimentation ponds *(Nuphar , Lemna, Spirodela, Wolffiella);* **4.** rushes *(Iris, Juncus, Glyceria, Carex, Phragmites);* **5.** ditch; **6.** embankment covered with grasses and rushes *(Carex)*

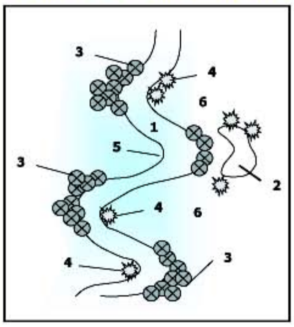


1. ditch; **2.** rushes *(Phragmites, Typha, Glyceria);* **3.** sedimentation ponds *(Nuphar , Lemna);* **4.** Shrubs *(Salix)*

PROPOSED STRUCTURE OF AN ECOTONE AIMED AT PROTECTING A RIVER



SCHEME OF PLANT DISTRIBUTION ALONG THE RIVER BED



1. main river bed
2. old river bed, by-pass
3. area of compact tree vegetation
4. single trees or shrubs
5. open river bed (enable easy access to water)
6. wetland areas

It is suggested to situate compact tree cover only along the north and north-east banks (up to 100 %). Along the south, south-east and south-west banks tree cover should be more dispersed. It is not advised to apply dense tree and shrub cover along the river sections longer than 50 m.

MAKE SURE TO CHECK THESE RESOURCES:

Guidelines: chapters 4.E, 5.B-5.G

http://www.eman-rese.ca/eman/ecotools/protocols/terrestrial/vegetation/glossary.html

http://www.gisdevelopment.net/aars/acrs/2000/ts12/index.shtml

■ 10.C FLOODPLAINS AND NATURAL WETLANDS: REDUCTION OF NUTRIENT TRANSPORT

Rivers are located in the lowest parts of landscapes and therefore collect and transport pollutants downstream from catchments. In many regions, nutrients coming from non-point (dispersed) sources add up to more than 50% of the total nutrient load. Prevention of nutrient export from landscapes (see chapters 9.C, 10.A) is, therefore, necessary. The measures presented in this chapter prevent transfer of pollutants downstream via river systems. Lately it has been postulated that naturally flooded areas with evolutionarily developed vegetation can be very effective for this purpose (Science, 2002).

Fig. 10.4
Lowland river floodplain - the Pilica River, Poland (photo: I.Wagner-Lotkowska)

WHY ARE FLOODPLAINS IMPORTANT?

Floods are a natural element of undisturbed hydrological cycles of rivers. Floods occur with various frequencies, depending mostly on climatic characteristics of a region. During these events, large amounts of matter and nutrients derived from both landscape and riverbed erosion is deposited and retained in flooded areas. Consequently, floodplains are usually enriched with the transported material and, at the same time, river waters are purified by loss of this material. Floodplains can, therefore, serve as **natural cleaning systems** for reducing suspended matter, phosphorus, nitrogen and other nutrients and pollutants.

Floodplains are also very effective systems for **retaining water**. They can hold up to 1.5 million gallons of floodwater per acre. If they are destroyed, e.g., regulated and limited by engineered structures, the water that would have been contained within them to prevent flooding can no longer be stored effectively. This creates a flood risk in areas located downstream.

*Preservation of natural, and restoration of degraded, floodplains **improves the quality of water** and **stabilizes hydrological parameters** of rivers.*

FLOODPLAINS ALONG A RIVER CONTINUUM

A river system's characteristics change considerably along its **longitudinal dimension** (see chapter 3.F). Therefore, the role of floodplains also changes depending on their location in the river continuum.

In the case of **upland rivers**, catchment slopes are usually steep and - especially in impermeable, e.g., rocky areas - the retention of water in landscapes is often limited. In these cases, floodplains usually play an important role as a **flood prevention tool**. Their limited capacity in terms of water retention can be increased **by dry** pools. These can be filled during a flood event. The role of upland river floodplains in water quality improvement is less important than in lowland areas. Steep slopes usually restrict expansion of agriculture and, thus, the impact of these types of catchments on water quality is often low, unless deforestation is occurring.

In the case of **lowland rivers**, floodplains play a double role -**as both water quality and quantity tools**., They provide extensive areas for sedimentation of material transported from a catchment as the area of floodplains is usually greater than in upland rivers. Due to their diversified morphology and increased development of biomass, they also create conditions for a variety of other processes that can purify flood waters. At the same time, water retention in a landscape reduces propagation of flood waves downstream and reduces flood-induced hydro-peaking and low flow periods.

WHAT PROCESSES CONTRIBUTE TO WATER QUALITY IMPROVEMENT IN FLOODPLAINS?

Among the various processes taking part in nutrient retention in floodplains, the following are the major ones:

- **sedimentation, filtration**, and **sorption** of particulate matter within wetlands due to long water retention times and large sediment surface areas;

- **assimilation** of dissolved nutrients from both flood surface waters, as well as floodplain ground waters,, by vegetation (**phytoremediation of nutrients**);
- **oxidation** and **microbial transformation** of organic matter in sediments; and
- **denitrification** of nitrogenous compounds by microbial action.

HOW TO ENHANCE NUTRIENT UPTAKE IN A FLOODPLAIN

The following four-step approach can be applied to elaborate a basis for the use of floodplains for nutrient load reduction:

- identification and **release of flood waters** with the highest organic matter and nutrient content to a floodplain area;
- **optimising conditions for physical sedimentation** of transported material on the basis of a hydraulic model of the area;
- **shaping the spatial distribution and composition of plant communities** of a floodplain based on it's geomorphology and hydraulic characteristics; and
- **enhancing nutrient assimilation** and retention in biomass.

Releasing of flood waters high in nutrient content

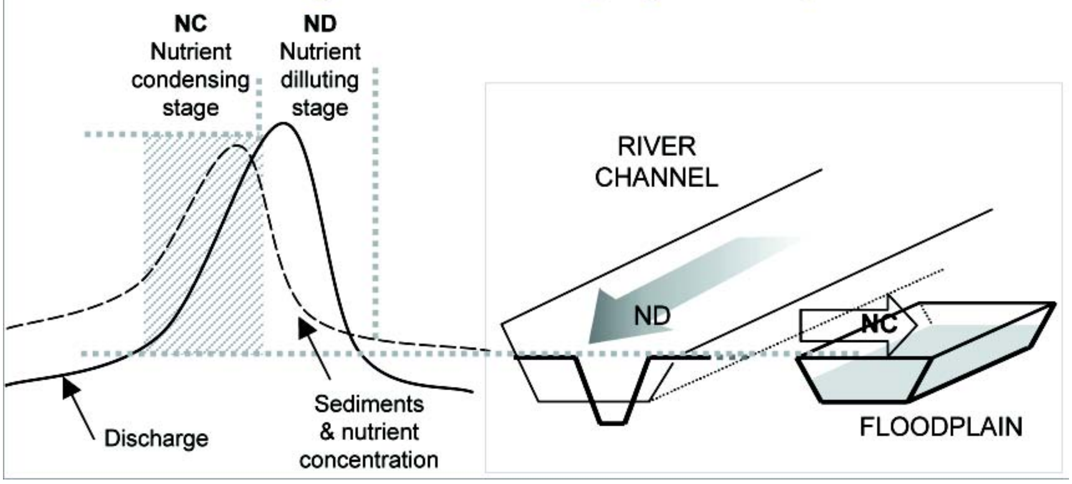
The timing of nutrient loads transported by rivers is determined by several factors interacting with each other and changing over a year (Owens & Waling, 2002; Meybeck, 2002). Climate, catchment characteristics and river hydrology are usually considered to be the major ones (see Guidelines, chapter 7). The mechanisms of nutrient concentration changes with discharge are usually related to hydrological cycle pathways, and the role of its particular components in runoff formation from a catchment (Genereux & Hemmond, 1990; De Walle et al., 1991; Rice et al., 1995; Pekarova & Pekar, 1996; Russel et al., 2001). Usually, in the case of degraded catchments with a considerable contribution of non-point source pollutants, the concentration of nutrients during high water periods increases (Galicka, 1993; Chikita,1996, Wagner & Zalewski, 2000; Zalewski et al., 2000). Surface runoff resulting from precipitation results in enhanced erosion and nutrient leaching and, thus,nutrient supply from a catchment.

In general, the following assumptions can be made:

- Nutrient concentrations during **moderate floods** are higher than during **flash floods**, when dilution of transported contaminants can occur (Wagner-Lotkowska, 2002). During flash floods nutrient loads can also be high, due to high hydraulic loading.

BOX 10.5

Releasing of nutrient concdensing stage into a floodplain



- Nutrient concentrations within a given river are greater during **frequent moderate floods** than during events of **longer duration, lower variability** and comparable hydraulic load. Nutrient loads transported in the first case are usually higher (Wagner-Lotkowska, 2002).
- The highest nutrient concentrations and loads during medium floods occur during **the first phase of a flood**, while the flood waters are rising (**nutrient-condensing stage**). In this phase of a flood, nutrient loads trans ported by a river are the highest (Wagner & Zalewski, 2000).
- Before river discharge reaches its maximum, nutrient concentrations and loads start to decrease and continue to decrease during the period following the flood peak (**nutrient-dilution stage**). The relationship between nutrient concentration and discharge often has the form of a clockwise hysteresis (Zalewski et al. 2000).

According to the above assumptions, in order to **improve the quality of water**, floodplains should be designed to retain nutrient and contaminant masses during the nutrient-condensing stage of moderate flow events (Box 10.5). Flooding can be controlled by adjusting the height of the threshold between a river and flooded area so that the inflow to the floodplain occurs at a specific level when nutrient concentrations start to increase during a rising hydrograph. This level should be determined empirically.

How to calculate nutrient load

A nutrient/pollutant load is the total amount of the nutrient/pollutant transported by a river, entering/leaving a lake or reservoir via a river, or from a pollution source over time.

$$L = C * Q$$

L - nutrient/pollutant load [mg day^{-1}]
C - concentration [mg L^{-1}]
Q - hydraulic load [L day^{-1}]

Optimizing conditions for physical sedimentation

Morphology of a floodplain determines the hydraulics during inundation of an area. The hydraulics determines not only water retention, but also about efficiency of sedimentation. Development of a hydrodynamic model of a floodplain, or an area being considered for use as a tool to improve water retention and quality, is important in the first stage of planning. Sedimentation can be enhanced by modification of the physical structure of an area and management of its vegetation cover.

Shaping the spatial distribution and composition of plant communities

Understanding and applying **phytotechnologies on floodplains** is important for two reasons: first, vegetation distribution determines the **hydraulics of an area**, and second, plant community composition controls the efficiency of dissolved **nutrient uptake and retention**.

Natural distribution and predomination of individual plant species is to a great extent dependent on the frequency of inundation and groundwater level (Box 10.6). Grass communities and rush vegetation usually appear on the highest parts of a floodplain. In periodically wet areas, hay meadows occur. Reedy rushes (e.g., *Caricetum gracilis* and *Carrex vesicaria*) occur in small mid-meadow hollows. Common reeds (*Phragmitetum australis*), with common reeds (*Phragmites australis*) as the dominant species, appear in places consistently covered by water, such as old river beds, where they form extensive monotypic aggregations.

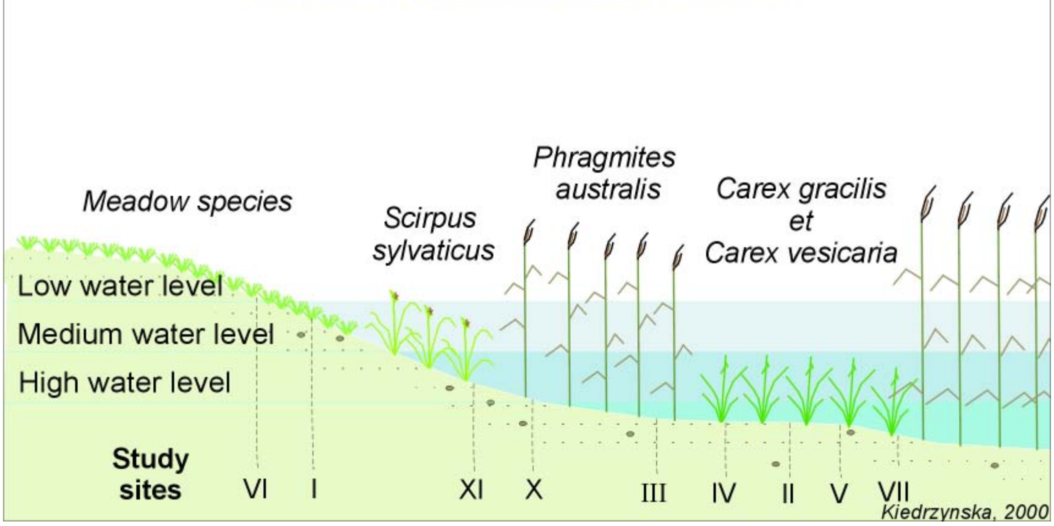
Maintenance of this biodiversity enhances the ecological stability of a floodplain ecosystem, as well as the efficiency of purification. Each of the communities is usually most effective in terms of biomass production and nutrient uptake under their optimal conditions.

Enhancement of nutrient assimilation processes

Knowing the potential **capability of** certain species of specific plants **to sequester nutrients** is very important for estimating the amount of nutrients that can be accumulated per surface unit. This capability depends on **biomass production and percentage of nutrient accumulation**.

As water and temperature are the major driving forces for biological processes, the greatest increase in biomass takes place in summer (temperate re-

BOX 10.6
Distribution of vegetation depending on water level

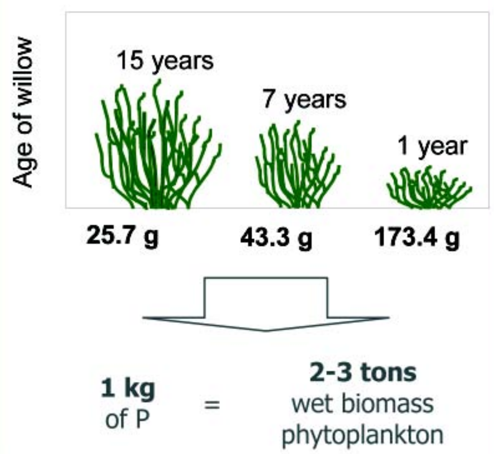


gions) or during wet seasons (tropics). The size of the peak summer biomass is important in a plant development cycle, as it determines to a great extent the amount of nutrients that can beaccumulated.

Biomass production depends on a plant species or community type. For example, reedy rushes can achieve a biomass of 14 000 kg of dry mass ha^{-1}, sedge rushes and rushes of the forest bulrush - 3 800 and 2 800 kg ha^{-1}, respectively; common reeds (*Phragmites australis*) - between 30 000 and 35 000 kg; reeds - between 6 000 and 35 000 kg of dry mass ha^{-1} (Seidel, 1966; Bernatowicz & Wolny, 1974; Koc & Polakowski, 1990; Ozimek & Renman; 1995). According to Goldyn & Grabia (1996), the harvest of grasses in a summer period totals between 11 000 and 14 000 kg of dry mass ha^{-1} (for more information, see chapter 10.B). The ability of plants to **accumulate phosphorus** in their tissues usually ranges from 0.1 to 1% (Fink, 1963). It may, however, vary considerably with different **plant species**. For example, the phosphorus content in the biomass of the common reed, *Phragmites australis*, ranges between 0,01 and 0,5%. For Carex species, the percentage phosphorus in the dry mass falls within the range of 0,08 to 0,8% (Bernatowicz & Wolny, 1974; Szczepanski, 1977; Ozimek, 1991; Kiedrzynska, 2001). Phosphorous in the biomass of *Scirpus americanus* amounts to 0,18% (Kadlec & Knight, 1995).

In some species, phosphorus storage differs depending on **plant age** (Box 10.7). Therefore, the management of vegetation focused on maximizing nutrient uptake should take these aspects into consideration. For example willow are usually removed every three years, what compromise between nutrient removal and economic benefits - high biomass, energetic value and efficiency of harvesting. To maximize phosphorus uptake in biofiltering systems, the vegetation should be properly managed. The best results are achieved by creating in-

BOX 10.7
Ammount of phosphorus removed with 100 kg of *Salix purpurea*



termediate patches of different types of land cover because it causes the vegetation to better adapt to abiotic conditions and increases the biodiversity of the area. Vegetation should also be seasonally removed from wetlands, e.g., every 3-5 years in the case of willows. This is because willows maintain the highest growth rate and effectiveness of phosphorus uptake within this period (Zielinska, 1997). Removing vegetation after the growth season prevents the release of nutrients back into the water in autumn.

MYCORRHIZA - HOW PLANTS ADAPT TO HIGH WATER LEVELS

The soil around plant roots are enriched with **symbiotic organisms, such a bacteria and fungi**, which create suitable conditions for plant growth. The microbiological activity of a rhisosphere is crucial for plant growth and natural resistance to pathogens (Azcón-Aguilar & Barea, 1992; Smith & Read, 1997; Linderman, 2000). Symbiotic fungi are an important component. Mycelium penetrate the top layer of soil, connecting sand grains in larger aggregates (Koske et al., 1975; Sutton & Sheppard, 1976) or excreting substances that act as a glue for soil particles (Miller & Jastrow, 2000). Due to mycelium, the absorbing surfaces of roots are much better developed, which improves nutrient transport to plants (e.g., Cox & Tinker, 1976).
Fungi colonize more than 90% of plant species in natural ecosystems (Read et al., 1992).
Mycorrhizal, mutual symbiosis is widespread in all kinds of environments. Two types are recognized:

- ectomycorrhizae; and
- endomycorrhizae.

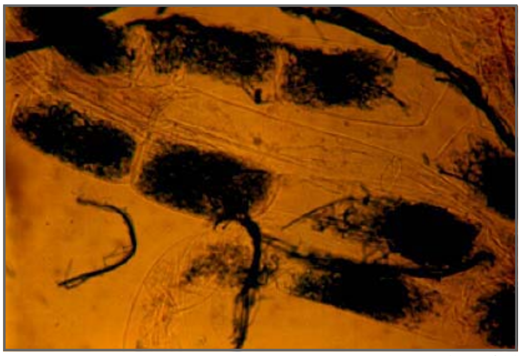


Fig. 10.6
Arbuscule in Hypericum sp. cells
(photo: B. Sumorok)

Fig. 10.5
Black mantle on Populus tremula roots
(photo: B. Sumorok)

In **ectomycorrhizal symbiosis** the mantle (Fig. 10.5) is connected to highly branched hyphae that **penetrate the root and grow between cells**. This hyphal network (hartig net) is the site of nutrient exchange. **Endomycorrhizal fungi** produce a highly branched hyphal structure called an arbuscule **within a plant cell** - it is the site of nutrient exchange (Fig. 10.6).
In temperature zone forests ectomycorrhiza are dominant, which is in contrast to tropical forests and herbaceous communities where endomycorrhiza are more important (Harley & Smith, 1983).
Mycorrhizal plants are more and more frequently used for restoration processes and for bioremediation - **phytostabilization, phytodegradation and phytoextraction**. Selected species bind and accumulate heavy metals in their tissues (Bloomfield, 1981; Blaylok et al., 1995; Salt et al., 1995) and can be removed from reclaimed areas by cutting (Kumar et al. 1995).
In the process of reclamation of polluted areas, the reed *Phragmites autralis* is used; the mycorr-

hizal status of this plant can vary from non-mycorrhizal to mycorrhizal (Harley & Harley, 1987; Willby et al,. 2000, Oliveira et al., 2001). The plants most frequently used as biofilters are different species and varieties of willow, which can be either ecto- or endomicorrhizal (Harley & Harley 1987).

RECOMMENDATIONS FOR PHYTOTECHNOLOGICAL APPLICATIONS IN FLOODPLAIN AREAS

Results obtained in the first year of implementation of the UNESCO/UNEP Demonstration Project on Application of Ecohydrology and Phytotechnology in IWM (Pilica River, Poland) provided information on the application of phytotechnology in floodplain areas.

The following recommendations have been formulated for willow planting:

Recommendations for willow planting

- only extensive willow planting can be applied in floodplain areas;
- no, or only shallow, ploughing is to be applied prior to establishment of willow patches in order to minimize soil erosion and leaching of nutrients;
- **no fertilizers and other agents** can be applied so as to prevent an increase of eutrophication, or nutrient pollution;
- monocultures of energetic species can not be planted in order to **preserve the natural biodiversity in river corridors**. The structure of **patches of autochthonous vegetation and autochthonous/energetic willows** (if allowed in a given region) should be maintained. Controlled patches of energetic wil low should not exceed 30% of a floodplain area. Results of research on the rate of growth and phosphorus accumulation by various vegetation communities and willow species showed that application of various vegetation patches enhances phytoremediation processes. This results from adaptation and optimum growth of particular species in various environmental conditions. In order to optimize biomass growth and phosphorus accumulation, vegetation should be adapted to the timing of flooding and number of days with high ground water and surface water levels.

Socio-economic aspects

Floodplain areas are natural, self-sustaining systems where purification processes are driven by natural forces. Combining water purification, due to specific phytotechnologies like phytoextraction or rizodegradation, can not only solve specific water pollution problems, but also provide other benefits. Using fast gowning plants (willows, reeds, or other native species in a region) can provide economic profits for local communities. According to the ecohydrology concept, potential threats, e.g., water pollutants, can be converted into opportunities such as energy sources. Biomass production, which can be later utilized for bioenergy, is such an example.

Development of the logistics for bioenergy utilization in a region can involve not only the biomass produced on a floodplain, but also that from **forestry** and agricultural overproduction (e.g., **straw surplus**). An alternative solution can be the introduction of specialized **energy crops** - especially willow - in areas remote from river corridors.

MAKE SURE TO CHECK THESE RESOURCES:

Guidelines: chapter 7