018530 - SWITCH

Sustainable Water Management in the City of the Future

Integrated Project
Global Change and Ecosystems

D5.3.1: Literature review on the use of natural systems in urban water management

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SWITCH WP 5.3 - Maximizing the use of natural systems in urban water management

D5.3.1: Literature review on the use of natural systems in urban water management

The hydrological water cycle runs via a wide variety of ecosystems, and is aided by bio-geo-chemical activities in these natural systems. The processes in natural systems relating to water purification and remediation can be employed for effective urban water management in two ways: a) by applying the processes of natural systems in 'eco-technologies' (e.g. AWWT, constructed wetlands, stabilization ponds), or, b) by employing full scale natural systems (e.g. river bank filtration, natural wetlands, phyto-technology, eco-hydrology).

One of the first products of this work package has been a thorough literature review:

- Part A: Wastewater treatment by microphytes and macrophytes: a review for SWITCH Learning Alliances and Researchers
- Part B: Urban ecohydrology: Ecohydrological restoration of aquatic habitats in urban areas - aims, constraints and techniques

Two conference presentations have been based on part A of the literature review:

- ROUSSEAU D.P.L. and E. SALATI FILHO (2007). Wastewater reuse and nutrient recovery as tools for water resource protection: how can natural systems contribute? Proceedings Latinosan 2007, Conferencia Latinoamericana de Saneamiento, 12-16 November 2007, Cali, Colombia.
- ROUSSEAU D.P.L., J.J.A. VAN BRUGGEN, P. VAN DER STEEN and P.N.L. LENS (2009). Constructed treatment wetlands contributing to the paradigm shift in sustainable urban water management. Proceedings 'Sustainable Development - a Challenge for European Research' conference, 26-28 May 2009, Brussels, Belgium (http://ec.europa.eu/research/sd/conference/2009/index_en.cfm).

More detailed literature reviews on specific aspects of the technololgies and approaches can be found in the numerous MSc and PhD theses that have been produced in this workpackage (see deliverable D5.3.12).

Wastewater treatment by microphytes and macrophytes: a review for SWITCH Learning Alliances and Researchers

SWITCH Deliverable D 5.3.1. - part A

Drafted by UNESCO-IHE and UNIVALLE

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GENERAL INTRODUCTION (*based on Phan Van, 2006*)

Water scarcity has been increasing all over the world and in many countries may become absolute by the year 2025 (Seckler et al., 1999). This problem becomes more apprehensive when recognizing that the severity of surface water pollution is a worldwide problem (Yan et al., 1998; Nhapi and Gijzen, 2005). To tackle the problem, several measures for sustainable water resource utilization have been developed, of which wastewater reclamation and reuse is currently one of the top priorities (Anderson et al., 2001; Chu et al., 2004).

Many different technologies for wastewater reclamation have been designed. However, they are generally based on highly optimized physical, chemical and microbial processes (Brix, 1999). As a result, they are technically sophisticated and therefore not affordable for financially weaker societies. Countries with an annual Gross Domestic Production (GDP) per capita of US$ 300 to 400 are most likely not able to reclaim their wastewater even with a very common conventional technology like activated sludge (Gijzen, 1998). Developing countries, therefore, have very few opportunities to access the conventional technologies. Within this context, it is thus important to find an appropriate alternative for reclaiming wastewater in developing countries. On top of that, conventional technologies are also known to consume large amounts of energy and chemicals during the treatment process (Oswald, 1995), making them in many cases – be it in developing or developed countries – not the most sustainable solution.

Recent years have therefore witnessed a major shift in the reclamation strategies for wastewater from high-tech to environmentally sound, sustainable, low-cost and effective technologies based on ecological principles, namely ecological technology (Saha and Jana, 2003). In many cases they offer a more holistic alternative to improve the environmental quality.

In contrast to conventional technologies which are mainly constructed of steel-reinforced concrete, the ecological technology for wastewater reclamation involves establishing natural aquatic ecosystems which comprise components containing water, e.g. ponds, and bioresources locally available, e.g. macrophytes (Pearson, 1996; Saha and Jana, 2003).

The environmentally-sound attribute of ecological technology is its capability of resource recovery and reuse. For instance, nutrients in nitrogenous and phosphorous wastewater compounds are recycled into usable biomass by means of the ecological food chains functioning in aquatic ecosystems (De Pauw and Salomoni, 1991). Contrarily, in conventional technologies, instead of converting them into a protein source of a usable biomass, the nutrients are treated in quite expensive ways (Mujeriego et al., 1999). For example, they convert organic nitrogen to nitrate and then nitrogen gas by mechanized processes, and it requires two or three kilowatt-hours for each kg of N_2 released (Oswald, 1995). Thus, it is clear that ecological technologies can tackle the waste stream in a more integrated and holistic way.

The different types of natural systems for wastewater treatment or ecotechnologies correspond with the different ecosystems along the land-water gradient, starting from the land-side with high-rate infiltration fields, overland flow systems, constructed wetlands and finally waste stabilisation ponds or lagoons. The latter two are by far the most popular systems, and will be the further subject of this review.

CHAPTER 1 – MACROPHYTE SYSTEMS

CONSTRUCTED WETLANDS

1.1. HISTORY AND APPLICATIONS OF CONSTRUCTED WETLANDS

Although wastewater treatment is a relatively young technology, avoiding septic conditions by evacuating wastewater from human settlements has a considerable history. Angelakis *et al.* (2005) for instance describe the advanced sewer system at Knossos (Crete), dating from the second millennium B.C. Bertrand-Krajewski (2002) elaborates on the 'Cloaca Maxima' in ancient Rome and on early sewer systems in London and Paris, while Poulussen (1987) strikingly depicts the development of water sanitation in Antwerp (Belgium). Once outside the city boundaries, the wastewater was often conveyed to nearby natural wetlands which at that time were considered as useless lands (Vymazal, 1998a; Kadlec *et al.*, 2000a).

From the fifties and sixties of the past century on, however, ecologists started to realise the value of these wetlands and initiated many studies on this topic. They more or less unintendedly discovered the purification capacities of these wetlands which set off the development of constructed wetland technologies. The first relevant research seems to be the one by Dr. K. Seidel at the Max Planck Institute in Plön (Germany) as early as 1955, but it was not published in English before 1976, thus hindering dissemination of the acquired knowledge. Her research also seemed heavily criticised since the investigations and calculations were mainly aimed at nutrient removal through plant uptake which would require a regular harvesting regime and very large surface areas (Vymazal, 1998a).

Due to a growing 'green awareness' in the seventies, the practice of dumping wastewater in natural wetlands was abandoned in favour of constructed wetlands (CWs). Another positive boost was possibly due to the first energy crisis in 1973. Energy-devouring technologies all of a sudden lost their attractiveness to the advantage of the low-energy ones. Indeed, natural systems for wastewater treatment are characterised by the use of renewable, naturally occurring energies such as solar and wind energy, as opposed to conventional treatment technologies which are highly dependent on non-renewable fossil fuel energies. The above-mentioned stimuli soon outweighed the classic distrust against new technologies and, from then on, constructed wetlands development took an exponential growth. Kangas (2004) summarised this early period and called it the 'big bang model' of constructed wetlands' development (Fig. 1.1).

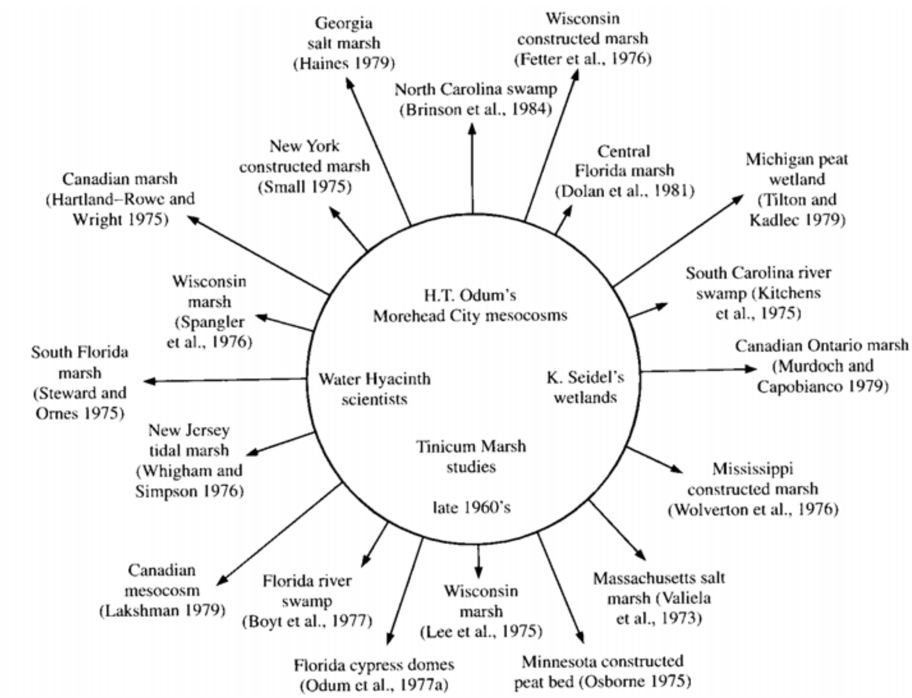


Figure 1.1. The "big bang" model of a technological explosion of early treatment wetlands projects (after Kangas, 2004).

Once past this initial period of optimism and enthusiasm (seventies), the next decade (eighties) was characterised by precaution and scepticism due to the discovery of several drawbacks of the technology and failures of some prototypes. Further research solved most of these problems and led to the maturity of the technology in the nineties. The logical last step is commercialisation which has really boosted in the latest years (Kangas, 2004).

Constructed wetlands nowadays have many applications, ranging from the secondary treatment of domestic, agricultural and industrial wastewaters to the tertiary treatment and polishing of wastewaters treated by means of activated sludge plants and even to the treatment of stormwaters. Table 1.1. summarises some specific case studies that were conducted to evaluate the potential of CWs for treating certain wastewater flows.

Table 1.1. Selected case studies with constructed wetlands.

Wastewater type	Reference
Domestic wastewater	
Secondary	De Wilde (2001); De Moor (2002); Story (2003)
Tertiary	Meuleman (1999); Cameron *et al*. (2003)
Domestic greywater	Dallas *et al*. (2004)
Pig manure	Hill & Sobsey (2001); Meers *et al*. (2005)
Dairy wastewater	Geary & Moore (1999); Mantovi *et al*. (2003)
Agricultural runoff	Comin *et al.* (1997)
Motorway runoff	Hares & Ward (2004); Pontier *et al*. (2004)
Wastewater from schools	Davison *et al*. (2002)
Wastewater from breweries	Billore *et al*. (2001)
Aquaculture reject water	Comeau *et al*. (2001); Schulz *et al*. (2003)
Surface water	Braskerud (2002); Coveney *et al*. (2002)
Landfill leachate	Urbanc-Bercic (1998); Rousseau *et al*. (2004a)
Acid mine drainage	Kalin (2004); Whitehead *et al*. (2005)
Stormwater	Green *et* al. (1999); Carleton *et al*. (2001)
Sludge dewatering	De Maeseneer (1997)
Abattoir wastewater	Rivera *et al*. (1997)
Heavy metal laden wastewater	Cheng *et al*. (2002a)
Pesticides and herbicides	Cheng *et al*. (2002b); Runes *et al*. (2003)
Acidic coal pile runoff	Collins *et al*. (2004)
Oil-contaminated water	Ji *et al*. (2002)
Volatile Organic Compounds	Kassenga *et al*. (2003)
Perchlorate contaminated water	Tan *et al*. (2004)
Woodwaste leachate	Tao & Hall (2004)

1.2. TYPES OF CONSTRUCTED WETLANDS AND GENERAL LAY-OUT

Wetlands can be very generally defined as *transitional environments* between dry land and open water or between terrestrial and aquatic ecosystems (Vymazal, 1998a). The different types of natural systems for wastewater treatment correspond with the different ecosystems along the land-water gradient, starting from the land-side with high-rate infiltration fields, overland flow systems, constructed wetlands and finally waste stabilisation ponds or lagoons.

The following classification only considers the middle range of ecosystems, i.e. the so-called constructed wetlands, and is based on the internationally accepted International Water Associations' Scientific and Technical Report on Constructed Wetlands for Pollution Control (Kadlec *et al*., 2000b). The various types are differentiated by water flow mode and plant species characteristics.

- Above-ground water: free-water-surface (FWS) constructed wetlands
  - with emergent macrophytes or helophytes, e.g. *Phragmites australis* (common reed), *Typha* spp. (cattails), *Scirpus* spp. (bulrushes) – Fig. 1.2 panels Ia, Ib, Ic
  - with floating-leaved, bottom-rooted macrophytes, e.g. *Nymphaea* spp. (water lilies), *Nelumbo* spp. (lotus) – Fig. 1.2. panels IId, IIe, IIf
  - with free-floating macrophytes, e.g. *Eichhornia crassipes* (water hyacinth), *Lemna* spp. (duckweed) – Fig. 1.2. panels IIg, IIh
  - with submersed macrophytes, e.g. *Elodea* spp. (waterweed), *Myriophyllum* spp. (water milfoil) – Fig. 1.2. panels IIIi, IIIj
  - with floating mats, e.g. *Phragmites australis* (common reed), *Typha* spp. (cattails), *Glyceria maxima* (giant sweetgrass) – Fig. 1.2. panel IV

- Below-ground water: subsurface-flow (SSF) constructed wetlands
  - horizontal-flow systems (HSSF), planted with emergent macrophytes or helophytes, e.g. *Phragmites australis* (common reed), *Typha* spp. (cattails), *Scirpus* spp. (bulrushes) – Fig. 1.2. panel Va
  - vertical-flow systems (VSSF), planted with emergent macrophytes or helophytes, e.g. *Phragmites australis* (common reed), *Typha* spp. (cattails), *Scirpus* spp. (bulrushes) – Fig. 1.2. panel Vb

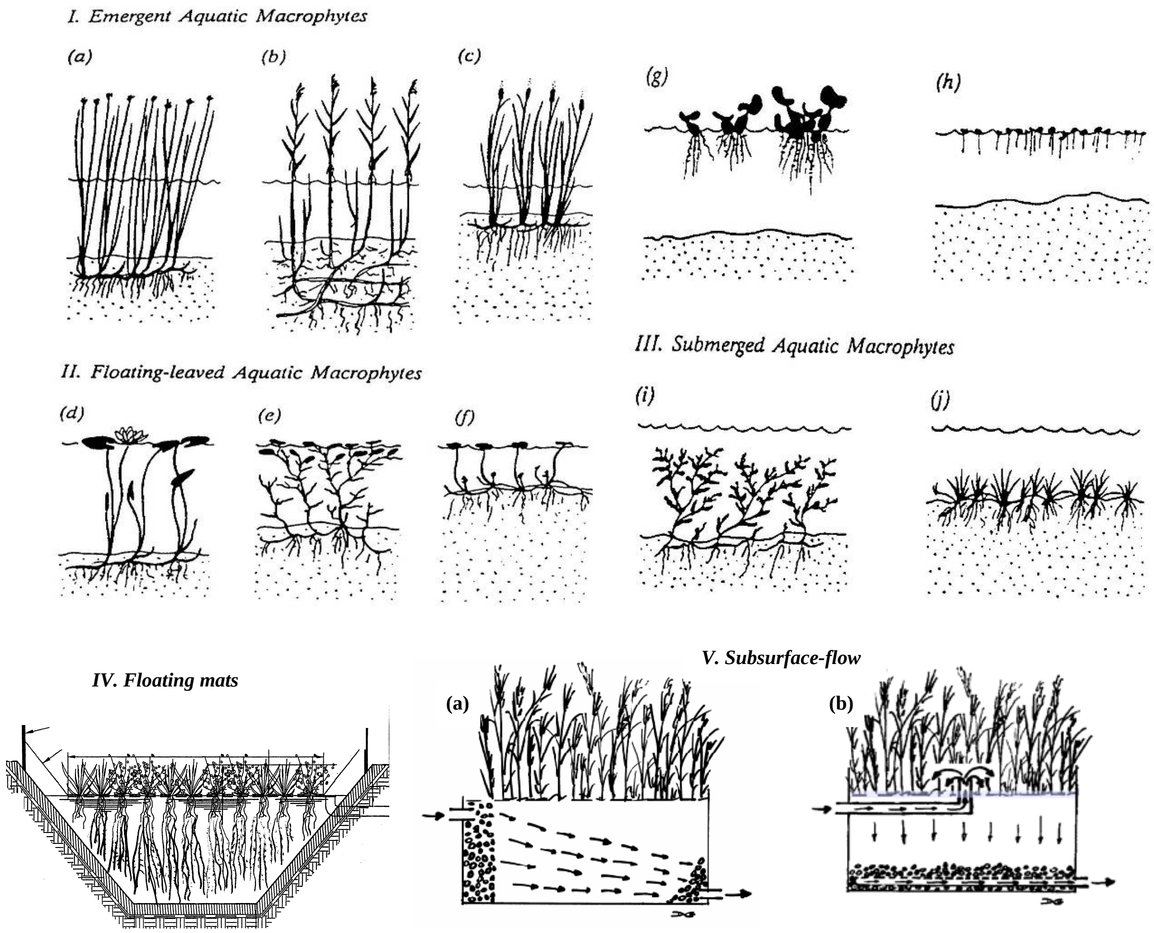


Figure 1.2. Schematic representation of different types of constructed wetlands (I, II, III after Vymazal *et al*., 1998b; IV after Van Acker *et al*., 2005; V after De Wilde and Geenens, 2003).

Generally speaking, most systems with above-ground water flow consist of a relatively shallow basin (depth between 0.3 and 1.8 meters), isolated from the groundwater by means of a plastic liner or by a local clay layer. Length-width ratios ≥ 2 are to be preferred in order to obtain near plug-flow conditions. The inlet distribution and effluent abstraction system should run along the entire width of the basin to avoid short-circuiting and the existence of dead volumes. When using free-floating macrophytes, floating barriers are often used to avoid the piling up of plants in one corner due to wind action.

Treatment wetlands with horizontal below-ground flow also consist of a shallow (0.5 – 0.8m deep) basin, isolated from the groundwater and usually filled with gravel although in some cases local soil has been used. For the inlet and outlet zone, coarser gravel is usually

applied to allow a better spreading respectively collection of wastewater. The treated wastewater is evacuated by means of a drainage tube at the bottom of the wetland. An appropriate choice of filter material (c.q. hydraulic conductivity) and a correct length-width ratio are indispensable to avoid above-ground water flow, which has a detrimental effect on treatment performance and can cause odour and insect nuisances.

Finally, vertical below-ground flow systems usually consist of one or more filter layers of coarse sand and/or gravel with a total depth between 0.6 and 1.0 meter. Wastewater is preferably spread equally over the top surface, then drains through the filter layers and is collected at the bottom by means of drainage tubes. Loading often happens intermittently, i.e. batch-wise. Choosing the right filter material is a trade-off between high respectively low hydraulic conductivities, i.e. less prone to clogging versus a longer hydraulic retention time.

Obviously, these different types do not necessarily function as stand-alone treatment plants but can be combined with each other or even with other low-tech or high-tech wastewater treatment units in order to exploit the specific advantages of the different systems. The quality of the effluent appears to improve with the complexity of the facility (Vymazal *et al*., 1998b).

A further distinction is made between engineered wetlands and constructed wetlands (de-Bashan and Bashan, 2004), although these terms are often used interchangeably. A constructed wetland usually refers to passive flow systems whereas an engineered wetland is a wetland that can be changed at will, i.e. operators can manipulate process conditions and operations according to conditions of both climate and wastewater.

BOX 1. Free-water-surface constructed wetlands

1. General description

Wastewater flows aboveground through a densely planted channel with emergent macrophytes such as *Phragmites* (reed), *Typha* (bulrush), *Papyrus* etc. The submerged plant parts form a filter for suspended particles and also provide a large attachment surface for microbial biofilms.

2. Design features

- *Pre-treatment*: at least primary treatment to avoid solids accumulation in the wetland.
- *Water depth*: should be 0.2-0.5 m.
- *Area*: as a rule of thumb, 5-10 m^2/PE is required for secondary wastewater treatment. More detailed design procedures can be found in Kadlec and Knight (1996).
- *Length-to-width ratio*: 2 or higher to promote plug-flow and to reduce short-circuiting.
- *Organic loading rate*: preferably lower than 80 kg BOD/ha/day.
- *HRT:* depending on type of wastewater and climate, in the order of 5-14 days.
- *Plants*: locally available indigenous aquatic plants are to be preferred and planted at densities of around 10-15 plants/m^2.
- *Operation and maintenance requirements*: servicing of pumps when present; cleaning the influent distribution system; removing weeds and saplings; harvesting the biomass.

3. Removal efficiencies and reuse possibilities

Removal efficiencies are dependent on climate conditions, type of wastewater etc. In general, the following ranges may be expected: 90% BOD, 60-90% SS, 20% N, 20% P and 99% pathogen removal.

4. Advantages and disadvantages

Advantages: easy to construct; moderate construction and operation costs; resistance to shock loading; excellent landscape integration; minimal sludge production; conversion of nutrients into potentially useful biomass; no energy needed except for pumping in case of flat topography; no noise generation.

Disadvantages: relatively high area requirement; seasonally dependent removal efficiencies; risk for mosquito and rodent proliferation; potential odor nuisance; relatively long start-up period.

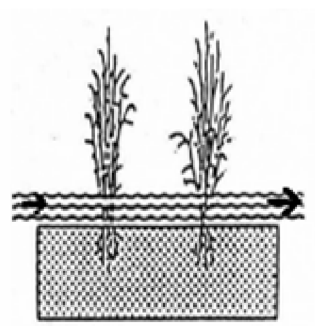


Fig.1 Free-water-surface constructed wetland for effluent polishing from a conventional WWTP (Aquafin Ltd, Belgium). Fig.2. Schematic representation of free-water-surface constructed wetland with emergent macrophytes.

BOX 2. Horizontal subsurface-flow constructed wetlands

1. General description

Wastewater flows in a horizontal way through a planted filter and remains below the surface. The inlet and outlet zone are filled with course gravel to allow an optimal distribution of wastewater over the entire width. The so-called treatment zone is most often filled with small gravel (Ø 5-10 mm) or coarse sand and planted with emergent macrophytes like *Phragmites* (reed), *Typha* (bulrush) etc.

2. Design features

- *Pre-treatment*: at least primary treatment to reduce the risk of clogging.
- *Water depth*: 0.5-0.8m as this is the maximum depth for emergent macrophyte roots.
- *Area*: as a rule of thumb, 3-5 m^2/PE is required for secondary wastewater treatment. More detailed design procedures can be found in Kadlec and Knight (1996).
- *Length:* 15m or less to avoid surfacing of wastewater.
- *Organic loading rate*: preferably lower than 75 kg BOD/ha/day.
- *HRT:* depending on type of wastewater and climate, in the order of 2-7 days.
- *Plants*: locally available indigenous aquatic plants are to be preferred and planted at a density of around 10-15 plants/m^2.
- *Operation and maintenance requirements*: servicing of pumps when present; cleaning the influent distribution system; removing weeds and saplings; harvesting the biomass.

3. Removal efficiencies and reuse possibilities

Removal efficiencies are dependent on climate conditions, type of wastewater etc. In general, the following ranges may be expected: 90% BOD, 60-90% SS, 20%N, 20%P and 99% pathogen removal.

4. Advantages and disadvantages

Advantages: relatively easy to build; moderate construction and operation costs; resistance to shock loading; less odor nuisance because of belowground water; no mosquito proliferation; no risk for drowning; low sludge production; easy integration in landscape; conversion of nutrients into potentially useful biomass; no energy needed except for pumping in case of flat topography; no noise generation.
Disadvantages: seasonally dependent removal efficiencies; sensitive to clogging; relatively high area requirement; relatively long start-up period.

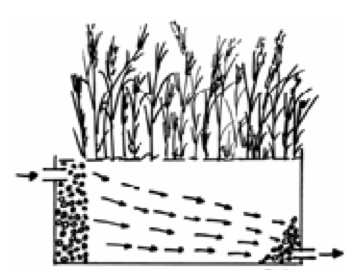


Fig.1 Two-step HSSF CW for secondary wastewater treatment in the UK (Severn Trent Water Ltd). Fig. 2. Schematic representation of a HSSF CW.

BOX 3. Vertical subsurface-flow constructed wetlands

1. General description

VSSF CW usually consist of one or more filter layers of coarse sand and/or gravel with a total depth between 0.6 and 1.0 meter and planted with emergent macrophytes. Wastewater is preferably spread equally over the top surface, then drains through the filter layers and is collected at the bottom by means of drainage tubes. Loading often happens intermittently, i.e. batch-wise.

2. Design features

- *Pre-treatment*: adequate primary treatment to reduce the risk of clogging.
- *Area*: as a rule of thumb, 2-3 m^2/PE is required for secondary wastewater treatment.
- *Organic loading rate*: preferably lower than 60 kg BOD/ha/day.
- *Hydraulic loading rate:* up to 800 mm/day have been achieved without clogging; typically however lower then 100 mm/day with intermittent loading.
- *Plants*: locally available indigenous aquatic plants are to be preferred and planted at a density of around 10-15 plants/m^2.
- *Operation and maintenance requirements*: servicing of pumps when present; cleaning the influent distribution system; removing weeds and saplings; harvesting the biomass.

3. Removal efficiencies and reuse possibilities

Removal efficiencies are dependent on climate conditions, type of wastewater etc. In general, the following ranges may be expected: 95% BOD, 60-90% SS, 50-60%N, 20-90%P (usually declines with time) and 99% pathogen removal.

4. Advantages and disadvantages

Advantages: relatively easy to build; moderate construction and operation costs; resistance to shock loading; less odor nuisance because of belowground water; no mosquito proliferation; no risk for drowning; low sludge production; easy integration in landscape; conversion of nutrients into potentially useful biomass; no energy needed except for pumping in case of flat topography; no noise generation.
Disadvantages: seasonally dependent removal efficiencies; sensitive to clogging; relatively high area requirement; relatively long start-up period.

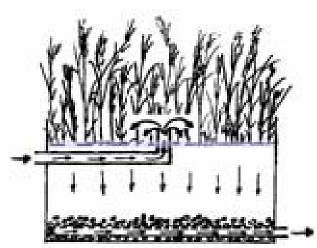


Fig.1 VSSF CW for secondary wastewater treatment in the Saint-Thomé, France. Fig.2. Schematic representation of VSSF CW.

BOX 4. Floating mats

1. General description
This form of constructed wetlands has only recently been developed. In floating wetlands, the aquatic vegetation is no longer rooted in a solid substrate but is growing on floating rafts. These rafts usually consist of two or more floaters with a support net in between for carrying the vegetation. The support net is usually covered by a layer of coconut fibres – although the use of *Sphagnum* has also been proposed – as a medium for root growth. The rafts are floating in an impermeable pond with depths mounting to 2m. When plug-flow conditions are required, baffles may be added to the system.

2. Design features
- *Pre-treatment*: raw sewage can be added as the large depth allows for sludge storage.
- *Hydraulic loading rate:* may vary considerably as the rafts follow the water level.
- *Plants*: locally available indigenous aquatic plants are to be preferred, preferably with long roots which can form a dense curtain in the water beneath the rafts.
- *Operation and maintenance requirements*: servicing of pumps when present; removing sludge from the inlet zone; removing weeds; harvesting the biomass.

3. Removal efficiencies and reuse possibilities
Removal efficiencies are dependent on climate conditions, type of wastewater etc. In general, the following ranges may be expected: 60-80% COD, 90% SS, 25%N, 20%P and 99% pathogen removal.

4. Advantages and disadvantages
Advantages: direct uptake of nutrients from the water through the plant roots; shade prevents algal proliferation; system can cope with varying water levels which is not the case in other systems; root network ensures physical filtration and provides large attachment surface for microorganisms; ecological value/shelter for fauna.
Disadvantages: seasonally dependent removal efficiencies; relatively high area requirement; relatively long start-up period.

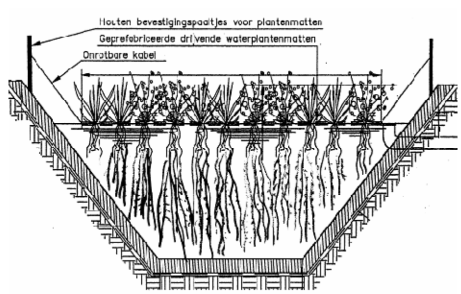


Fig.1. Treament of combined sewer overflow in Bornem, Belgium (Aquafin Ltd). Fig.2. Schematic representation of floating mat systems.

BOX 5. Duckweed ponds

1. General description

These are shallow ponds where the water surface is completely covered by a duckweed mat. The major roles of the duckweed are to eliminate algal proliferation by blocking all sunlight and to take up nutrients from the water. The leaves and roots function as attachment space for microbes. Floating duckweed may be heaped up to one side in larger ponds by wind action. In such cases floating barriers should be used to maintain a fully covered pond.

2. Design features

- *Pre-treatment*: raw sewage can be added as the large depth allows for sludge storage.
- *Water depth*: 0.5-1.8m depending on desired sludge storage capacity and harvesting mechanisms. For a small boat a depth of 1m suffices.
- *Length-to-width ratio*: 3:1 or greater to promote plug flow conditions in the systems.
- *Organic loading rate*: 45-90kg BOD/(ha·d) for average winter air temperatures above 15^{o}C; 22-45 kg BOD/(ha·d) for average winter air temperatures between 7-15 ^{o}C.
- *Hydraulic loading rate*: typically 5-18m/year.
- *Duckweed harvest, operation and maintenance*: It is necessary to have an effective surface mat of duckweed, but it is desirable to conduct a regular partial harvest to encourage vigorous growth and to remove dead and decaying plants. After each harvest, the density should be around 0.7 kg/m^2, which can produce a full cover to prevent the light penetration and growth of algae.

3. Removal efficiencies and reuse possibilities

A case study (Mirzapur, Bangladesh) shows that the duckweed system can obtain removal efficiencies of 90%-97% for COD, 95%-99% for BOD_5, 74% for TKN and 77% for TP treating domestic wastewater. The removal of pathogen depends on the environmental conditions within the pond system.

4. Advantages and disadvantages

Advantages: easy to build; low construction and operation costs; resistance to shock loading; plant cover reduces mosquito proliferation; duckweed controls algae growth; plants can be used as an animal fodder.

Disadvantages: relatively high area requirement; duckweed growth reductions at temperatures lower than 15 ^{o}C; herbicides and other materials toxic to the plants can affect their health; insect infestation can cause major damage to the plant.


Fig.1 Full scale duckweed pond system in Bangladesh (left) & Colombia (right)

BOX 6. Water hyacinth ponds

1. General description

These are shallow ponds where the water surface is completely covered by water hyacinths. The major roles of the plants are to eliminate algal proliferation by blocking all sunlight and to take up nutrients from the water. The leaves and roots function as attachment space for microbes. Some systems have been enhanced with artificial aeration to ensure aerobic conditions in the water layer under the plants.

2. Design features

- *Pre-treatment:* raw sewage can be added as the large depth allows for sludge storage.
- *Water depth:* 0.5-1.2m.
- *Length-to-width ratio*: 3:1 or greater to keep plug flow in the systems.
- *Organic loading rate*: 10 to 300 kg BOD/ (ha·d) for aerated systems, not higher than 100-110kg BOD/ (ha·d) for non-aerated systems.
- *Hydraulic loading rate:* typically 200-600m^3/ (ha·d) for secondary treatment.
- *Water hyacinth harvest, operation and maintenance:* Harvest frequency 2-5 weeks depending on the level of nutrient removal required and the plant growth rate. 15%-20% of the plants should be removed at each harvest. Stocking ponds with mosquitofish (*Gambusia*) or water spraying in the evening should be applied for mosquito control. Ponds should be monitored for the presence of insects that damage the plants. In case of infestations, spot harvests or even insecticides have to be used.

3. Removal efficiencies and reuse possibilities

Water hyacinth systems are capable of removing high level of BOD, SS, metal, and nitrogen, and significant levels of trace organics. When water hyacinth ponds are designed for secondary treatment with a raw sewage input, the detention time more than 50 days, organic loading rate of 30 kg/ (ha·d), water depth of 1.5m or less, water temperature above 10 ^oC, the expected effluent quality is BOD_5 < 30mg/L, SS <30mg/L.

4. Advantages and disadvantages

Advantages: easy to build; low operational costs; low energy requirements; resistance to shock loading; harvested plants can be used as fertilizer, animal fodder or energy source.

Disadvantages: large area requirement; insect infestations can cause major damage to the plants; water hyacinth is sensitive to cold weather; heavy metals can accumulate in plants and limit their suitability as fertilizer or feed materials; mosquito and odor control are necessary; the spread of water hyacinth must be closely controlled by barriers, since the plant can spread rapidly and clog previously unaffected waterways.

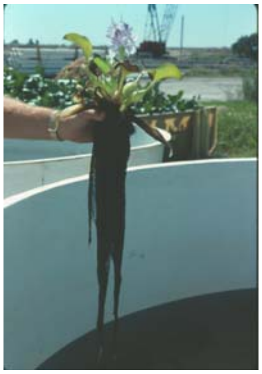


Fig.1 (left) Full scale water hyacinth system in California.

Fig. 2 (right) Picture showing the root system of water hyacinth.

1.3. PROCESSES IN CONSTRUCTED WETLANDS AND INFLUENCING FACTORS

1.3.1. Processes

Constructed wetlands are capable of removing and/or converting a range of pollutants such as organic matter (BOD, COD), suspended solids, nitrogen, phosphorus, trace metals, pesticides and pathogens. This is accomplished by a vast array of processes that are complex physical, chemical and biological interactions between water, substrate, filter material, macrophytes, litter and detritus, and micro-organisms (Table 1.2.). An introductory summary is given below, adapted from the comprehensive overview in Kadlec *et al*. (2000c). For SSF systems, more information is available in Chapter 3 of this work.

Suspended solids are mainly removed by physical processes such as sedimentation and filtration. Filtration occurs by impaction of particles onto the roots and stems of the macrophytes or onto the soil/gravel particles in SSF systems. For FWS systems, most of the SS removal occurs within the first meters, giving rise to a ‘bank’ of sludge that can hinder the water flow. Subsurface-flow systems can clog when too many pores become filled with particulates.

Dissolved organic matter first diffuses into the biofilms that colonise plant stems and roots, filter particles and basin walls. Depending on the available oxygen, it is then degraded in an aerobic, anoxic or anaerobic way. *Particulate organic matter*, when biodegradable, is normally mineralised into dissolved components after sedimentation or filtration.

Table 1.2. Removal mechanisms in constructed wetlands (after Vymazal *et al*., 1998b)

Mechanism	Contaminant affected								Description
	SS	CS	BOD	N	P	HM	RO	B&V	
PHYSICAL									
sedimentation	P	S	I	I	I	I	I	I	Gravitational settling of solids
filtration	S	S	I	I	I	I	I	I	Particles filtered mechanically as water passes through substrate, roots and rhizomes or fish
adsorption		S							Interparticle attractive force (van der Waals force)
volatilisation				S					Volatilisation of NH_3 at high pH
CHEMICAL									
precipitation					P	P			Formation of or co-precipitation with insoluble compounds
adsorption					P	P	S		Adsorption on substrate and plant surfaces
decomposition							P		Decomposition or alteration of less stable compounds by phenomena such as UV irradiation, oxidation and reduction
BIOLOGICAL									
bacterial metabolism		P	P	P			P		Removal of colloidal solids and soluble organics by suspended, benthic and plant-supported bacteria. Bacterial nitrification and denitrification
plant metabolism							S	S	Metabolism of organics by plants. Root excretion may be toxic to organisms of enteric origin
plant absorption				S	S	S	S		Under proper conditions significant quantities of these contaminants will be taken up by plants
Natural die-off								P	Natural decay of organisms in an unfavourable environment

SS = settleable solids, CS = colloidal solids, HM = heavy metals, RO = refractory organics, B&V = bacteria and viruses

P = primary effect, S = secondary effect, I = incidental effect (effect occuring incidental to removal of another contaminant)

Nitrogen removal is mainly accomplished by the successive microbial pathways ammonification, nitrification and denitrification. Plant uptake and consequent harvesting is only important in low-loaded systems. Some nitrogen can be permanently stored in the recalcitrant fraction of the detritus layer. NH_3 volatilisation can occur but is only significant at high pH, i.e. above 9.

Phosphorus is biologically removed by plant uptake. Again, the amount that can be removed through harvesting of the above-ground plant parts is only significant in low-loaded systems. Periphyton and micro-organisms also take up P but most of it is released again after cell death. The main removal mechanisms are adsorption to the filter and/or soil particles, adsorption to the detritus layer and precipitation with certain metals such as Fe, Al, Ca and Mg.

Viruses seem to be effectively removed by adsorption onto the soil or detritus. Possibly the time spent outside the host organism also plays a major role. *Bacteria* are reduced by sedimentation, chemical reactions, natural die-off, predation by zooplankton, nematodes and lytic bacteria and attacks by bacteriophages. Certain wetland plants and micro-organisms are also known to synthesise antibiotics that are released into the root zone. *Parasites* such as helminth eggs can also be effectively removed through sedimentation and adsorption.

Trace metals associated with particulate matter are removed by sedimentation and filtration. Adsorption onto the matrix surface and organic material is considered the main removal mechanism for dissolved trace metals. Cation exchange with carboxyl functional groups in dead or live plant tissue is a second important removal mechanism. Another removal mechanism of trace metals being largely dependent on redox conditions, is precipitation as insoluble salts, mainly sulphides and (oxy)hydroxides. Most helophyte plant species also accumulate trace metals in their root system whereas some floating and submerged species have been described to accumulate metals to a greater extent in their harvestable plant tissue.

1.3.2. Influencing design parameters

Probably the most important design parameter is the *hydraulic retention time* (HRT). Constructed wetlands are extensive systems that entirely depend on natural energy inputs such as sunlight and wind. They therefore require a large surface area to absorb these energy fluxes and a sufficient hydraulic residence time for the processes to take place.

Isolation from the groundwater by means of a *plastic liner* or *clay layer* is absolutely necessary to prevent groundwater contamination on the one hand, and to avoid groundwater infiltration on the other hand. Both fluxes can substantially influence the hydraulic residence time and therefore the treatment performance.

The *plant species* choice is based on a range of criteria. They should firstly be able to flourish under the local climatic conditions. A high biomass production is preferable when one intends to export nutrients from the system by harvesting. The more extensive the root system, the better the filtrative capacities and the more surface is available for biofilm development. Finally, they should be able to withstand hydraulic and pollutant shock loads.

For SSF systems, an appropriate choice of the *filter material* is extremely important to avoid clogging, to ensure a sufficient hydraulic conductivity and to provide enough sorptive capacity, especially for P removal.

1.3.3. Influencing external parameters

Temperature has a major impact on microbiological process rates and obviously on plant growth as well. Especially nitrogen removal seems to be almost completely inhibited at temperatures below 4 °C. Kadlec and Knight (1996g, 1996h) use an Arrhenius equation to express temperature dependency. Temperature factors (θ) for BOD, SS, TP and FC are given as 1.0, meaning removal of these variables is not temperature dependent. This can be explained by the fact that most related processes are physical or chemical in nature and not (micro)biological. TN on the contrary has a

temperature factor of 1.05, meaning that the removal efficiency is lowered by 39% when the temperature decreases from 20 °C to 10 °C.

Another important factor that affects the microbiological processes is *pH*. The optimal range fluctuates somewhat for the different processes but in general varies between 7.0 and 8.5.

Mass removal rates seem in most cases to be positively correlated with the *mass loading rates*, i.e. higher influent loads result in better treatment performance, up to a certain level of course (Ayaz and Akça, 2001). It is clear from the latter observation that the removal rates of tertiary treatment wetlands are typically lower than those of secondary treatment ones.

1.4. ECONOMIC FACTORS

Constructed wetlands are being promoted as a sustainable, low-investment and low-maintenance cost technology. Major expenses usually are land acquisition, earth moving, plastic liners to prevent groundwater contamination or infiltration and the filter material in case of SSF systems. However, after its functional life, the land can be readily made available for other purposes and therefore certain authors exclude this cost from the balance.

1.4.1. Costs

All costs given below should be interpreted with caution, for a number of reasons. Firstly, it is not always clear from the original sources which components are included, i.e. the wetland costs *sensu stricto* or also the costs for sewer construction, fencing, buildings etc. Secondly, many authors do not mention if taxes/VAT are included and at what rate. Thirdly, depreciation costs are not always clear and finally, inflation and fluctuating exchange rates can give a wrong idea about current costs.

Kadlec and Knight (1996a) summarised capital costs and operating costs, indifferent of treatment level or wastewater type, as given in Table 1.3.

Table 1.3. Range of capital and operating costs of constructed wetlands (after Kadlec and Knight, 1996a).

	Area (ha 1000m^{-3} d^{-1})	**Capital cost (1000 US$ ha^{-1})**	**Capital cost (US$ m^{-3} d^{-1})**	**O&M cost (US$ m^{-3})**	**O&M cost (US$ ha^{-1} year^{-1})**
Floating aquatic macrophytes	0.7 – 5	270	500 – 1,000	0.12 – 0.14	9,490 – 67,786
Wetlands	0.5 - 20	25 - 250	500 – 1,000	0.03 – 0.09	1,095 – 43,800

Capital costs in Table 1.3. exclude the more extreme cases, e.g. 4,741 US$ ha^{-1} for the Mt. View Marsh FWS CW (California, USA) or 1,731,936 US$ ha^{-1} for the Mandeville HSSF CW (Louisiana, USA) (Kadlec and Knight, 1996k). Indeed, capital costs are highly dependent on the local situation, i.e. soil type, groundwater table height, terrain slope, distance from settlement, discharge criteria, climate etc. Cooper and Breen (1998) state investment costs for secondary treatment wetlands between 120 – 480 € PE^{-1} whilst for tertiary treatment CWs this only amounts to 36 – 120 € PE^{-1}. Another important factor usually is the economy of scale: larger wetlands tend to be relatively cheaper per PE or per m^3 of wastewater treated. Indeed, for single-household systems, Haberl *et al*. (2003) mention an average investment cost of 1,000 € PE^{-1}, with a significant proportion made up by the primary treatment unit. One uncertainty is the ‘removal’ cost of the system after its functional life, now estimated around 20 years. Especially dumping or cleaning of saturated filter materials of SSF wetlands could result in a significant extra cost.

Operation and maintenance costs are rarely given in literature, but one median O&M cost for FWS CWs is mentioned in the order of 1000 US$ ha^{-1} year^{-1} (Kadlec and Knight, 1996g) whereas O&M costs for SSF CWs are estimated between 2500 and 5000 US$ ha^{-1} year^{-1} (Kadlec and Knight, 1996h). Merz (2000) reveals a scale advantage for larger wetlands: O&M costs of Australian wetlands of > 5 ha are estimated around 1500 AS$ ha^{-1} year^{-1} whereas for wetlands < 5 ha costs can be up to a factor 10 higher. This trend can also be found for very small CW as Haberl *et al.* (2003) report O&M costs in Austria of 300, 200 and 150 € PE^{-1} year^{-1} for CWs of 5, 10 and 20 PE respectively. What are the major O&M expenses? Energy consumption,

if any, is usually limited to pumping and represents only a minor cost since most wetlands are designed to function gravitationally. Chemicals are rather rarely applied. Exceptions are the addition of materials with a high P-sorption capacity in SSF wetlands and the use of pesticides to eliminate plant pests such as lice or mosquitoes. Sludge production is minimal in tertiary systems. Maintenance costs are therefore mainly labour costs for site inspection, effluent sampling and control, cleaning of distribution systems and pumps, weed control, plant harvesting etc.

1.4.2. Benefits

Treated effluent can be reused for irrigation of agricultural crops, depending on its quality. Other applications are watering of gardens, golf courses, public parks etc. Merz (2000) for instance states that irrigation reuse is practised with about 30% of Australian CWs. Effluent can also be reused for flushing toilets, for cleaning purposes, as cooling water after desalination (Peng *et al*., 2004) and as a reliable water supply for natural wetlands or nature reserve areas (Worrall *et al*., 1997; Sala *et al*., 2004). A last option is to use the effluent for aquacultural purposes, with fish production for food or feed or even duck culture (Polprasert and Koottatep, 2004).

Harvested plant biomass can possibly create an extra income. Indeed, certain plant species have commercial value, some as ornamental plants, others as raw material. Mulching and composting of harvested plants can for instance yield soil additives, pulping of plants provides fibers and silaging produces livestock fodder (Polprasert and Koottatep, 2004). A pond-wetland system in Thailand generates some income by selling ornamental plants (golden torch and bird of paradise - *Heliconia* spp.) at about 0.2 US$ per flower (Shipin *et al.*, 2004). El Hafiane and El Hamouri (2004) describe the use of *Arundo donax* for tomato crop production and for the creation of artisanal objects, generating an annual income of 1750 - 2900 US$ per ha per year (price of one plant about 0.007 US$). Calla lilly (*Zantedeschia aethiopica*) was demonstrated to grow well on wastewater and seems to have a high market value in Mexico (Bachand and Horne, 2000). From the above examples, it is clear that the practice of using plants for commercial purposes takes place mostly in developing countries where people try to optimise the benefits of constructed wetlands. In developing countries, a paradigm shift still needs to take place.

Cicek *et al.* (2004) investigated the possibility of using harvested plant biomass from a natural wetland to generate power. Different technologies were evaluated and yielded considerable amounts of energy. Cogeneration of heat is one possible additional benefit, greenhouse gas credits (carbon sequestration, renewable energy sources) a second one. Bolton (2004) also mentions this possibility of obtaining carbon credits from biomass and peat formation in a constructed *Melaleuca* wetland.

When combining wetlands with ponds, aquaculture can be done quite succesfully. An integrated pond-wetland system in China yearly yields between 20000 – 30000 kg fish. Unfortunately, no data are given on the area of this system. Together with large quantities of commercialisable plants like duckweed and reed, this results in significantly lower operational costs. The effluent of this system is used for irrigation during dry periods (Peng *et al*., 2004).

Another benefit includes the creation of a new habitat for flora and fauna. Knight *et al*. (2000a) summarise data from the North American treatment wetlands DataBase (NADB) concerning sightings of mammals, birds, amphibians, reptiles, fish and invertebrates and vegetation mapping surveys. Initial concerns about bioaccumulation of certain pollutants and spreading of diseases via visiting fauna seemed in most cases premature. Very few treatment wetlands have been specifically designed to contribute to wildlife conservation. According to Connor and Luczak (2002) there are indeed many obstacles like a lack of understanding of conservational needs and ecological principles among engineers, the additional costs entailed, lack of comprehensive design manuals and a lack of obviously tangible benefits to local communities. Several positive examples are summed up by Connor and Luczak (2002) as counter arguments. The Western Treatment Plant of Melbourne for example (10850 ha with lagoons, land infiltration and grass filtration) has been included in the Ramsar convention as a wetland of international importance for bird conservation. Other examples from the ornithological literature include the Aisleby sewage farm in Bulawayo, Zimbabwe, the Phakalane Sewage Ponds in Gabarone, Botswana, the Arcata wetlands, California and the Al-Ansab sewage treatment plant in Muscat, Oman.

Knight *et al*. (2000a) finally mention education (nature study), exercise activities (walking, jogging) and recreational harvest (hunting, trapping) as other positive contributions of CWs. Gearheart and Higley (1993) add picnicing, relaxing and art (photography, painting) to this list. Such additional benefits have seldomly be economically valued. Knight *et al*. (2000a) only describe for a number of wetlands the 'human use days', expressing the total amount of time spent by humans for the above-mentioned activities. The 61 ha large Arcata wetland facility in California has 5 miles of foot trails and attracts more than 130000 visitors each year (Gearheart and Higley, 1993). Carlsson *et al.* (2003) conducted a choice experiment among citizens of Southern Sweden and found that biodiversity and walking facilities are the two greatest contributors to welfare, while a fenced waterline and introduction of crayfish decrease welfare.

1.5. EXAMPLES OF APPLICATIONS IN URBAN ENVIRONMENTS

Very few examples exist of the application of constructed wetlands for wastewater treatment in urban environments. The main reason for this is the large amount of area that is required for adequate wastewater treatment: area which is often not available in highly urbanised conditions or comes at a very high cost, thereby offsetting the other potential cost savings of constructed wetlands. Another factor seriously limiting the application of CWs would be the so-called NIMBY syndrome (Not In My BackYard) because of common beliefs of people that wetlands are a source of bad odour and of mosquitoes. These can however be largely prevented, as indicated above.

On the other hand, CWs do offer the benefit that they can be incorporated into the urban amenities by giving them a parkland function. However, serious care should be taken to avoid drowning risks and to avoid direct contact between humans and the pathogen-loaded wastewater.

As a result of this, applications seem therefore limited to

- Less densely populated peri-urban areas where more land is available and the costs of land are lower;

- Low-strength or pre-treated (secondary treated) wastewater which will require less space to be treated and will reduce risks of odour and mosquito proliferation.

1.5.1. Granollers, Spain (based on García and Domingo, 2006)

This system located in Can Cabanyes, Granollers near Barcelona, Spain consists of a 1ha free-water surface constructed wetland and is one of the restoration measures for a degraded zone near the river Congost. Other restoration measures included the construction of a nature-education centre and some walkways along the wetland and the river. It has been in operation since April 2003.

The wetland is of the so-called marsh-pond-marsh type, combining zones of open water with belts planted with reed *(Phragmites)* and bulrush *(Typha)*. The depth varies from 1.5 meter in the open water zones to 0.4m in the planted zones. Impermeability has been ensured by the provision of a compacted clay layer. It is being fed with secondary treated effluent of the wastewater treatment plant of Granollers, situated on the opposite river bank. Construction costs of the system were in the order of 72,000 Euro.

The system currently serves 3 main purposes: (1) effluent polishing before discharge, especially in terms of NH4 and pathogens; (2) landscape restoration and (3) habitat function. In the future, when more detailed data about the removal efficiencies and effluent quality will be available, reuse of the effluent is envisaged in nearby horticultural companies.

The first results from the study presented by García and Domingo (2006) indicate that the system is indeed fulfilling most of its purposes. At a hydraulic loading rate of 10 mm/day, flowrate 100 m3/day), average NH4 concentrations were reduced from 31 to 4.5 mg N/L, with some 55% of the effluent samples fulfilling the required standard of 2 mg N/L. The standards are mostly exceeded during winter and fall, when nitrification is limited due to lower temperatures. About 85% of the samples had a faecal coliform concentration lower than 2400 / 100 mL, which was the target value used for design.

The improvement in water quality is also evident from faunal observations: whereas amphibians are absent in the inlet zone, they seem to thrive in the outlet zone. From field observations carried out during the year 2004, it became clear that the wetland had a great ecological value for the peri-urban area of Granollers, as evidenced by the 86 present species of vascular plants and the 35 avian species visiting or nesting in the wetland. As the system will become more mature, an even higher biodiversity may be expected.

Contrary to many other cases, this system has been and still is well-maintained. Possible explanations might be the many visitors, the fact that it is a pilot experiment requiring close monitoring and the scientific interest by local universities. Vegetation control, sludge removal, pump maintenance and water quality monitoring require a budget of approximately 12,000 Euro per year.

Pictures courtesy of
Granollers Municipality

1.5.2. Besòs Fluvial Park, Spain (based on Huertas *et al*., 2006)

The Besòs river in the northern part of Spain, has long-time been one of the most altered fluvial basins in Catalonia and was considered the second-most contaminated river, after the river Rhine. The final part of the river flows inside a heavily industrialized and densely populated area in greater Barcelona, before discharging into the Mediterranean. Extreme flow variations are occurring in the river. During long dry spells it only transports treated wastewater; violent storms can cause the flow rate to increase up to 2000 m3/s, causing severe flooding in parts of the basin. Both water quantity and quality problems had caused a serious decline in aquatic vegetation and a near-extinction of all riverine fauna.

In the 1990s, a big conversion of parts of the final section has been undertaken (along a stretch of approximately 4 km), involving re-naturalization of the concrete channel, bending it and converting the reclaimed bed surface into an urban park and tertiary treatment facilities in the form of horizontal subsurface-flow constructed wetlands. Wastewater for the constructed wetlands comes from the Montcada i Reixac activated sludge secondary wastewater treatment plant which treats mainly domestic wastewater. Depending on the flow rates, at least 50% of the effluent (0.2 – 0.3 m^3/s) is diverted to the 60 wetland plots before final discharge into the river. Subsurface flow wetlands were selected in order to avoid odour and mosquito nuisance for close by residents. Each plot has an average depth of 0.7m, an area varying between 960 and 1750 m^2, is isolated by means of a plastic liner, filled with gravel and planted with several emergent plant species. After some years however, *Phragmites australis* had outcompeted all other plant species.

Water quality improvements in the wetlands were significant, with a further 40% decrease of suspended solids levels, 62% for COD, 20% for NH4, 58% for P and 1.1 log units for fecal coliforms. Though this had a positive effect on the Besòs river water quality, conditions are still not sufficient to support a healthy aquatic wildlife and further nutrient reduction schemes are envisaged. Some wildlife did colonize the wetlands however.

Despite a few complaints from nearby residents about odour and mosquitoes, the general appreciation by the public is very positive. Many people use the park for

bicycle riding, for running and walking and for picnics. To ensure their safety, a flood warning system has been installed which calls for evacuation of the park whenever needed.

1.5.3. Shenyang city, China

In the Hunnan district, a new zone of Shengyang city in eastern China, a number of horizontal flow constructed wetlands have been designed both for sewage treatment and rainwater treatment. Among the total surface area of 10,000 m^2, a reed bed with an area of 6500 m^2 is designed as sewage treatment system. The capability for sewage treatment is 1000 m^3 per day. The sewage is being collected from nearby residences. Outflow of the reed bed is being mixed with the collected rainwater runoff and introduced to the succeeding wetland, which has a capacity of 3000 m^3 per day. The wetlands started operating on October 15th, 2004.

COD in the effluent of the whole system is about 50 mg/L. The effluent is being reused both for irrigation and other purposes like street flushing.

Picture from http://www.waterchina.cn/news.asp?id=10032

1.5.4. Guandu Nature Park, Taipei, Taiwan R.O.C.

Guandu Nature Park is situated in northern Taiwan at the junction of the Danshui and Jilong rivers. The landscape consists of a mosaic of freshwater and brackish ponds, mudflats, marsh, rice paddies, and woodland, in which a rich variety of organisms occur. The mission of this park is to protect these valuable natural resources. Guandu is a major stopover site for migrating birds, especially waterfowls and shorebirds, as well as an important wintering and breeding ground for many species. Over 220

species of birds have been recorded at Guandu so far, qualifying this wetland as an Important Bird Area (IBA) recognized by BirdLife International.

The park is situated at the outskirts of Taipei city and can be easily reached by public transportation, making it a favorite destination for city residents during free days. To accommodate visitors, an educational centre has been built with some expositions, an observation room with telescopes and binoculars, a cafe and 3 conference rooms. Inside the park, walkways and bird-watching cabins facilitate access for visitors.

Recently, some constructed wetlands have been added to the park as well. To improve the water quality of Old Guizikeng River, whose major pollutants come from factories, domestic usages and dumping located at upper stream, a series of vertical-flow constructed wetland have been installed. Another series of constructed wetlands treats wastewater from some nearby high-rise buildings and from the visitor centre. More information about the park can be found at: http://www.gd-park.org.tw.

1.5.5. Polderdrift, Arnhem, The Netherlands

In Arnhem (The Netherlands), grey water of 40 houses (Polderdrift community) is treated using a vertical-flow constructed wetland and reused for toilet flushing. Rain water is partially harvested and used for the laundry machines and partially infiltrated in situ. The black water is still evacuated to a conventional wastewater treatment plant.

Van Betuw (2005) reports that this scheme results in 57% less water consumption and 85% less wastewater discharge. It is further worth mentioning that the tenants were involved during the design phase in the selection of environmental measures and that they continue to be involved by taking the responsibility for simple maintenance tasks. Next to an environmental incentive, there is also a financial stimulus as the inhabitants are paying less wastewater levies. There is a continuous need to inform new tenants about the nature of the water distribution system to make sure that no cross-connections are made between the potable water and low-quality water networks.

Unfortunately, after some years, many operational problems occurred: faulty pre-treatment equipment caused clogging of the upper layers of the wetland and inexplicable water losses occurred. At this moment a solution has not been found yet.

Other successful grey water reuse and rainwater use case studies in urban environments agree that public acceptance is high but also warn that the public has an incorrect perception that grey water is innocuous. In order to safeguard public health, continuous process verification, plumbing management and customer education are therefore needed.

1.5.6. GeWooNboot, The Netherlands (based on Shrestha, 2007)

Due to climate change and rising water levels, many institutions in the Netherlands develop a fresh look upon living with large water bodies. In 2006 ECOFYT (www.ecofyt.nl) was involved in the building of a constructed wetland system for an autarkic house boat. In accordance with the goals of this project, the effluent of the waste water system is to flow back to the boat, where a Reverse Osmosis system is to make drinking water for the inhabitants. The result is a very short circuit for drinking water, waste water and drinking water again.

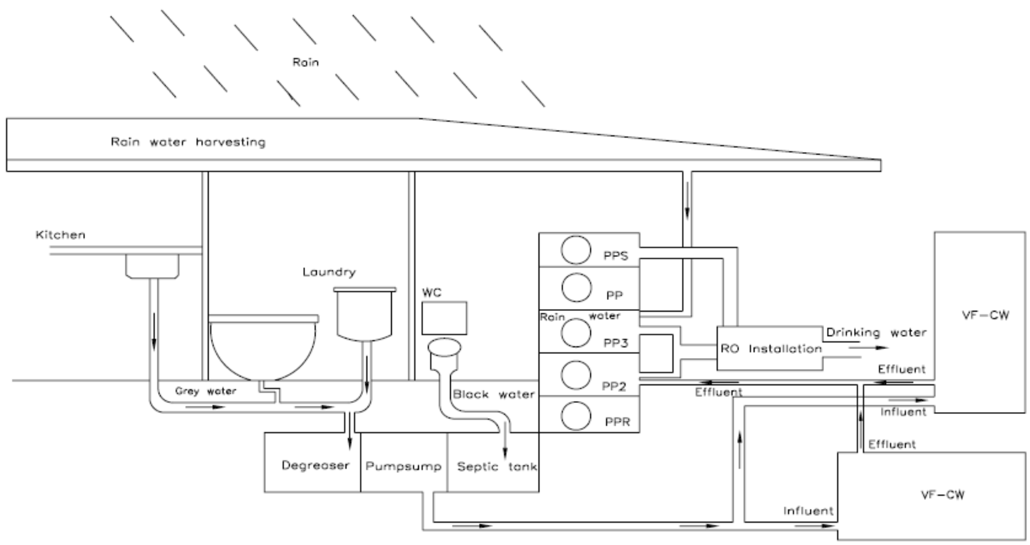
System lay-out. Inspired by the architects' view on how the houseboat would have to look like, the wetland section was built in two steel containers, floating alongside the boat. Inside the boat the waste water from the toilet is collected in a septic tank whereas the waste water from kitchen and shower is collected in a degreaser. Both tanks overflow in a primary pump sump. Periodically, the water is intermittently pumped to the wetlands and from there, after treatment, to a tank inside the boat again. Another tank is to store rainwater from the vegetated roof. Together these two tanks provide the water for the RO system. The RO system is extended with a coal

filter, a decalcifying filter and a fibre filter. After the RO, UV treatment is provided against bacterial hazards. The discharge water from the RO is fed back through the degreaser, to the wetland. Precipitation delivers the sole addition of water to the system. But the roofs' surface is rather small whereas the vegetation of the roof makes that only part of this water comes available. In very wet periods, the system may get overfilled, in which case either rain water or wetland effluent is discharged on the surface water.

Results. Technically, the system has proven to be a solid concept; no technical failures of any importance have occurred. On the subject of water quality, however, improvements will have to be made. One of the main problems that are being observed is the build-up of electrical conductivity/salinity due to continuous recycling. Other water quality data collected in 2007 resulted in the following removal efficiencies of the vertical flow wetland: 75% TSS, 97% NH4-N, 28% TP, 55% COD and 2.2 log units reduction in total coliforms. The drinking water produced by the RO system complied with common standards, with the exception of nitrate concentrations.

In general, first results gave rise to the following points of attention:

1. Recirculating the same water time after time results in build up of both pollution and hydraulic loads.
2. Trying to withhold phosphorus in the wetland seems contradictory to what the RO needs for influent. Addition of calcium and iron grit to the filter material for removing TP increases the water hardness but is not problematic when discharging to surface water. Here, however, the RO is struggling with the °D factor.
3. Combining vegetated roofs with reuse of rain water seems contradictory as well, since the quality and quantity are not changed for the better. The pH level is positively influenced by the vegetation but the colour of the water is brown and turbid and not fully removed by the coal filter in the system. Finally the quantity of water coming from a vegetated roof may sometimes only be 20%, the rest being stored in the soil or evapotranspirated.


Rain
Rain water harvesting
Kitchen
Laundry
WC
PPS
PP
Rain water
PP3
PP2
PPR
Grey water
Black water
Degreaser
Pumpsump
Septic tank
RO Installation
Drinking water
Effluent
Influent
VF-CW

CHAPTER 2 – MICROPHYTE SYSTEMS

WASTE STABILIZATION PONDS

2.1. INTRODUCTION TO POND TECHNOLOGY

Of current ecological technologies, waste stabilization ponds (WSPs) have advanced most in terms of application and reliability, and they can help to reclaim both domestic sewage and a wide range of industrial wastewaters in order to meet specific effluent standards (Table 2.1; Pearson, 1996). WSPs have also been the most common ecological technology to be integrated with resource recovery such as phytoplankton production (Oswald, 1991; De Pauw and Salomoni, 1991) or fish production (Edwards, 1992). In stabilization pond technology, many ponds with various functions are serially-linked as a flow-through reactor to allow the wastewater flowing from pond to pond. The integration of resource recovery and reuse is often carried out in the final pond(s) of the series or in a separate pond(s) receiving the effluent of the WSPs. Stabilization pond systems, like other eco-technological systems, however require an extensive land area. This is the main disadvantage of the ecological technology for wastewater reclamation (Hosetti and Frost, 1998). Therefore, studies on optimization/minimization of land requirement are necessary.

There were some successful studies on minimizing the land requirement of WSP systems. Wastewater Storage and Treatment Reservoir technology (WSTR) has emerged as an alternative of the stabilization pond system for land saving purpose (Llorenz et al., 1992; Pearson, 1996). A WSTR is a single and deep reservoir/pond that acts as a batch-fed reactor, i.e. storing and reclaiming wastewater concurrently in the same pond/reservoir, based on an operational regime of “filling, resting and using”. Its effluent is mainly being used for irrigation. The reclaiming efficiency of this system was completely comparable to that of a stabilization pond system (Llorenz et al., 1992; Pearson, 1996). When being incorporated with separate ponds in order to store the effluent of the WSTR on a sequential batch-fed basis (Mara and Pearson, 1992), it was possible to efficiently meet any required irrigation regime and maximize the area of land that could be irrigated (Pearson, 1996).

A further overview of the most important technologies is given below.

2.2. TYPES OF POND TECHNOLOGIES

Pearson (1996) published an excellent overview of different WSP technologies and their applications, as shown in Table 2.1.

Table 2.1. Pond technologies and applications (after Pearson, 1996)

Pond Type	Key Applications	References
Anaerobic	Organic, solids removal, industrial treatment	Alabaster et al 1992, Saqqar & Pescod '95
Anoxic	Organic, solids removal	Pescod '96
Facultative - primary & secondary	Organic, solids removal, pathogen removal	Mara et al '92, Pearson et al '95
Intermittent aerated facultative	Organic, solids removal	Fuog et al '95, Mara et al '92
Maturation	Pathogen, nutrient removal	Mara et al '92, Pearson et al '95
Disinfection	Pathogen removal (from conventional treated effluents)	Mara et al '92, Pearson et al '95
High Rate Algal (HRAP)	Algal bimoass production (ABP), organic removal	Oswald '91& '95, De Pauw & Salomoni '91
Advanced Integrated Systems	ABP, methane recovery, pathogen removal	Green et al '95a & '95b
Attached-growth	Organic removal, industrial treatment	Prolprasert & Sookhanich '95
Macrophyte - rooted & floating	Organic, solids, nutrient removal, biomass recovery	Middlebrooks '95
Waste Storage Treatment Reservoir	Organic, pathogen removal, effluent storage	Juanico & Shelef '91, Mara & Pearson '92
Sewage-Fed Fish Ponds	Fish production, effluent polishing	Edwards '92
Septage and Nightsoil	Organic, pathogen removal, tankered nightsoil and septage	Mara et al '92

2.2.1. Waste stabilization ponds (WSP)

There exist voluminous literatures on all technical as well as socio-economic aspects of the WSP technology as reviewed for example by Pearson (1996), Von Sperling and Chernicharo (2005) or Shilton (2006). Therefore, only a brief introduction of WSPs is given.

The principle of ecological food chains is engineered within a series of earthen ponds in which the reclamation process is phased out into variously functional ponds in relation to a specific group of involved organisms and to a corresponding level of wastewater reclamation. Generally, it consists of three different types of pond:

anaerobic, facultative and maturation ponds. The wastewater flows continuously into the pond series and sequentially from one type of pond to another in order to discharge a satisfactorily reclaimed effluent at the end (Mara, 1997).

1. Anaerobic ponds are commonly 2 to 5 m deep and receive high organic loading (BOD> 3000 $kg.ha^{-1}.day^{-1}$). Anaerobic ponds operate wit minimum hydraulic retention times of one day and their inclusion in a pond system can often give a land area saving of over 75% at design temperature above 16°C (Pearson, 1996). No phytoplankton is present except for a thin layer of *Chlamydomonas* because of the toxicity of undissociated ammonia and high sulphide concentrations (Mara and Pearson, 1986; Mara, 1997). The degradation of organic solids to methane and carbon dioxide under bacteriological activities is the most important process (Edwards, 1992)**.**

2. Facultative ponds are shallower, 1 to 2 m deep, and of one of two types: primary facultative ponds which receive raw wastewater or secondary facultative ponds which receive settled wastewater (e.g. from anaerobic ponds). They are designed mainly for BOD removal on the basis of a relatively low organic loading rate (100 to 300 $kg.ha^{-1}.day^{-1}$). A healthy phytoplankton community exists and BOD removal by the pond bacteria is mostly supported by oxygen of phytoplankton photosynthesis (Mara, 1997).

3. Maturation ponds are 1 to 1.5 m deep and receive the effluent from a facultative pond. The phytoplankton populations are much more diverse than those of the facultative ponds and consist especially of non-motile genera. The primary function of maturation ponds is the removal of excreted pathogens owing to the synergism of solar irradiance, temperature, and high pH and high dissolved oxygen concentrations caused by the active photosynthesis of phytoplankton (Curtis et al., 1992; Mara, 1997) though the pathogen removal can also be efficient within facultative ponds (Liang et al., 1998)**.** Maturation ponds achieve only a small removal of BOD, but their contribution to nutrient (nitrogen and phosphorus) removal can be significant.

Generally, the functions of anaerobic ponds and facultative ponds are mainly BOD_5 and nutrient removal, although the latter can be continued significantly in the maturation ponds. On the contrary, maturation ponds are mainly designed for pathogen removal. Therefore, designing combinations of these types of ponds depends on organic loadings and required standards of the effluent. If the influent is strong wastewater with a high organic waste content (BOD_5 >300 $mg.l^{-1}$), then an anaerobic pond must be used; contrarily low-strength influent (BOD_5 < 150 $mg.l^{-1}$) only requires facultative ponds. In case pathogen standards (e.g. faecal coliforms) of the effluent are strict, clearly maturation ponds are needed. In addition, when levels of faecal coliforms are satisfactorily met, these ponds are often integrated with fish production as plankton communities develop strongly and the organic load (BOD_5) is much lower (Bartone and Khouri, 1990; Shereif et al., 1995, Liang et al., 1999b).

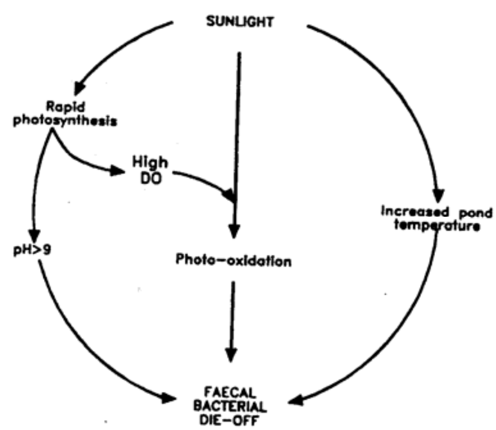


Fig. 2.1. Conceptual mechanisms for faecal coliform die-off in ponds (Source: Mara, 1997).

The removal efficiencies of organic pollutants in WSPs are dependent on many factors, of which the hydraulic retention time and loading levels are most important. The WSP can reclaim wastewater to introduce a quality of effluent which is generally comparable with other technologies in BOD_5, nitrogen, and phosphorus concentrations (WHO, 1987**;** Pearson, 1996). However it has been repeatedly confirmed that the excreted pathogen percentage removal in WSPs can be as high as > 95%, i.e. higher than in the other systems **(**WHO, 1987; Pearson, 1996; Hosetti and

Frost, 1998). The effective performance of WSP in heavy metal removal was also proved (Polprasert and Charnpratheep, 1989)**.**

The above brief description of the WSP design and function indicates the simplification of engineering the ecological food chains principle in practice. The capital costs are mainly for earthworks to construct ponds. The major energy source for system operation is only solar radiation. As a result, the construction, operation and maintenance costs of WSPs are much lower than current conventional technologies, especially in the tropics (Arthur, 1983; Mara, 1997). Oswald (1995) reported that the overall cost of an earthwork reactor for wastewater reclamation is at least an order of magnitude less than that of alternative reactors such as those constructed of steel-reinforced concrete. Comparing different technologies for wastewater reclamation, Brix (1999) demonstrated that the 'greeness' of a technology depends on the consumption of non-renewable energy sources. This means that the less this consumption, the greener the technology.

Despite the fact that several advantages of ecological technologies for wastewater reclamation have been proven, their high requirement for land area has been often considered as a major disadvantage (Hosetti and Frost, 1998). With a series of ponds in combination with an anaerobic pond, Mara (1997) proved that the land area need per caput for wastewater reclamation by WSPs could be reduced down to 0.54 m^2 at 25°C. It is evident that more extensive/intensive studies are still needed to minimize the land area required by ecological technologies.

Box 1. Anaerobic ponds

1. General description

Anaerobic ponds are earthen basins with a depth of 2-5 meters. They receive high organic loads and inhibit photosynthetic activity of algae, resulting in the absence of oxygen at all levels. Under these conditions the ponds work as an open unmixed anaerobic reactor. They are primarily designed for removing BOD_5 and used as a first step for domestic wastewater treatment purposes. A schematic layout of anaerobic ponds is shown below.

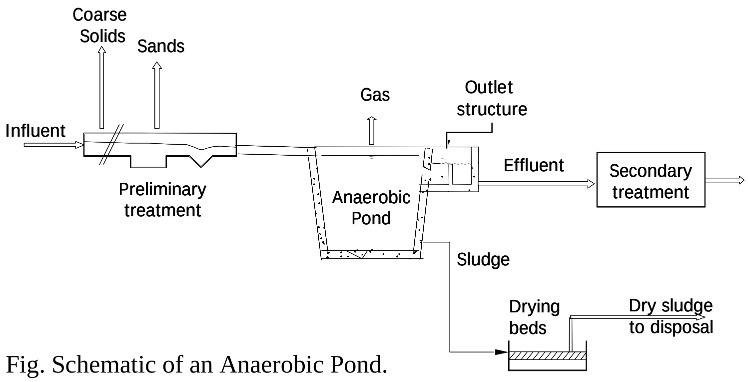


Fig. Schematic of an Anaerobic Pond.

Removal of organic compounds occurs by sedimentation and degradation of organic material by anaerobic bacteria, resulting in carbon dioxide and methane formation. Also, particulate matter that does not undergo degradation settles onto the bottom of the ponds. This kind of treatment largely depends on temperature. If temperature is below 10ºC (temperature needed for the methanogenesis) there is minimal digestion and the pond only has a sedimentation effect (Mara et al., 1992)

2. Design features

The criteria used for the design of anaerobic ponds are given below, with ranges based on the following references: Yánez (1993), Metcalf & Eddy (1991), WEF (1990), Romero (1994), IMTA (1997), Mara (1992) and Arthur (1994).

- *Water depth*: 2 – 5 meter, with deeper ponds allowing extended sludge storage.
- *Temperature*: For optimal operation, temperature should be > 15 °C.
- *pH*: optimal range is 6.2 – 7.2, under certain conditions limestone can be added to increase alkalinity.
- *HRT*: 2-5 days, a longer HRT is not recommended because otherwise the anaerobic pond will start working as a facultative pond.
- *Volumetric organic loading rate*: 100 – 400 g BOD_5/m^3.day, with the higher loading rates at higher temperatures.
- *Sludge production rates*: typically 0.3-0.4 m^3/capita/year.
- *Minimal distance from community*: 1000m recommended to avoid complaints about odour.
- *Land requirements*: 0.02 – 0.06 m^2/inhabitant.
- Soil permeability: lower than 5 mm/hour.

3. Operation and maintenance
In order to prevent odor and vermin problems, minimum operation and maintenance must be carried out on a regular basis.

Daily inspection and maintenance activities:
- Conducting a walkabout of the perimeter of the wastewater treatment system and each pond
- Recording meteorological data (temperature, rainfall, and wind) on an operational control sheet on a daily basis.
- Keeping qualitative records of hours of sunlight, air temperature (maximum, medium and minimum temperatures), rainfall, evaporation, wind direction, and air humidity if there is a meteorological station on the site.

Periodical maintenance activities
- Cleaning the ditches that protect against rainwater and removing any deposits of sand or any other obstructing material.
- Painting fences and warning signs

Sampling must be included in the pond monitoring schedule at least once a month to determine whether the pond meets the quality parameters based on the final use of the effluent. Furthermore, it is advisable to take periodic measurements of the depth of the sludge layer at different points in anaerobic and facultative ponds (Mara et al., 1992). The removal of accumulated sludge at the bottom of the pond should be done with a frequency of 5 to 10 years, depending on the quantity of inert material in the influent and the temperature of the wastewater.

Sludge accumulation: Solids in anaerobic ponds accumulate mainly on the primary units, which need to be cleaned after a certain period of operation. The sludge accumulation rate at the bottom of an anaerobic pond ranges from 0.08 to 0.113 l/inhab a day (m3/inhab/year (Yánez, 1993; Mara, 1976; Mendoça, 2001) and for design purposes the higher limit can be used which equals 40 m^3/inhab/year.

In practice it is convenient to do a proper cleaning process when the sludge height reaches 50% of the depth of the pond. The difference in the number of years between two consecutive cleanings can be calculated by considering a volume loss of 50% because of the effect of sludge accumulation (Yánez, 1993; Mara, 1976; Mendoca, 2001).However, sludge accumulation in an anaerobic pond occurs very fast. The accumulation rate varies from 0.03 to 0.05 m^3/inhab/day in warm climates and the sludge evacuation is done when sludge reaches one third of the total volume of the pond (Mara, 1998; IMTA, 1994).

Generation of odors: In anaerobic ponds is possible that the formation of bad odors might occur due to the reduction of sulphates ($S0_4^{2-}$) in the wastewater into hydrosulphuric acid (H_2S) by the action of sulphate reducing bacteria (Desulphvibrie). Bad odours are not generated when sulphate concentrations in wastewater are below 500 mg/l. Thus, this problem can be controlled if the pH is kept above 7 by adding lime or soda (Peña, 1996; Mara et al., 1992).

4. Removal efficiencies

The removal efficiencies reported by several authors (Metcalf & Eddy, 1995; Mendoça, 1999; Yánez, 1993; Romero, 1994; IMTA, 1997; Polprasert, 1995) for anaerobic ponds are: 50-70% BOD, 50-70% TSS, 70% helminth removal and 1 log unit faecal coliform removal (note that these data are based on standard HRTs of 1-5 days; typical influent concentrations of 200 mg/l soluble BOD_5 and 200 mg/l TSS and for effluents still containing algae, microorganisms and suspended solids). Effluent is not suitable for reuse but must be further treated.

5. Advantages and disadvantages

Advantages: Low land area requirements; capability of mineralizing large amounts of organics with a good reduction of BOD_5 and SS; especially suitable for waste treatment with high concentrations of organic matter; reduce area needed for subsequent treatment; low production of waste biological sludge; no oxygen requirements; possibility to capture methane and generate heat and electricity; low nutrient requirements.

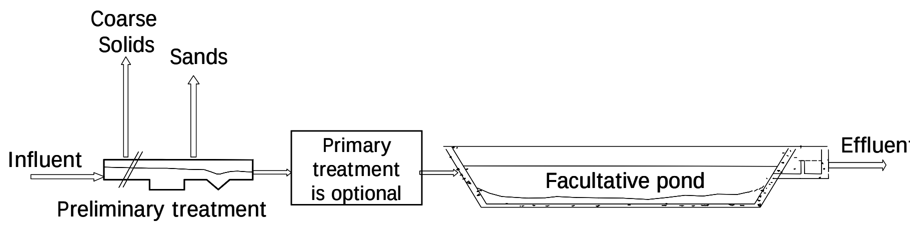
Disadvantages: process is very sensitive to environmental and operational conditions such as temperature, load variations and pH, which tend to produce periods of low efficiency; accumulation of unpleasant surface layers and unfavourable aesthetic conditions which normally impacts maintenance; effluent has a high content of organic matter and colour and requires post-treatment; potential production of bad odours due to the sulphydric gas; sludge needs to be removed more often than other types of ponds because of the rapid accumulation of solids in a small area.

Figure 1. Anaerobic Pond. Research Station in Ginebra, Valle del Cauca, Colombia

Box 2. Facultative ponds

1. General description

Facultative ponds are shallow water deposits constructed with earth and embankments (or dikes) and, occasionally, containment walls. They are designed for the treatment of either raw wastewater or previously treated effluents. When wastewater is discharged into these reservoirs, a process known as self-purification or natural stabilization takes place which involves the occurrence of physical, chemical and biological reactions that result in the removal of solids, organic material, nutrients, and pathogens. The effluent of facultative ponds is usually further treated using maturation ponds. A schematic layout of a typical facultative pond is given below.



Facultative ponds (FP) are mostly used for treatment of municipal wastewater. They can operate as a primary treatment unit or receive settled wastewater (typically from anaerobic ponds) and operate as a secondary facultative pond (Polprasert, 1995; Yánez, 1993; WEF, 1990; EPA, 1983; Mara et al., 1992; Mara, 1998; Arthur, 1994).

The fundamental feature is that FP combine the characteristics of both aerobic and anaerobic ponds. They have an aerobic layer where the required oxygen for bacterial metabolism is supplied by the photosynthetic activity of algae in the pond, and as depth increases, the pond becomes anaerobic with a layer of sludge at the bottom. The aerobic layer depth depends on the production of oxygen by algae, which varies during the day. Anaerobic fermentation occurs in the lower layer and aerobic stabilization occurs in the upper layer. Settleable solids are deposited on the pond bottom, thereby releasing methane and carbon dioxide (Polprasert, 1995; WEF, 1990; IMTA, 1997; Van der Steen, 2002a; Peña; 1996; Mara et al., 1986).

The key to the successful operation of facultative ponds is oxygen production by photosynthetic algae and surface reaeration (UNEP, 2001; Mara et al., 1986). The algae are necessary for oxygen production but their presence in the final effluent represent a reduction of the efficiency of the system.

2. Design features

Based on references WEF & ASCE (1995), Reed (1995), UNEP (2002), WEF (1990), Tchobanoglous (1998), Metcalf & Eddy (1991), Romero (1994), Mendoça (1999), Polprasert (1995), Mara (1992), Arthur (1994), IMTA (1997), EPA (1983); the following ranges for design parameters are suggested:

- *Water depth*: 1.2 – 2.5m with higher depths when additional sludge storage is needed because no adequate pretreatment is present
- *Temperature*: 5 – 30 ^{o}C with higher temperatures yielding higher process rates

- *pH*: optimal range is 6.5 – 8.5
- *HRT*: 5 – 30 days; longer detention times needed at lower temperatures and higher loading rates c.q. when no pre-treatment is available
- *Organic loading rate*: < 200 kg BOD/ha/day; dependent of local temperature
- *Sludge production*: 0.015 – 0.02 m^3/capita/year
- *Minimal distance from community*: 1000m recommended to avoid complaints about odour
- *Land requirements*: 2 – 5 m^2/inhabitant
- *Soil permeability*: lower than 5 mm/hour

3. Operation and maintenance

The maintenance requirements for facultative ponds are simple, but maintenance needs to be performed on a regular basis in order to prevent odor and vector issues. Routine maintenance includes the following tasks (Mara et al., 1992; Arthur, 1994):

Daily inspection and maintenance activities:

1. Conducting a walkabout of the perimeter of the wastewater treatment system and each pond for the purpose of:
- Cutting any plants that grow on the side slopes and internal/external dams to keep these plants from spreading to the ponds.
- Removing sand and sediment from the entrance and exit structures.
- Fixing any damages on the embankments/dikes caused by rodents, snakes and ants, thereby trying to create a hostile environment to these kinds of animals.
- Checking for water leaks on the side slopes.
- Checking the status of preservation and cleanliness of the rainwater drains.
- Checking whether the distribution of flow rates (if the pond has multiple points of entry and exit) is equitable, considering the number of branches.
- Regulating the flow rates of influents and effluents from the pond, thereby checking whether the operating levels are suitable and constantly keeping track of the quality of both influent and effluent.
- Spraying the surface layer of anaerobic ponds with clean water to avoid proliferation of vectors. The surface layer is not to be removed because it facilitates the treatment process.
- Removing foam or surface layers and floating macrophytes from the surface of facultative and maturation ponds in order to maximize photosynthesis and minimize proliferation of mosquitoes.
- Inspecting whether there are weak enclosure walls or broken fences. This is a precautionary measure to avoid access of animals or individuals to the premises.
- Checking to ensure that signs are placed at prominent locations, indicating that the pond is a wastewater treatment system.

2. Recording meteorological data (temperature, rainfall, and wind) on an operational control sheet on a daily basis.
3. Keeping qualitative records of hours of sunlight, air temperature (maximum, medium and minimum temperatures), rainfall, evaporation, wind direction, and air humidity if there is a meteorological station on the site.

Periodical maintenance activities

- Cleaning the ditches that protect against rainwater and removing any deposits of sand or any other obstructing material.
- Painting fences and warning signs

Operation and maintenance tasks performed at stabilization ponds should be included in a monitoring plan to check the quality of effluent and ensure that the system is running properly so that corrective action is taken if evidence is found that the quality of effluent is deteriorating. The monitoring plan should include sampling at least once a month and conducting tests to determine whether the ponds comply with quality parameters that are consistent with the final use of the affluent. It is advisable to conduct periodical measurements of the depth of the layer of sludge at different points in anaerobic and facultative ponds (Mara et al., 1992).

Sludge Build-up, Management and Removal: Stabilization ponds are oversized sedimentation units. Therefore, primary ponds retain almost 100% of settleable solids. Unlike activated sludge and biofilters, no biological flocculation occurs in stabilization ponds and thus, no secondary sedimentation takes place. This leads to a sludge build-up level in ponds which, for practical purposes, is considered negligible.
The volume of sludge accumulation in primary facultative ponds ranges from 150 to 200 l/inhabitant a year of accumulation of wet sludge.

The accumulation of sludge from sedimentables solids is close to 800 l/hab a year, but the anaerobic digestion process that takes places at the ponds bottom reduces this volume to the above mentioned volume of 150 to 200 l/hab a year.

When sludge needs to be removed (based on the design of the pond and taking into account that there needs to be more than one primary pond), the pond is drained and dried before cleaning. Thus, the dry volume of sludge is a lesser amount (approximately 50 l/hab per year).

Vector and odor control: Since stabilization ponds are built to improve health and sanitation conditions, it is therefore necessary to ensure that the ponds do not become places that harbor vermin (e.g. mosquitoes, snails, etc.) that can spread diseases such as malaria, yellow fever or schistosomiasis. The best way to control mosquitoes is performing good maintenance of both ponds and embankments (or dikes) Making changes to the water level can also be useful for eliminating larvae. In extreme cases, insecticides can be used.

Although the use of larvae-eating fish can be a good mechanism to control mosquitoes, this kind of fish does not always survive in stabilization ponds.

Overloaded facultative ponds and anaerobic ponds can generate bad odors because of sulfurs. The loading limit for primary facultative ponds at 20ºC in tropical areas is 350 kg BOD_5 /hectare. The limit for secondary ponds is close to 250 kg of BOD_5/hectare per day.

4. Removal efficiencies and reuse opportunities
Based on WEF & ASCE (1998), Reed (1998), Metcalf & Eddy (1995), WEF (1990), Romero (1994), Polprasert (1995), IMTA (1997), Von Sperling (1996), EPA (1983); the following range of removal efficiencies can be expected: 70-90% BOD, 40-100% TSS, 20-60% TP, 30-50% TN and 1 log unit faecal coliform removal.

Re-use for agricultural purposes: Irrigating crops using effluents from stabilization provides a proper balance of nutrients for plants (especially nitrogen, phosphor, and potassium salts), thus increasing crops production and reducing the costs of artificial fertilizers. Furthermore, the effluents of stabilization pond systems provide additional benefits because, in the presence of algae, they supply humus to the soil, thereby improving its structure and water retention ability.

Re-use for Aquaculture: Reuse effluents from wastewater treatment systems in stabilization ponds has been extensively used in aquaculture in Germany and Hungary for more than 50 years, and more recently in the United States. The effluents of a stabilization pond system, but particularly the effluents of a maturation pond provide an alternative which has become increasingly popular in Latin American countries, which also represents an inexpensive alternative.

5. Advantages and disadvantages
Advantages: Low capital and operation and maintenance costs; It involves minimum training of the personnel responsible for operation and maintenance; Sludge evacuation and disposal only take place every 10 to 20 years; Compatibility with other treatment systems; No expensive equipment is needed; Minimum or no consumption of electrical power; Easy to build and operate; Reliable, easy to maintain; They can resist changes in organic loads or hydraulic loads; High stabilization of organic matter; Produce stabilized sludge that can be used for agricultural purposes; Treated water can be reused in agriculture and aquaculture.
Disadvantages: Large land areas are required; Effluent has a high concentration of algae, which can origin problems to receiving water bodies; Potential negative impact on groundwater; It may generate bad odors and mosquitoes; Evaporation losses; Algae is extremely sensitive to the components; They can supply an effluent with a high load of suspended solids; They should be built at a prudent distance from inhabited cores; High production of algae which remains in the effluent, thus causing problems because the concentration of suspended solids could exceed the specifications for toxic discharges.

Fig. Facultative pond in Ginebra, Colombia

Box 3. Maturation ponds

1. General description

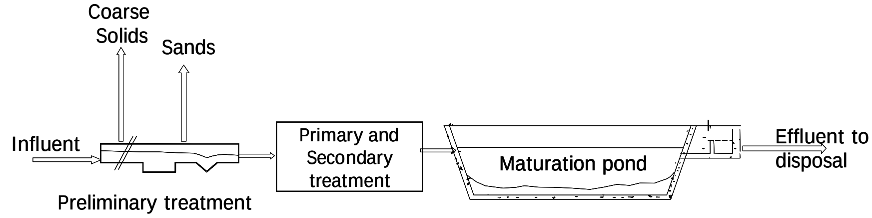
Maturation ponds are also called high-rate, tertiary or polishing aerobic stabilization ponds. Maturation ponds receive the effluent from a facultative pond or from any other secondary process facility. They are shallow ponds to allow light to penetrate their entire depth. As a result, aerobic ponds have active photosynthetic activity trough the entire water column during daylight hours, thus producing large amounts of oxygen. Figure 1 shows a layout of a typical maturation pond.

The main purpose of maturation ponds is to eliminate pathogens and to supply a high quality effluent that is suitable for being reused mainly in agriculture or aquaculture, groundwater recharge, or discharging to bodies of water. The size and number of tertiary ponds depend on the quality of the final effluent. A set of small ponds is more efficient than a single pond (of the size equal to the sum of the individual ponds). To the extent possible, all ponds must be of the same size.

Sedimentation is the main mechanism to remove eggs of helminths and protozoan cysts. Viruses are removed by adsorption and sedimentation. Bacteria are removed primarily due to the climatic effect and temperature conditions because the increase of these factors leads to an increase of the mortality rates of bacteria; pH values above 9, which result from algae photosynthesis (CO_2 reduction), and high exposure to sunlight kill bacteria (Mara *et al.*, 1992). There are other determining factors such as high concentrations of dissolved oxygen, photo-oxidation, algae-produced toxins, inadequate substrate, and predators including protozoans and micro-invertebrates (Polprasert, 1995; IMTA, 1997; Peña, 1996).

Although maturation ponds eliminate pathogens, they also allow proliferation of algae, which typically constitute the bulk of suspended solids in the effluent. These systems remove only a small amount of BOD_5, but their contribution to the removal of nutrients (nitrogen and phosphor) can be significant (Mara *et al.*, 1992; Peña, 1996; Arthur, 1994). Ammonia nitrogen in maturation ponds evaporates into the atmosphere at high pH concentration values.

The total rates of removal of nitrogen and ammonia nitrogen are 80% and 95%, respectively. Phosphor in the biomass settles in the form of organic phosphor and may precipitate as inorganic phosphor at pH values equal to or greater than 9.5. The rate of removal of phosphor is close to 45%. The higher the number of maturation ponds, the higher the rate of removal (Peña, 1996). Table 1 shows the removal efficiencies of maturation ponds as reported by several authors.



2. Design features

Based on Romero (1994), Polprasert (1995), IMTA (1997), Arthur (1994) and Metcalf and Eddy (1991), the following ranges of design parameters can be defined:

- *Water Depth*: maximum 1 – 1.5 meter to allow full light penetration
- *Temperature*: optimal temperature 20 ºC but functioning between 0 – 30 ºC
- *pH*: optimal range is 6.5 – 10.5
- *Hydraulic detention time (days)*: 5 – 20 days recommended
- *Organic loading rate*: < 17 Kg BOD_5/ ha.d
- *Minimal distance from community*: 500m recommended
- *Area*: 0.8 - 4 m^2/inhabitant required
- *Soil permeability*: < 5 mm/hour

3. Operation and maintenance

Since maturation ponds are generally designed together with anaerobic and facultative ponds, daily routine and periodical inspection and maintenance tasks are the same as those described for facultative ponds. Routine maintenance includes the following tasks (Mara et al., 1992; Arthur, 1994):

Daily inspection and maintenance activities:

- Conducting a walkabout of the perimeter of the wastewater treatment system and each pond.
- Recording meteorological data (temperature, rainfall, and wind) on an operational control sheet on a daily basis.
- Keeping qualitative records of hours of sunlight, air temperature (maximum, medium and minimum temperatures), rainfall, evaporation, wind direction, and air humidity if there is a meteorological station on the site.

Periodical maintenance activities:

- Cleaning the ditches that protect against rainwater and removing any deposits of sand or any other obstructing material.
- Painting fences and warning signs

Operation and maintenance tasks performed at stabilization ponds should be included in a monitoring plan to check the quality of effluent and ensure that the system is running properly so that corrective action is taken if evidence is found that the quality of effluent is deteriorating.

The monitoring plan should include sampling at least once a month and conducting tests to determine whether the ponds comply with quality parameters that are consistent with the final use of the affluent. It is advisable to conduct periodical measurements of the depth of the layer of sludge at different points in anaerobic and facultative ponds (Mara et al., 1992).

The individuals responsible for the operation of stabilization ponds must receive clear precise instructions about the frequency of operation and maintenance tasks. Their work needs to be done under constant supervision.

4. Removal efficiencies and reuse opportunities

Based on Romero (1994), Reed (1998), Polprasert (1995), IMTA (1997) and Metcalf and Eddy (1991), the following ranges of removal efficiencies can be mentioned: 60-80% BOD, 10-30% TSS, 40-60% TN, 3 log units faecal coliforms and 100% for helminth eggs.

Maturation ponds are mainly used for refining effluents from facultative ponds, achieving significant reduction of microorganisms, and enabling safe re-use of effluents in agricultural and aquacultural applications. Maturation ponds can be used in combination with aquaculture, where the last maturation pond is seeded with floating aquatic plants (hyacinths or duckweed). The advantage of this practice is the generation of biomass and the reduction of the impact of algae on the concentration of suspended solids in the effluent (Van der Steen, 2002a).

5. Advantages and disadvantages

The main advantage of maturation ponds is the elimination of pathogens from wastewater. The main disadvantage of these kinds of ponds is related with the removal of suspended solids because of the large production of algae and the land requirements. The advantages and disadvantages are similar to facultative ponds.

2.2.2. Wastewater Storage and Storage Reservoir (WSTR)

Another measure for reducing the land requirement of WSPs has been the use of a system consisting of only one but much deeper pond, known as deep stabilization pond or Wastewater Storage and Treatment Reservoir (WSTR) (Mara et al., 1996). Actually, this type of pond was used in Israel in the 1970s and these reservoirs were initially conceived merely for seasonal storage of wastewater but it soon became evident that they provide additional stabilization to wastewater, hence term "stabilization reservoir" **(**Juanico and Shelef, 1994**)**. At present, they are being used in many parts of the world, for examples, in Israel **(**Juanico and Shelef, 1994**),** Portugal (Torres et al., 2000) and in Brazil **(**Mara et al., 1996**).** Its depth varies from 5.5 to 15 m (Juanico and Shelef, 1994).

A WSTR operates on a filling-resting-using basis, i.e. it is filled with wastewater, and then wastewater is depurated naturally and used for irrigation eventually (Mara et al., 1996). It is interesting to know that in the WSTR wastewater is reclaimed with a combination of anaerobic and aerobic processes owing to its depth (Torrez et al., 1997a**,** Torrez et al., 2000). This resembles a system of anaerobic and facultative WSPs. In the WSTR the active zone of the system is located from the surface to 1m depth and behaves as a continuously stirred tank reactor (Torrez et al., 2000). This means that its active zone is the same as a common shallow pond.

Similar to WSPs, there have been many studies on WSTRs with regard to design, behaviour, operation and performance (Lorenz et al., 1992; Abeliovich and Vonshak, 1993; Juanico and Shelef, 1994 Mara et al., 1996 Torrez et al., 1997a**,** Torrez et al., 2000), and plankton dynamics (Eren, 1978; Soler et al., 1991; Llorenz et al., 1993).

Llorenz et al. (1992) monitored a WSTR and demonstrated a high removal efficiency of BOD_5, 86% to 97%; COD, 71% to 92%; Total Kjeldahl Nitrogen, 51% to 98.8%; Total phosphorus, 43% to 93%; and total coliforms, 91%; faecal coliforms and faecal streptococci, 99%.

From the above facts it is clear that the wastewater stabilization process can occur in both flowing (WSP) and stagnant waters (WSTR). The idea behind the establishment of different compartments such as anaerobic, facultative and maturation ponds, is to assign separate functions to corresponding compartments of the system in order to accelerate the efficiency of the whole system. However, when the compartment set-up is not made artificially, the WSTR ecosystem can naturally form its own components, e.g. the active zone, compatible with the functions of the WSP. It was proven that the active zone of the WSTR is located from the surface up to 1 m depth and that it behaves like a continuously stirred tank reactor (Torres et al., 2000). Indeed, during the stabilization process, it was demonstrated that the dynamics of the phytoplankton community in the WSTR were comparable with those of high rate oxidation ponds (used for producing phytoplankton biomass through wastewater reclamation) (Llorens et al., 1993).

Regarding the microbiological safety of the effluent, Mara and Pearson (1993) demonstrated that the effluent of a WSTR satisfied even strict recommendations of the World Health Organization (WHO, 1989) for unrestricted irrigation and aquaculture (1 helminth egg per liter and $\leq 10^3$ faecal coliforms per 100 ml) with a sequential batch-fed regime.

2.3. PROCESSES IN WASTE STABILIZATION PONDS AND INFLUENCING FACTORS

Fate of organic substances in aquatic ecosystems is controlled by the principle of ecological food chains. Based on this ecological principle, the wastewater stabilization pond technology was established as summarized in Fig. 2.2.

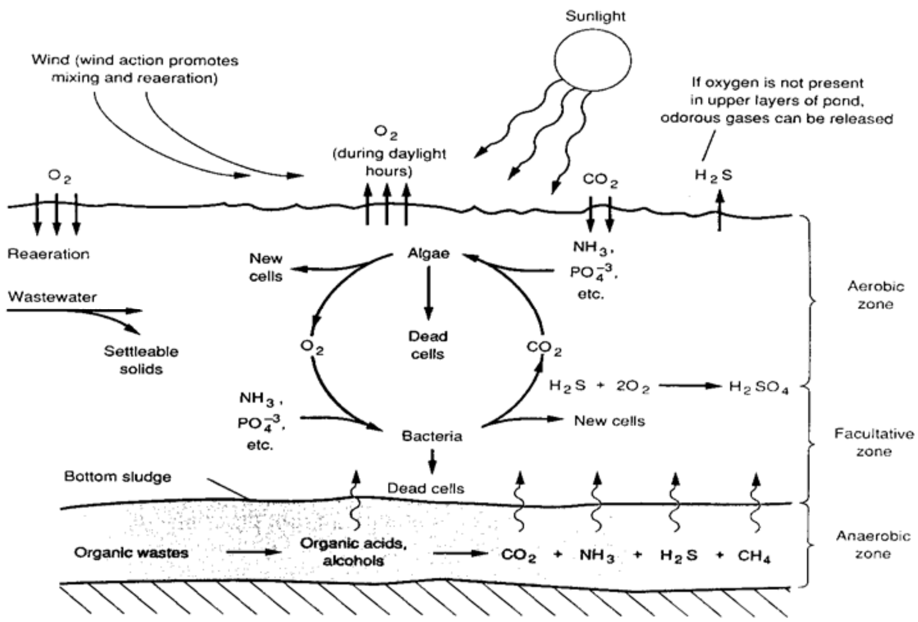


Fig.2.2. The symbiosis between phytoplankton and bacteria in waste stabilization ponds (Source: Tchobanoglous, 1991).

As shown in Fig. 2.2, it is a symbiosis of bacteria and phytoplankton. Bacteria provide phytoplankton with nutrients and carbon dioxide by decomposing organic wastes. Phytoplankton, in turn, generates dissolved oxygen through photosynthesis in order to support bacterial activities. Simultaneously, when phytoplankton (primary producers) develops its biomass, it will be a resource for zooplankton (primary consumers) to graze on. Actually, this ecosystem functions in a way more complicated than that it is described. The appearance, actions, dynamics of its components, such as species of living organisms, characteristics of pollutants, etc., are interconnected, interdependent and interactive, causing multiple interactions among themselves, making an organic whole (Yan et al., 1998).

2.4. ECONOMIC FACTORS

As for other (natural) wastewater treatment systems, reported costs are highly variable as a consequence of differences in climate, topography, soil, wastewater type, resource availability etc. The main investment costs are related to land acquisition; since WSPs require large surface areas, they are generally only feasible in rural areas where land prices are relatively low. Mara (2004) nevertheless also reports on WSPs treating the wastewater of major cities such as Melbourne (Australia) and Nairobi (Kenya).

In Bixio and Wintgens (2006), a summary is given of capital costs for two European countries:

- France: 120 € per capita for systems < 1000 PE (range 90-450 € per capita)
- Germany: 364 € per PE

Operation and maintenance costs in Germany are in the order of 0.62 € per PE.

Another rigorous economic analysis was undertaken for a hypothetical large WSP system for the city of Sana'a in Yemen (Arthur, 1983). Capital costs were 22.7 USD per capita, annual operating costs 0.84 USD per capita.

Possible benefits can be obtained from reusing the effluent for irrigation or aquaculture.

2.5. EXAMPLES OF APPLICATIONS IN URBAN ENVIRONMENTS

2.5.1. Case study Ho Chi Minh City (after Nguyen et al, 2006)

The Binh Hung Canal is a 4 km long canal situated in the northeast of Ho Chi Minh City. It serves a drainage area of 785 hectares and presently receives domestic wastewater from a population of some 120,000 people living in a very poor area of the city. In addition to this, industrial and environmental harmful activities like textile-dying, seafood processing and paper mills discharge an unknown amount of industrial wastewater into the canal. This overload of pollutants results in completely anaerobic

conditions in the canal and a bad smell. The black appearance of the canal has resulted in it being known as the Den (black) Canal.

Because of a lack of space due to encroachment (Figure 8.2), a wastewater treatment plant has been designed which combines aerated lagoon technology with stabilization ponds. The current design discharge capacity is 30,000 $m^3.day^{-1}$. The ponds cover a surface area of approximately 22 ha.

Local residents benefit from the system not only in the sense of the elimination of the odour and sanitation problem, but also due to the fact that the surroundings of the maturation ponds have been arranged as public park space.

Fig. 2.3. Aerial view of the Den Canal wastewater treatment plant in Ho Chi Minh City (Vietnam). Picture courtesy of Jan van Lint (Belgian Technical Cooperation).

2.5.2. Western Treatment Plant in Melbourne, Australia (www.melbournewater.au.com)

The Western Treatment Plant serves the central, northern and western suburbs of Melbourne which contain around 1.6 million people, around 55% of Melbourne's population. It is the largest sewage treatment facility in Australia, occupying an area of 100 km^2 and treats an average daily flow of around 500 ML/d. It is situated some 30 km west of Melbourne, adjacent to the town of Weribee. This treatment plant was

already established in the 1890s. Treated effluent is used for the irrigation of some 8500 hectares of pasture. Other resource recovery activities consist of capturing the biogas formed in the anaerobic lagoons for energy production. It is also an important bird sanctuary and was therefore included in the list of wetland areas protected by the RAMSAR convention.

Fig. 2.4. Aerial view of the Western treatment plant in Melbourne (Australia). Picture from www.melbournewater.com.au.

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Ecohydrological restoration of aquatic habitats in urban areas: aims, constraints and techniques

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SWITCH Deliverable 5.3.1 - part B

Content:

1. Ecohydrology concept and principles

1.1. Introduction to aquatic ecosystems in urban areas

A 'system' can be defined as an "organized integrated whole, made up of diverse, interrelated and interdependent parts". In the context of this definition, the 21st century urban environment is a system that is still far from being perfect, considering integration of its anthropogenic functions with ecosystem functioning. Until recently, aquatic ecosystems and green areas in cities have been often considered as independent and relatively expensive subsystems. Actually, they should be considered instead as vital assets, considering their potential for provision of ecosystem services for society.

From the point of view of environmental science, urban environment can be considered as a highly condensed anthropogenic system, which is organised for efficient flow of water, matter, energy and information. This extremely productive "organism" can efficiently provide the services required by the society such as safe drinking water and efficient sewerage, which is very important due to very high population density. However, increase of society's education and environmental awareness rises also the public demand for improvement of the quality of life. Therefore other expectations, depending to a great extent on proper ecosystem functioning, appear. These include ecosystem services such as those determining human safety (e.g., mitigation of floods and droughts), health (e.g., water quality improvement by self-purification, clean air), as well as those fulfilling materialistic and spiritual aspirations - high quality living space, recreational areas and aesthetic values. These services depend to a great extent on the functioning of aquatic ecosystems and their ability to cope with high impacts, determined among others by the size and distribution of "green areas". However low availability and high prices of land in cites make maximising environmental amenities at low management a real challenge for any society. Therefore one of the alternative solutions is increasing the absorbing capacity of ecosystems, in order to improve their ability for coping with the highly condensed human impacts in urban areas. The methods for achieving this are implicitly provided by the main principle of ecohydrology (Zalewski et al., 1997), which postulates to "use ecosystem properties as a management tool" for enhancement the efficiency of some regulatory processes. The solutions have to be synergistically integrated into the city "system" by their harmonisation with engineering solutions (Zalewski 2000).

1.2. Ecohydrology - genesis of the concept

The progress that took place in ecological sciences towards the end of the 20th century resulted in major advancements of understanding and knowledge. A level was attained that enabled an attempt to integrate ecological sciences with more advanced scientific fields, such as physics or hydrology, which together with the application of mathematical tools (e.g., mathematical models) created a platform for the development of a new discipline – ecohydrology (Zalewski at al., 1997; Zalewski, 2000), within the framework of the

UNESCO International Hydrological Programme.

Ecohydrology is a scientific concept, which quantifies and explains relationships between hydrological processes and biotic dynamics at a catchment scale, and is applied to solving environmental problems (e.g., Zalewski 2006). It has been defined as a sub-discipline of hydrology focused on ecological aspects of the water cycle. This concept is based upon the assumption that sustainable development of water resources is dependent on the ability to restore and maintain the evolutionarily established processes of water and nutrient circulation and energy flows at the catchment scale.

With respect to the atmospheric/terrestrial and aquatic phases of the water cycle, two independent developments have occurred:

(i) Progress in understanding the interplay between water-plant-soil (the "atmospheric / terrestrial" phase of ecohydrology), attained as a consequence of the cooperation of hydrologists, plant physiologists and soil scientists (e.g.,. Eagelson 1982, 2002; Rodriguez-Iturbe 2000; Baird and Wilby 1999), provided a background for the use of landscape management in the regulation of the water cycle.

(ii) Development of the "aquatic phase" of ecohydrology (e.g., Zalewski et al. 1997) was based mostly on the integration of advances in hydrology and the recent progress in limnology. It not only provided the potential to predict the processes in the aquatic environment (e.g., those related to eutrophication) but, based on an understanding of abiotic-biotic interactions, it allowed attempts to regulate naturally-established processes of water, nutrient circulation and energy flow in aquatic ecosystems in order to reverse their degradation and enhance the absorbing capacity.

Following that, the key principle of ecohydrology is "dual regulation" (Zalewski 2006) of biota by hydrology (e.g. regulation of biotic interactions by manipulating reservoir's hydrodynamics for reduction of eutrophication symptoms; Zalewski et al. 1990) and vice versa - hydrology by biota (e.g. constructed wetlands; Mitsch & Jorgensen 1989, 2004) for enhancing the absorbing capacity of ecosystems against impacts.

For sound integrated urban water management (IUWM), integration of both the atmospheric/terrestrial and aquatic ecohydrology phases is necessary.

1.3. Creating opportunities for the degraded environment

The importance of the ecohydrological approach in enhancement of an ecosystem's absorbing capacity increased following the publication of a paper by Meybeck (2003), who defines the present era as the "Anthropocene". Based on an in-depth analysis of literature he demonstrated that the modification of aquatic systems by human pressures (e.g., aquatic habitat degradation, flood regulation, ecosystem fragmentation, sedimentation imbalance, salinization, contamination, eutrophication) increased to a level that can no longer be controlled by natural processes alone (e.g., climate, relief, vegetation). This is

particularly true in highly-modified urban areas, where the level of pressure is so intense, that self-restoration and self-regulation of ecosystems is impossible. The decline of water quality, biodiversity, and increased flood risks, result to a great extent from the degradation of natural cycles. For instance increased diffuse pollution results from disruption of biogeochemical cycles (e.g. due to unification or fragmentation of landscape, deforestation, biodiversity decrease), while increased flood risk results from modification of the water cycle (e.g., increase of impervious surfaces in cities and decrease of vegetated sections of catchments leading to intensification of runoff). This provides evidence that the traditional "mechanistic" approach focused on elimination of threats, based exclusively on e.g., reduction of point-sources pollution by conventional wastewater treatment plants or flood control by only hydrotechnical solutions, can not solve the problem. Elements of the technical approach, especially in highly-impacted urban areas, remain valid and necessary. However they should be complemented by amplification of the environment opportunities, enabling efficient functioning and enhancing of their defence mechanisms (Fig. 1). In the case of water management practices, that means extension of the number of potential tools used to reconstruct ecological processes in landscapes and aquatic habitats, and improve their assimilative capacity. Otherwise, water management constitutes more a trial-and-error approach than the implementation of a sound policy towards a sustainable water use.

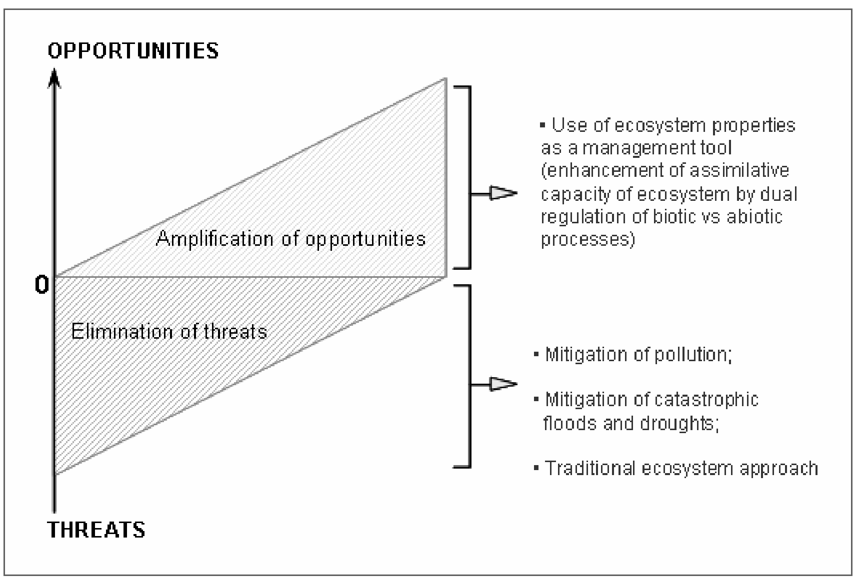

Fig. 1. Ecohydrology as a factor maximising opportunities for aquatic habitat rehabilitation in Integrated Urban Water Management (Zalewski 2002, modified)

Implementation of the "aquatic" phase of ecohydrology is to a great extent dependent on the quality of aquatic habitats. The hydrological features, such as water depth, flow velocity and variability, discharge, flood and drought characteristics, constitute one group of the five major features of aquatic habitats supporting aquatic life. According to the ecohydrology approach, understanding the relationships between

hydrological features and biological processes may be a useful tool for management. Its application is based on the following tenets (Zalewski 2006):

1. The dual regulation of hydrology by managing biota and, vice versa, regulation of biota by altering hydrology;
2. The integration of various types of regulation, at the catchment scale, to achieve synergy serving to stabilise and improve the quality of water resources;
3. The harmonisation of ecohydrological measures with hydrotechnical solutions (e.g., dams, irrigation systems, sewage treatment plants, levees in urbanised areas).

The empirical experiences gained over 10 years of development and implementation of the ecohydrology concept and its testing in a range of catchments and ecosystems subject to low to medium disturbances, include the following aspects:

- The relationship between vegetation, soil and water has been elucidated on the basis of the understanding of physiological properties of plants, as presented by Eagelson (1992, 2002) and Baird and Wilby (1999).
- A considerable progress has been made in understanding the role of vegetation in water cycle processes at the landscape scale, through research by Rodriguez-Iturbe (2000) and that done within the International Geosphere-Biosphere Programme (IGBP), the Biospheric Aspects of the Hydrological Cycle (BAHC) project (Vorosmarty, 2000).
- The multifaceted role of buffering by ecotone zones between land and water, which have been well defined within the framework of the UNESCO MAB Programme (Naiman et al. 1989; Schiemer et al., 1995, Zalewski et al., 2001; Gilbert et al. 1997).
- The application of ecological engineering, such as the management of wetlands for water purification by reducing excessive nutrient loads, on the basis of the ecological theory and mathematical modelling, as developed by Mitsch and Jorgensen (1989).
- The effect of hydrological regimes on vegetation succession of grasslands and swamps, as analysed by Witte and Runhar (2001).
- The reduction of nutrient loads to lowland reservoirs by enhancement of nutrient retention in floodplains, as demonstrated by Wagner and Zalewski (2000).
- The control of eutrophication symptoms and elimination of toxic algal blooms through regulation of water levels for control of trophic cascades, as discussed by Zalewski et al. (1990, 2000) and water retention time (Tarczynska et al., 2001).
- The research undertaken on the control of water quality and dissolved oxygen content in ice-covered dam reservoirs, during the winter, by regulating the outlet operation (Timchenko et al.

2000).

- The regulation of the timing of water releases into downstream rivers, in order to maintain fish migration, preserve biodiversity and fish production (the Parana River below the Porto Prima Vera Dam), as investigated by e.g., Agostinho et al. (2005).
- The examination of possibilities of managing coastal waters and diminishing their eutrophication using ecohydrology at a catchment scale, as initiated by Wolanski et al. (2004).

2. Possibilities of ecohydrology application in the urban environment

The empirical experience from medium-disturbed ecosystems should be translated into the problem solving in more impacted systems, especially in overpopulated and economically constrained urban areas. As mentioned before, compared to natural and semi-natural systems, the pathways of water, energy and matter in urban spaces are extremely constrained and their flows are intensive. Prudent control of these flows and their transition through the urban system is critical for reducing the environmental degradation. It is important that proposed measures should also be cost efficient, in order to make them affordable for the society. Since urban environments are now inhabited by over half of the humanity, this issue becomes particularly critical for the achievement of the Millennium Development Goals of the United Nations.

One fundamental assumption in sustainable urban water management is separation of water resources from nutrients/pollutant cycles (Maksimovič 2001). Highly concentrated streams of pollutants may easily overload the absorbing capacity of the biological system. Once this capacity is exceeded, the resilience of an ecosystem, expressed as the ability to maintain the structure and function under stress, dramatically declines. In order to avoid such situations, technical infrastructure of the urban areas has to be complemented with constructed or managed ecological systems with high potential for pollutant and water retention. This functional integration of city's water services and infrastructure with green areas and their inherent components, aquatic habitats constitute here additional challenge. Some efforts towards achieving such a consensus are given in a recent extended publication on Urban Aquatic Habitats by Wagner and the co-editors (2008b).

According to the first principle of ecohydrology, quantification of the water cycle at the catchment scale should be the starting point for the formulation of a systemic approach (Zalewski 2000; 2005; 2006). It should be based on analysis of the distribution of aquatic habitats and pollution sources in the city space, and analysis of water-mass dynamics in various climatic conditions. Such analysis allows identification of hot spots, where actions should be undertaken for reducing the probability of flood generation and pollutant discharge, and are the starting point for the separation of water and pollutant (matter) cycles.

Urban aquatic habitats are usually under elevated hydraulic stress, due to high imperviousness catchment surface and the resulting intensification of runoff. Simplified stream channels are converted into raceways for the accelerated transfer of water out of the city space. Such hydrotechnical approaches to flood

protection in cities were too often adopted without considering that accelerated outflow from city catchments reduces infiltration and lowers groundwater level. Such conditions seriously impacts physiological processes of landscape vegetation (e.g., rate of growth and transpiration and pest resistance) and reduce their capacity for water cycle regulation, soil formation and water (stormwater) retentiveness. The new way of thinking has gradually abandoned the general pattern of rapid removal of excess water from the city landscape, and took into account the landscape potential for its storage. Deceleration of runoff during wet weathers reduces peak-flows without inducing flood-risk. It also mitigates dry weather low-flows and their impacts on water quality and stability of aquatic ecosystems. The runoff and stormwater transfer can be reduced by using the natural and man-made biotic structures. Promoting diversified vegetation cover and green spaces in city landscapes in order to retain water in the terrestrial phase of the water cycle is one of them. Additionally, creation of constructed wetlands and impoundments in river valleys, creation or restoration of floodplain areas, introduction of detention polders, and construction of wetlands at stormwater outlets allow to increase the water retentiveness in aquatic habitats. Such an approach reduces also the amount of pollutants transferred with surface runoff by enhancing sedimentation and assimilation in vegetation biomass by phytoremediation (2 Fig. 2). According to the second principle of ecohydrology, understanding the vegetation adaptations to the hydrological characteristics of natural or constructed aquatic habitats may enhance both water retentiveness and pollutant assimilation in biomass. Results of pilot experiments in the City of Lodz show, that rate of nutrients and heavy metals uptake by vegetation increase up to 20 times, if properly adjusted to hydrological conditions (Wagner et al., 2008 a). Such adaptations, based on the understanding of ecosystem properties, can be used as tools in urban aquatic ecosystems and increase their absorbing capacity against pollution.

Several examples of ecohydrological management measures are based biotic structure response to changes of hydrological features of habitats. One example is reduction of man-made reservoirs supply with nutrients by enhancement of their retention on floodplains (e.g, Wagner and Zalewski, 2000), and reducing the reservoir eutrophication based on the relationships between patterns of river fluxes and intensity of toxic algal blooms appearance (Zalewski et al. 2000, Tarczynska, et al., 2001). Management of the hydraulic residence time and hydrodynamics of impoundments can be used for sedimentation control and improvement of self-purification rate. Another example is the reduction of eutrophication symptoms - toxic cyanobacterial blooms - by regulating habitat hydrodynamics and subsequent dynamics of biotic structure (Zalewski et al., 1990) and shortening the hydraulic residence time (Tarczynska, et al., 2001). These experiments were conducted on the reservoir supplying a city of 800 000 of inhabitants in Poland with drinking water.

2.1. *Multidimensional benefits of the ecohydrological approach for the urban environment and the society*

The expression a “green city” is synonymous with the notion of a healthy urban environment with a high quality of life. Moreover, it implicitly means that a significant part of the urbanised space is covered by semi-natural terrestrial and aquatic ecosystems. Freshwater and terrestrial ecosystems have an excellent

potential for moderation and control of the water cycle and pollution (Fig. 2) that should be considered while management plans are being developed. Such areas in cities provide citizens not only with regulatory ecosystem services, but also aesthetic, cultural and recreational values. However first and foremost improve human health in direct and indirect ways. There is growing evidence that higher and more stable moisture of the city air reduces the amount of dust which in turn reduces asthma, allergies and other related diseases. Also the opportunities for recreation in green areas are important for the proper physical and psychological regeneration of inhabitants.

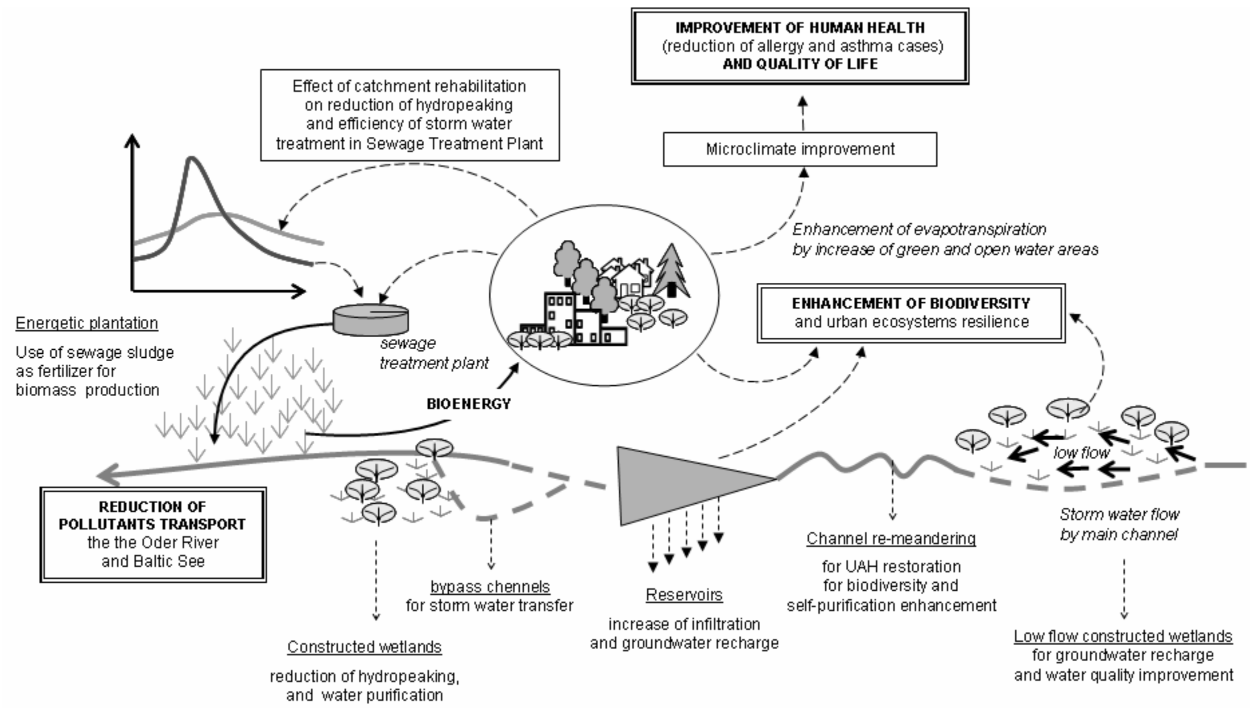

Figure 2. Rehabilitation of a municipal river: an example of possible multidimensional benefits for the urban environment and the society (Zalewski, Wagner, 2008)

Well-managed water habitats are visually the most attractive elements of modern cities landscapes, and are usually considered by city planners as “axes” or “nucleii” around which individual green areas and urbanised spaces are functionally organised. One of the key questions posed by socio-economists concerning the city development constraints in the era of globalisation was: what is the major factor for a successful city development in Europe? The answer was not surprising – creative and innovative leaders. Following that line, the next question was: what is the primary factor that those people consider while choosing a given city as a place to live in and work? The answer was quite surprising – the quality of the environment.

2.2. Implementation of the ecohydrological approach

The general scheme of the development and implementation of the ecohydrological approach (Fig. 3) has to consider the context of the generally accepted goals – e.g., sustainable development - and the documents creating a vision for environmental problem-solving (e.g., the United Nations Millennium Declaration). From the strategic point of view, it should be compatible with the already implemented policies, such as IUWM or the EU Water Framework Directive.

The first step should include an integrative analysis of the hydrological and ecological dynamics of the catchment, as well as an assessment of the quality of aquatic habitats and ecosystems, e.g., on the basis of habitat features or a bioassessment. At this point, adoption of the ecohydrology principles and assumptions becomes necessary for developing an implementation plan.

The next step involves integrative analysis of the dynamics of hydrological and biological processes. The existence of parallel data on biological system processes under different hydrological conditions allows for assessing the ecohydrological dynamics of the system and regulatory feedbacks for potential application in water management schemes (e.g., the rate of self-purification at different temperatures and stages of the hydro-period). Identification of the range of possible regulatory feedbacks between ecological and hydrological processes and hydrotechnical facilities in the catchment is an important factor for aquatic habitat management and rehabilitation and enhancement of the assimilative capacity of the system.

All the above measures have to be developed together with consideration of socio-economic conditions. The prerequisite of the implementation of ecohydrology is public involvement, which encourages decision makers and the public to accept and follow the new way of thinking. Up to now education and stakeholders' discussions were considered to be the best ways. However, comparative research on several ecohydrology projects seems to imply that a good starting point is the opportunistic character of human nature, seeking demonstration of the tangible benefits, such as reduction of threats (e.g. droughts and floods) and enhancement of ecosystem services (e.g. water quality improvement, biomass/bioenergy production and biodiversity). In many societies, especially those in countries of limited resources and low economic status, environmental conservation is considered as a luxury or at least as target with questionable value to the society. This is why it is important to demonstrate that environmental conservation may generate ecosystem services and, as a consequence, employment, which then amplifies the cascade of the positive socioeconomic/ environmental feedbacks. The experience from the UNESCO & UNEP Demonstration Project in the Pilica River valley (e.g., Wagner-Lotkowska et al., 2004) contributed to the conclusion that, especially in the cases of increasing tensions between the society and water /environmental resources, the most efficient stimulation for public involvement should the assumption of "ecosystem services first". A visible and profitable outcome for the society should be provided in the first stage of implementation. This is why adaptive assessment management, taking into account possible drivers and adapting to them, becomes the best way not only for understanding the complexity of the ecohydrology feedbacks and revising the new management strategy, but also for further progress of

implementation on the basis of social acceptance. One of the social benefits may be the reduction of health risk in densely populated city areas.

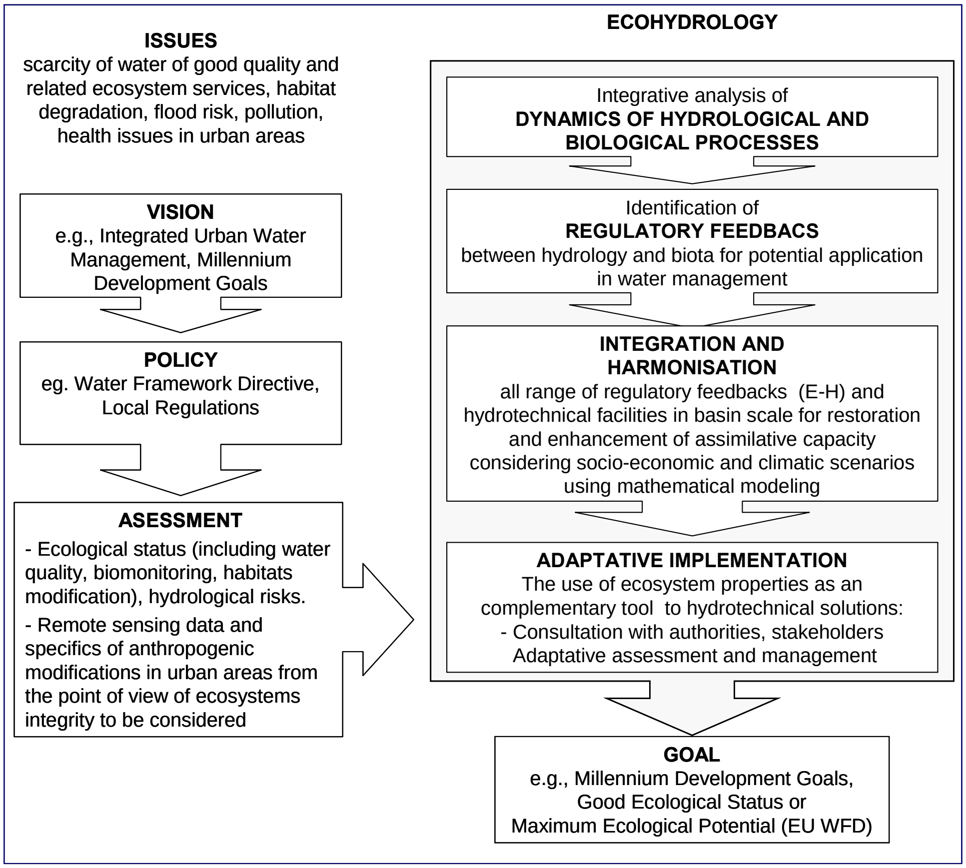

Figure 3. Schematic of implementation of the ecohydrological approach in urban areas (Zalewski, 2004, changed)

3. Urban rivers restoration

3.1. Restoration – general remarks

3.1. River in the landscape – parties approach

Rivers are unique systems which functioning is based on high internal variability of abiotic regulators and high disturbance rate – on the one side, and strong, stabile connectedness with surroundings on the other. Their uniqueness result also from the fact that they are open systems characterized by a high level of heterogeneity across a range of spatio-temporal scales (Ward, 1989) which could be classified to four dimensions:

- longitudinal dimension - from source to estuary;
- lateral dimension - the system composed of the main channel and floodplain;

- vertical dimension - the interplay between river water and groundwater in the surrounding area; and
- temporal dimension – demonstrated in processes of succession and rejuvenation.

The ecological perspective imposes also viewing of riverine landscapes as consisting of patches of different terrestrial and water habitats separated with transition zones (ecotones). Therefore at landscape scale rivers themselves play a function of corridors for organisms but also nutrients and energy flow between an upstream and a downstream. At small scale they appear to be a complex system of water habitats differing with water depth, temperature, trophy, flow velocity and land-water patches being channels for organisms and matter moving into and out of the water. In this sense connectedness should be understood as the strength of interactions between patches, across ecotones and along habitat continuum, or according to Ward et al. (1999) as the ease with which organisms, matter or energy traverse the ecotones between adjacent ecological units.

The hydrologists perceive the system differently. Riverbanks' and riverbed structure are important as regulators of flow regimes. They are to absorb changes of flow, regulate water exchange between units (river and floodplain, river and groundwater) and properly respond to sediments transport and their accumulation patterns. Connectivity between units is thus to maximize the desired properties and dynamics of the system and all its elements (Pringle, 2003). Thus the watershed level of analysis is common for both – hydrological and ecological approaches. There are however major differences in focus areas and understanding of processes, which may collide when the influence of hydrology on ecological functions of the river ecosystem is considered or when the role of biota and biotic processes in reshaping of hydrological patterns has to be reckoned. There is a need to reconcile and integrate approaches as both hydrological and ecological characteristics are pillars of river ecosystem resistance (Zalewski, 2000). Hydrological connectivity between compartments has major implication for biodiversity (Ward et al. 1999), which supports and drives of ecosystem functions and decides about ecological integrity of landscapes (Pringle, 2003). Periodic flooding, flow variability and sedimentation pattern improve lateral, vertical and longitudinal interactions and related services. Lateral connectivity conditions the roles of plants and animals in the watershed, especially the efficiency of biogeochemical barriers and land/water ecotones as buffering zones (Naiman et al., 1989), determines processes of sedimentation and erosion – thus geomorphology of river and its basin, and regulates the delivery of nutrients, soil and debris to water and its valley. Longitudinal connectivity ensures migration of aquatic species downstream and upstream – hence succession and system recovery, and is crucial for delivery of organic and inorganic materials up and down the river what maintain and enhance ecological processes. Finally, vertical connectivity decides about differentiation of habitats in terms of local water quality, temperature, and turbidity and development of communities of alga, fungi, bacteria and benthic invertebrates which defines the self-purification potential of the stream.

A consequence of reduced landscape integrity / connectedness maybe deterioration of environmental quality and human well-being. Changes of connectivity are however inevitable related to demography of human population and as result demands to spatial planning. Spatial planning approach considers river as one of components in the complex system of spatial and social networks and centers. It develops against landscape matrix built with natural and artificial elements. According to this approach connectedness at the landscape level is recognized on the basis of risk management, gathering of people interest, enhancing social interactions and improving attractiveness of places. The general aim is to make urban environment sustainable through making it attractive and livable to a wide range of residents. Hence it favours ecological and/or hydrological approaches as far as they reduce - by preservation and enhancement of river systems - the need of inhabitants for leaving the city permanently or simply driving out for fresh air and recreation (May, 2006).

3.2. Objectives and aims of river restoration

However the interplay between demands of different users of environment had generally led to a degradation of biogeochemical cycles and reduction of connectedness between rivers and their watersheds, the level of impact may vary locally and regionally. In consequence there is a need for adjustment of river conservation strategy to river state in order to obtaining the best results at acceptable costs. Boon (1992) has proposed five - step strategy:

1. preservation – applicable for natural or semi-natural river systems characterizing with untouched hydrodynamics,
2. limitation - when rivers maintained high ecosystem quality and when ecological key factors function without major impediments, this strategy is aimed at limitation of catchment development;
3. mitigation - based on the implementation of measures that allow the survival of habitats and organisms simultaneously with development of economic and recreational functions, this strategy is proposed for low quality rivers,
4. restoration - applied for degraded rivers with seriously disturbed hydrodynamics and only scattered and small remnants of populations present, and finally
5. dereliction - related to relocation of limited resources towards more promising restoration projects, when the chance for successful restoration are minimal.

Steps 1 and 2 are hardly applicable in urban areas and for big rivers. The urbanization process irrevocably results in modification of rivers, their valleys and often the whole basins. Usually it started from most attractive places – providing water, fertile soils, enabling communication and transport, hence valleys of big rivers. For that reason the majority of big rivers all over the world underwent dramatic changes, often going back to the beginning of civilization, which were related to rapid development of agriculture and

industry driven by demographic changes and increase of people aspirations. Step 3 can be applied in cases, when environment improvement may be observed after releasing the pressure to ecosystem, thus when it still posses self-regulatory potential.

Urban rivers are usually deprived of such potential, and proactive management is not sufficient if significant improvement of river ecosystem is to be observed. Step 4, therefore, is the most relevant to that case.

Restoration process should be understood as the one which ideally brings back the degraded river to its original condition. It includes restoring the water quality, sediment and flow regime, channel morphology, communities of native aquatic plants and animals, and adjacent riparian lands. The goal of restoration is often impossible to achieve. Re-establishing of the historical, original state would required replication of conditions which no longer exist, and are not well known, at all four mentioned earlier dimensions. In such case the less ambitious but more realistic aim is river rehabilitation. Rehabilitation is based on improving of the most important aspects of the stream environment towards creation a stream resembling its original condition. In cases when environmental changes are irretrievable and the catchment conditions are no longer favourable to the riverine ecosystem, the solution is remediation. Remediation goal is to improve ecological conditions of the stream, but that improvement may not lead to the state resembling original state of the stream. It means that the end point of remediation maybe a new ecosystem (Lovett and Edgar, 2002).

The aim of restoration activities should be therefore adjusted to the state of river ecosystem and its surroundings. The other important criteria for urban river improvement result from spatial planning, people perception of current and desirable state of the river, availability of resources and local policy goals. Hulse and Gregory (2004) described the decision making process as balancing between two extremes of ecosystem state - ecosystems having low ecological potential and burdened with high ecological and economic constraints and ecosystems of high ecological potential and with low demographic and economic constrains. The main criteria for making decision are potential increase of ecological benefits (and possibly human well-being) and spatial, demographic, economic limitations together with economic gains and loses. Very high constraints and critically low ecological potential may even lead to the decision of dereliction (Fig.4.).

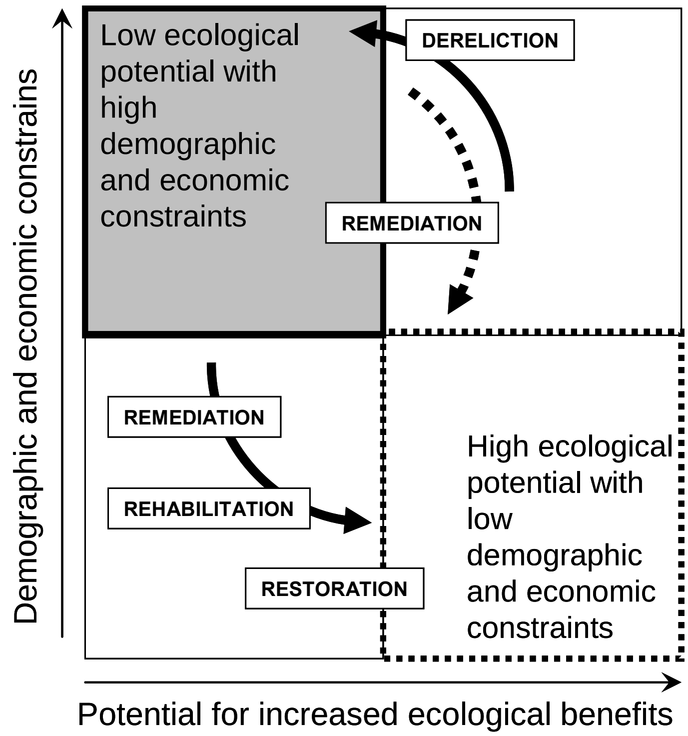

Fig.4. The framework for decision making process on restoration activities objectives and techniques (modified after Hulse and Gregory, 2004).

Despite existing economic and ecological constraints there may occur discrepancies between goals, expectations and risk perception related to involved actors, which have to be considered and reconcile during the planning, implementing and monitoring of restoration project (Tab.1.).

Tab.1. Examples of conflicting goals in urban river restoration projects

SOCIO-ECONOMIC AIMS, AWARENESS, PERCEPTION	**ECOLOGICAL TARGETS**
- increased risk of flooding after river re-meandering	- restoration of river bed geometry and hydrological pattern
- unlimited access to water	- protection of river banks and riparian vegetation
- water for domestic and industrial use	- limited water uptake
- river damming for flood reduction and increased water storage	- dam elimination for restoration of hydrological pattern
- development of water-sports and recreational areas	- creation of habitats for wildlife
- increased risk of water-related diseases	- re-establishing of natural buffering structures – backwaters, wetlands, riparian strips
- high aesthetic value expected	- restoration of 'original' or resembling

	vegetation structure
- introduction of attractive species	- restoration of natural species structure

3.2. Assessing ecological potential of the river

3.1. Buffering mechanisms

Ecological potential of a river is dependent of presence of numerous buffering mechanism. They emerge from the structure of river ecosystem itself (interplay between biota and environment), its valley and the floodplain (Tab.2.). The stabilization of ecosystem functions occurs through regulation of nutrient fluxes, prevention of erosion and intense sediment transport, regulation of light access and hence rate of primary production, enhancement of biomass removal from the system and its outside deposition, improvement of habitat structure towards higher capacity for sediment and chemicals immobilization, enhancement of biodiversity thus efficiency of energy flow.

The better developed „defense" mechanisms the higher is resilience of ecosystem hence its capacity for disturbance assimilation. Urbanization deprives rivers of their protection. Population increase, spatial limitations, use of resources in the first instance affect river catchment and quality and quantity of water. Proper spatial planning and mitigation policy applied et early stages of urbanization process may however favour maintenance of some regulatory potential and thus increase chance for restoration success.

Tab. 2. River system "defense" mechanisms.

LOCATION	**MECHANISM**	**PROCESSES**
River bed	Microbial self-purification	Microbial decomposition
	Biomass drift	Alga mats removed by flow from headwaters, process of biomass, nutrients, xenobiotics and heavy metals transport downstream
	Load throw-off by floating ashore	Drift in standing waters where algae are detached from sediments to the surface and transported landwards by wind
	Wash ashore	Filamentous algae and *Lemna* mats drift bankwards, physical biomass interception by macrophytes
	Skimming	Use of aquatic biomass by terrestrial/aquatic consumers, when part of biomass is deposited outside the system
	Grazing	Terrestrial outlet system, terrestrial consumers enable biomass removal from the system
	Predator-prey interactions	Stabilization of biomass production and trophic structure of community
	Filtration	Uptake of suspended matter by filtrators, water cleaning

	Competition	Regulation of community structure, maintenance of freshwater biodiversity and clear water state in reservoirs
Riparian zone	Alder strips	Blocking diffusion of matter from bank deposition to water (by filamentous alder roots) – 10m strip reduces input of nitrate by 10-15% and phosphorus by 20-30%, bank stabilization, habitat diversification
	Macrophyte zone	Barrier for sediments and alga mats, accumulation of nitrogen and phosphorus, regulation of bed shading thus primary production rate, sediment aeration – regulation of biochemical processes, enhancement of matter decomposition through shaping the habitats for microorganisms
	Riparian grass, shrub and tree strips	River bed shading counteracting the development of algae in shore areas, nutrient uptake and diversification of habitats supporting biodiversity
River valley	Marshlands, wetlands, peat lands	Regulation of water and nutrient circulation (storage potential)
	Grasslands	Medium efficiency biogeochemical barriers, protection against erosion, habitat diversification
	Woodlands	Long-term accumulation and immobilization of nutrients and other chemicals, regulation of water circulation

(Börner, 1992; Mander, 1985; Schieferstein, 1999; Shönborn, 1995; Shönborn, 2003)

3.2. Methods for river state assessment

Bioassessment

For decades the focal point of river assessment has been analysis of chemical and physical water parameters. Well-known, easy – applicable and precise methods allowed continuous monitoring of number of variables, what was considered as critically important in case of urban rivers. Norms specifying tolerable contamination level allowed for improvement of water security and setting sensitive early-warning systems.

The new strategy of environmental management, which shifted attention from maintaining good water quality toward maintaining of the value of ecosystem as a whole, revealed the limitation of applied techniques. Water quality not necessarily is a sign of good ecological status of the river. It is especially explicit in cases where use of modern, efficient treatment and well implemented law led to significant improvement of water quality, while habitat structure and biological diversity remained very poor. All the more when restoration is a management target, the urgent demand for more comprehensive monitoring and evaluation of ecosystem state is an undisputable fact. The evaluation method needs to be based on such a component of aquatic system, which responds to overall conditions of a whole river ecosystem. That is why new assessment techniques are focused on structure of biocenosis, which reflects quality of water and

habitat, and the complex biotic interactions between species. This approach is currently supported also by European policy (e.g. Water Framework Directive, Habitat Directive) and international regulations (CBD, Ramsar convention).

The conceptual background for modern river monitoring programs was provided by theory of ecological integrity. It states that ecosystem maintains its integrity only when the pattern of internal and external processes and interactions between ecosystem attributes produce the biotic community corresponds to the natural state of the region-specific habitats (Karr, 1981). That resulted in development of biological monitoring and bioassays. They use: phytoplankton, phytobenthos , macrophytes, benthic invertebrates and fish as indicators of status of environment.

Selection of an indicator group of organisms regards differences in accuracy and error that might occur in evaluation process as a consequence of different life strategies of organisms.

Indicator variability decreases along the axis: phytoplankton > zooplankton > macroinvertebrates > macrophytes > fish. It means that assessment based on phytoplankton reaction, which exhibit high seasonal variability, will have higher error frequencies and, lower statistical power than one using fish as indicator (Fig.6)(Łapińska, 2004).

The best results however can be obtained by use of various indicator group simultaneously. It results from the fact that some groups are efficient as early, while some others as late-warning indicators and there is stressor-type related efficiency. Thus selection of complementary early- and late-warning indicator groups increase the probability of detecting an impact if it occurs and become a common practice. For example macrophytes, which have low seasonal variability, but exhibit slow changes in community structure, are useless as early warning indicator. But, for the same reason, when change is detected in macrophyte species composition, then the probability that impact hasn't occurred is low (Johnson, 2001). Highly variable phytoplankton community as well as periphyton group are excellent indicators of nutrient enrichment as they tend to respond very rapidly to changes in water trophy. Response from macro invertebrates is not that rapid, but they are more sensitive to habitat characteristics (also more habitat-bound) and long-term trophy changes. Statistically the most accurate fish indicators are not useful in case of events of nutrient enrichment but they are the most appropriate if the ecosystem-stressor is temperature or chemical contaminant.

There are three main methodological approaches used for riverine quality bioassessment:

- single metric approach based on single parameter of indicatory group e.g. species richness, density of individuals, similarity or diversity of communities (Saprobic index, Trent Biotic Index, DSFI, BBI, IBE)
- multimetric approach, which aggregates several metrics, e.g. Index of Biotic Integrity for macroinvertebrates or for fish; and
- multivariate approach based on measures of the mathematical relationships among samples (e.g.,

similarity in structure of two communities) for 2 or more variables (e.g., qualitative presence-absence of species, or quantitative abundance or biomass of species) (Jaccard similarity coefficient, cluster analysis, discriminant analysis, ordination techniques, generalized linear models, logistic regression, Bayesian models) (Łapińska, 2004; Dahl, 2004) (Tab.3.).

The choice between approaches and their application depends on the anticipated number of stressors affecting the system, questions which need to be answered and experience of results users (Tab.4.).

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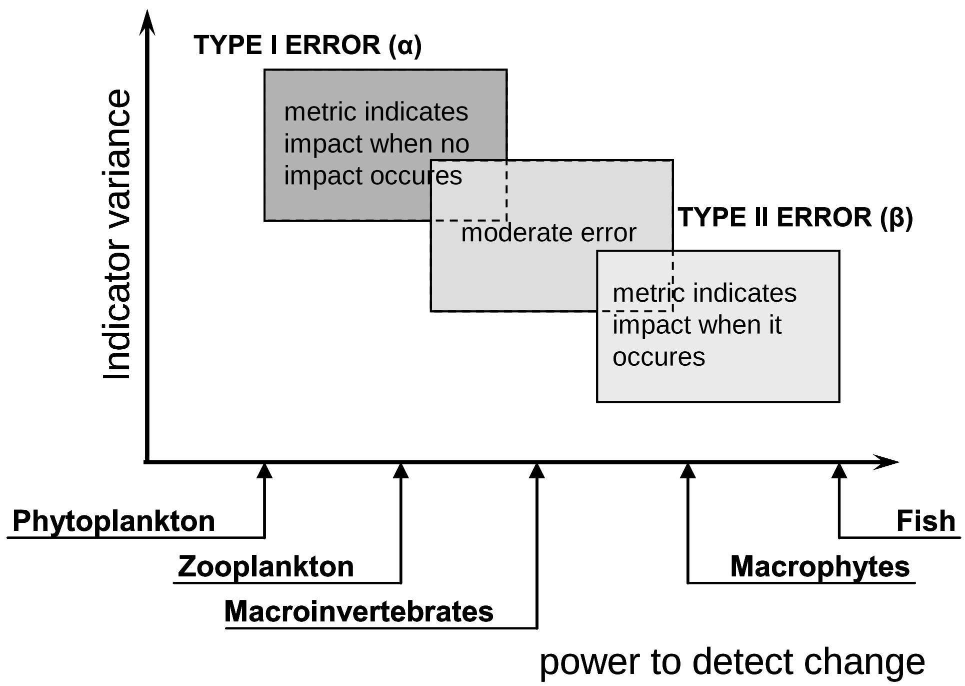


Fig.6. Bioassesment – conceptual model presenting errors assessment for different indicator groups (Łapińska 2004 after Johnson 2001)

Tab.3. Examples of bioassessment methods (Dunn, 2000; Phillips et al., 2001; Parson et al., 2002; Łapińska, 2004)

METHOD	FOCUS & CRITERIA	INDICATORY GROUP
River Invertebrate Prediction and Classification System RIVPACS	- uses macroinvertebrate information for assessment of ecological conditions of river sections;	Macroinvertebrates

	- based on comparison between observed and expected fauna;	
The Australian River Assessment System AUSRIVAS	- uses macroinvertebrate information for assessment of ecological conditions of river sections; - macroinvertebrates are collected from reference sites – sites of least impaired conditions	Macroinvertebrates
Index of Biotic Integrity IBI	- the multimetric index based on invertebrate or fish assemblages - employing 12 metrics reflecting structure and function of assemblage - index score is calculated at site and compared to the score expected at unimpaired site - based on reference condition approach – testing sites against the reference one	Macroinvertebrates and fish
USEBA Rapid Bioassessment Protocols- RPB HABSCORE	- uses fish, macroinvertebrates or periphyton for stream condition assessment - the multimetric index - to improve interpretation, define reference conditions and calibrate the index, physical and chemical data are also collected at sites	Macroinvertebrates, fish and periphyton
Multi-Level concept for Fish –based, River-type specific Assessment of Ecological Integrity MuLFA	- concept for fish-based assessment of ecological integrity of running waters design for large-scale monitoring programmes (e.g. WFD) - based on assessing the deviation from undisturbed reference conditions - sensitive to low- and high-dose human disturbances, general in character and applicable to all river types - assess both site conditions and ecosystem value	Fish
System for Evaluating Rivers for Conservation SERCON	- designed for assessment of river conservation value with regard to physical diversity, naturalness, representativeness, rarity, species richness and special features - calculated on the basis of scores derived for each variable and subsequently combined to produce indices for conservation criteria - data collected with the RHS protocols	Different groups of organisms (e.g. fish, birds)
Pressure – Habitat – Biota PBH	- developed for application in medium and small sized rivers - measuring variables represent the pressures (physical restructuring, pollution, exotic	Different groups of organisms (e.g. fish, macrophytes, diatoms)

	species), the habitat of stream (area, heterogeneity, stability) and the biota (e.g. diatoms, riparian vegetation, macrophytes, macroinvertebrates and fish)	

Tab.4. Choosing the method, or a combination of methods, should consider method advantages and, especially, disadvantages (Faush et al., 1990; Dahl, 2004)

	ADVANTAGES	**DISADVANTAGES**
Single metric approach	- best applied for assessing the effects of single stressor - long history in Europe - commonly use - simple	- results not explicit - aimed at detecting a specific type of degradation,
Multimetric approach	- conceptually simple; - easy to compare to reference values; - ecologically sound; - easy to understand, interpret and apply by water managers	- dependent on sample size and ecoregion
Multivariate approach	- higher precision than other approaches	- conceptually complex; - difficult to understand, interpret and to apply by water managers

<u>Physical and geomorphological assessment</u>

Assessment of the ecological river status cannot exclude habitat structure as physical habitat provides a template for biological processes and thus regulates river ecosystem dynamics (Southwood, 1977; Townsend and Hildrew, 1994). Consequently it influence directly composition and diversity of species.

That is a reason why many bioassessment methods have already incorporated physical assessment protocols to describe habitat conditions of indicator biota groups, e.g. river assessment systems like SERCON or RHS. Evaluation of physical structure of river bed and valley lies also within a broad framework of environmental restoration and is considered as the first step to achieve ecological integrity in degraded river ecosystems.

Human pressures to river system can be classified to 5 major categories according to the ecosystem features being affected (Łapińska, 2004) (Tab.5.). The primary factors of riverine ecosystem deterioration are water quality decline and flow alternations. In urban catchments, rivers are especially threatened with point source pollutions contaminating water with the whole range of chemicals, including toxic ones and carcinogens: fertilizers, pesticides, herbicides, household hazardous wastes, oils, anti-freeze, heavy metals, pet and yard wastes, and pseudo-hormones. Simultaneously the heterogeneity of habitats is reduced as river channel often play a role of storm water receiver and disposer, and their structure is to be modified in order to diminishing risk of flooding. Canalization, water uptake, isolation from floodplain and ground waters and hence deprivation of water storage capacity results in dramatic changes of discharges, susceptibility to droughts and short, extremely high peak flows. Frequency, magnitude and irregularity of the events

changes environmental template towards conditions hardly or not at all tolerable by organisms. Lack of suitable habitats not only reduce of refuges accessibility, but also significantly limit food source. Finally as a secondary effect - the strength of biotic interactions and the trophic structure of assemblages undergo irreversible degradation.

All above impact categories should be considered prior preparation of river management and restoration plans.

Tab.5. Physical features of river system being affected by human pressures in urban catchments (Łapińska, 2004 after Karr et al. 1986).

FLOW PATTERN	**HABITAT STRUCTURE**	**WATER QUALITY**	**FOOD SOURCES**	**BIOTIC INTERACTIONS**
- water depth - flow velocity - flow variability - discharge - flood magnitude - flood frequency - drought frequency	- habitat diversity - habitat connectivity - channel sinuosity - siltation - sedimentation pattern - bank stability - substrate type - plant cover	- nutrients - termal regime - toxins - pseudo-hormones - salinity - turbidity - oxygen concentration - pH	- primary production of algae and macrophytes - exergy - particulate organic matter - aquatic and terrestrial invertebrates	- species structure (invasions of exotics) - endemic species - threatened, endangered, sensitive species - species richness - trophic structure - age and genetic structure - predation - competition

Recently several physical assessment methods can support this process and help in deciding between restoration options of degraded river ecosystems (Tab.6.). They include evaluation of geomorphological characteristics of river bed and valley, distribution of habitats within river channel (riffles, runs and pools), presence and variety of patches of uniform substrate, vegetation and flow velocity and light access, and finally preservation of longitudinal river characteristics (zonation).

Tab.6. Methods of physical and geomorphological assessment (Newson et al. 1998; Dunn, 2000; Phillips et al., 2001; Parson et al., 2002).

METHOD	**CHARACTERISTICS**	**LINK TO BIOTA**
Geomorphic River Styles	- based on geomorphological processes theory - enables to predict future channel character and its response to disturbances	- between geomorphology and biota on habitat basis
State of the River Survey	- assessment at range of levels: catchment, river sections, tributaries, using data components individually or	- between parameters measured and stream biota (substrate, riparian vegetation)

	together	
River Habitat Survey (RHS)	- assessment of river habitat quality based on their physical structure - uses database of habitat requirements, site classification and association of flora and fauna to different habitats - 500 meter long sites are randomly selected with 50m intervals in between; 10 spot checks is performed and numerous features are recorded - can be linked with RIVPACS and SERCON	- on a basis of biotope and functional habitat approach Biotope approach – use of habitat units by biota is inferred from known physical conditions functional habitat approach – the habitat is defined from knowledge of inhabiting biota
The Integrated Habitat Assessment System (IHAS)	- measures components of a stream habitats relevant to macroinvertebrates: substrate, vegetation, physical conditions - assessment based on rating of components and scoring in order to deriving continuum of habitat quality	- assumption of habitat units relevance to macroinvertebrate occurrence
The Instream Flow Incremental Methodology (IFIM)	- computer models and analytical procedures designed to predict changes in fish habitat due to flow alternations - software includes: Physical Habitat Simulation System, Legal Institutional Analysis Model, Physical Habitat Assessment Model, Stream Network Temperature Model and System Impact Assessment Model	- assuming that flow-dependent habitat and water temperature determine carrying capacity of rivers for fish

3.3. Techniques applied for urban river restoration

For centuries a conventional solutions to water problems in cities were based on heavy engineering and were focused on the fastest possible removal of stormwaters and waste waters from the city. Simultaneously the aim was to minimize the costs, what decided about incorporation of rivers into sewage systems and release of untreated or poorly treated waters into river channels. Newly emerging paradigms underline a need for water preservation, reuse, and integration of different components of urban river systems, including technical and natural ones, and stormwater systems (Pinkham, 2004). This tendency creates opportunity for implementation of ecohydrological methods in urban areas.

Tab. 7. Change of paradigms applied in urban water management (Pinkham, 2004; modified)

CONVENTIONAL APPROACHES	EMERGING PARADIGMS
STRUCTURE	
human waste as nuisance - has to be quickly disposed after minimum required treatment	**human waste as a resource** - should be captured and used for land and crop nourishing
storm water as nuisance - has to be conveyed away as quickly as possible	**storm water as a resource** - should be harvested as water supply for supporting urban aquifers, waterways and vegetation

demand as a matter of quality - end-user water demand is the only end-use parameter used for infrastructure choices, - all supply-side water treated to potable standards and - all wastewater is collected for treatment in one system	**multi-facet demand** - choices should match the varying characteristics of water required/produced by different end-users
STRATEGY	
built to demand - need to increase capacity with increasing demand	**management of demand** - taking advantages of cost-effective options before increasing infrastructure capacity
one use - one-way water path from supply through single use, treatment to disposal	**reuse and reclamation** - multiple water use by cascading in from higher to lower quality needs and water return to supply by reclamation
bigger/centralized system is better - large systems attain economies of scale e.g. treatment plants	**small and decentralized system desirable** - small systems are effective comparatively with diseconomy of scale and distribution of conventional networks
limited complexity and standard solutions - small number of technologies defines the range of infrastructure choices	**diverse solutions** - in complex and resource-limited urban systems, multiplicity of situation-tuned solutions is required, new technologies and strategies
SYNERGY	
grey infrastructure - infrastructure built with concrete, metal, plastic	**green infrastructure** - infrastructure compiling grey infrastructure with natural capacity of soil and vegetation for absorbing and treatment of water
accidental system integration - water supply, storm water and wastewater system integrated institutionally, but physically separated	**designed physical and institutional integration** - ensured strategic linkages between water supply, waste water and storm water systems and highly co-ordinated management
public relations - approaching public and institutional only for approval of pre-chosen solutions	**public engagement** - collaboration towards search for effective, multi-benefit solutions

Ecohydrology of urban areas votes for river restoration, remediation and rehabilitation, wherever conditions are favourable, indicating the role of river corridors in maintaining and enhancement of biodiversity and ecosystem services as well as improvement of human well-being. The long-term target of ecohydrology is gradual increase of assimilative capacity of urban ecosystems as a result of integrated activities at scale of catchment, valley and river channel. It includes re-establishing of structures and processes stabilizing ecosystem functions – continuity of flows between river and its surroundings, continuum of river habitats when and where it is realistic, reconstruction of wetlands and buffering strips – through modification of hydrological regime. On the other hand use of 'green feedbacks' – regulatory

properties of plant cover (Zalewski et al. 2003) for stabilizing of microclimate, water conditions, soil properties and enhancement of plant succession.

Due to heavily modified catchments of urban rivers it is unrealistic to restore the cycling of water and nutrients towards the state resembling natural ones. However restoration plan has to consider catchment structure and should be included into a general masterplan for urban wastewater system (Geiger and Dreiseitl, 1995). Any credible historical information on the former course of the river and its natural reservoirs should also be analysed as conditio sine qua none of successful restoration and restitution of the basic river attribute – connectivity. The medium integrating all elements of the system, also technical with "green" ones is water.

3.1. Restoration and regulation of hydrological dynamics

It has to be stressed that not every urban river may be restored, because most of them cannot change their present function as urban channels and receivers of stormwater, CSO discharges and treated sewage. Changing function of such channelized rivers into open watercourses usually is also impossible, because of their unfavourable location in densely built-up city districts.

A proper masterplan should therefore select those river segments, which are susceptible to restoration process and have potentially an ecological value. On the other side, other river courses may be additionally hydraulically loaded (if there is such possibility) by the extreme flows then disconnected from a river to be restored.

Apart from ecological profits, restoration of urban rivers can bring other advantages (Stecker 1996, Zawilski et al. 1998, Zawilski 2001) e.g.:

- riverbeds can be used to transport relatively clean stormwater,
- they can help in relieving some combined and storm sewers, and treatment plants from wet weather peak flows and loads - in particular a fraction of less polluted rainwater should not be diverted into the urban sewerage and further to the municipal treatment plant,
- by creating more attenuated flow in rehabilitated riverbeds a danger of riverbed damage and flooding of surrounding catchment areas can be reduced.

1. Most desired is restoration of moderately changed urban rivers flowing through green or residential areas. The optimal situation for a receiver exists when there is a possibility to connect separate sewers dewatering catchments of limited surface pollution. This makes it possible to avoid expensive investments protecting receivers against pollution. For such reason, use of roof runoff for supplying watercourses to be restored is very advisable (Conradin and Buchli 2004). In this system, roof runoff supplies natural or even artificially created small urban watercourses equipped with landscape ponds and wetlands as well as educational pathways.
2. On the other hand, urban rivers usually are classified as so-called heavily modified water bodies or even artificial water bodies for which special requirements were formulated in EU (Directive 2000/60/EC, Zeman et al. 2004). "Good ecological potential" is the status of a heavily modified or

an artificial body of water, so classified in accordance with the relevant provisions of Annex V of the Directive containing requirements for monitoring information.

3. The flow dynamics in urban rivers are changed in comparison to natural conditions due to the sealing of the catchment and decrease of water retention on planted areas. Even the increase of the terrain sealing up to 10% usually cause a considerable change in the river flow regime. Additionally, temporally big loads of conservative and soluble anthropogenic pollutants are introduced into the riverbed during intense rainfalls and snowmelt. Urban rivers suffer from uncontrolled discharge of numerous stormwater and combined storm overflows organized in the past as a traditional solution of dewatering of build-up areas. Still new urban catchments are connecting to the riverbeds, fortunately recently with the use of modern alternative solutions.

4. Each restoration master plan should consider the following items (Zimmermann and Sieker 2005):

- pollutant load - e.g. Suspended Solids (SS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD)
- nutrient load (nitrate and phosphorus),
- ammonium and oxygen concentrations in the receiving water,
- hydraulic stress (expressed as floods with a return period of 1 yr.),
- flood runoff (return period 100yrs.), and
- restoration costs (expressed as monetary value).

5. Application of the computer modeling is recommended and it should cover the period of 30-years with the complete rainfall data as well as the use of GIS and monitoring information regarding to land use, geology, infrastructure and flowing water quantity and quality. The degree of the urban catchment turns out to be decisive for the river flow regime and should be established with a high accuracy, especially if the terrain slope is considerable. Digital maps and aerial photos can be used for this purpose.

6. Computer simulation can be applied for assessment of several options of land use, catchment drainage and flow mitigation.

7.

8. From the technical point of view, the following solutions should be applied :

<u>1. Attenuation of peaks flows with the use on-catchment or in-watercourse storage reservoirs</u>

9. Optimal solution is restoration of the river flow to the pre-urbanization “natural” level. This would require either establishing a very low runoff coefficient or a considerable throttling of catchment outflow equivalent to a considerable storage of runoff.

10. Storage of stormwater on the catchment itself is more profitable and can be organized with the use of numerous local detention elements type Stormcell or equivalent ones (Andoh et al. 2001). Storage runoff from roofs does not require any pre-treatment unless roof covering are made from materials not environmentally friendly (for instance zinc or copper sheet). In other cases, especially for street and parking lots a separation of mineral particles and oil derivatives from runoff is obligatory unless residential areas with private houses with gardens are concerned.

11. The necessary unitary storage volume should be about 40-100 m^3/hectare of sealed surface or even more if possible. This volume guarantees radical decrease of peak stormwater flow (Zawilski and Sakson 2002, 2004).

12. Sometimes, the desired attenuation of peak flows may be foreseen in detention ponds situated in rivercourses (Zawilski 2001). Usually the sufficient area of such ponds is equal to few percent of

connected catchment area. However, in the case of torrential storms, the storage of the total runoff in the ponds is not possible and emergency overflows are necessary to be activated. Big flows of 10-year return period may be diverted to a parallel channel of a sufficient cross-section or to a large floodplain.

2. Creation of floodplains minimizing the risk of flooding of riparian areas

13. Floodplains are usually formed spontaneously in the past but often disappeared during anthropogenic transformation of riverbeds. As for restored urban rivers, the common flows can be equalized but the river corridor still can be foreseen as the transportation measure in case of very intensive precipitations and its overflooding often is not to be avoided.
14. Therefore, floodplain restoration as a formation of the river corridor collecting water during heavy rainfalls is favourable. Such floodplains, however, are difficult to be regained due to property, space and technical problems. If planned, they should be kept as free space without developing and trees and protected against possible damage.

3. Elimination of acute pollutants (nutrients and heavy metals) present in stormwater and CSO overflows

Discharges from storm and combined sewerage are the source of undesirable organic and inorganic pollutants and gross solids which should be removed with the use of sediment and oil separators as well as screens or vortex separators. This option is rather expensive due to both construction and maintenance cost.

Best Management Practices (BMP) can be widely used, if possible. Source control measures (swale and trench systems and wetlands) if properly constructed were found to be very effective in reducing stormwater pollution.

Grassed swales appeared to be an excellent device to treat polluted stormwater (Backström 2001); therefore they should be included into the system of storm sewerage.

In some cases, a pre-treatment of runoff can be foreseen in the river ponds supplied with a forebay (a sedimentation volume). This system can be organized as a cascade of ponds with the first, upstream one serving as pre-treatment device for polluted stormwater.

Also, separate detention-sedimentation tanks equipped with a baffle intercepting floatables and oils can be built at the storm sewer outlets.

15. Heavy metals are also present in sediments originated from stormwater and CSO discharges (Kominkova and Pollert 2004). In few cases polluted storm runoff proved to be toxic for some aquatic organisms (Marsalek et al., 1999).
16. A special attention should be paid to snowmelt runoff containing dissolved salts used as deicing components. The best way to overcome this problem is limiting use of such chemicals on the urban catchment of the river to be restored.

4. Organizing of a monitoring system

17. After implementation of a river restoration plan, an effective monitoring system for flow and water quality should be established. If possible, such a system can be operated even prior to a masterplan for river restoration giving the designers information on hydrological situation and pollutant fate. Such measurements can be used for calibration of engineer software predicting both quantitative and qualitative parameters of the river course.

5. Assurance of minimum flow during longer periods of dry weather

18. In many cases of small urban rivers, there is a danger of disappearance of flow during longer periods of dry weather, especially if the restored river segment is situated on an urban catchment close to the river source and bigger sanitary and combined inlets are to be disconnected. Storage of stormwater along the river or on the catchment may partially soften the problem creating a possibility to keep the river flow for a period of days or even weeks. Also, the rivercourse may be supplied by infiltrating ground water from storm sewerage. Connecting drainage pipes collecting groundwater or any other type of clean water (for instance from water treatment plants or industry) should be considered. In the extreme case, supplying the rivercourses by pumped groundwater has to be applied but it should not be a common rule.

19. In each case, soil properties should be examined. Restored riverbed with sandy soils and low level of groundwater can be not tight enough to keep permanent dry weather flow, anyway in the first period after restoration. One can consider facing the riverbed with a geomembrane or a natural loam/clay material. However, if there is a possibility to exchange water between the local ground and the riverbed, application of artificial tightening should not be used or considered with caution.

6. Changing the flow regime in the riverbed

20. Hydraulic capacity of a restored river channel is usually much less than a regulated one. This is because the friction factor (roughness) is much greater due to the presence of natural covering of the riverbed (gravel, stones, brush and grass). In the consequence, a special check design calculations should be performed in the purpose to establish new values of water depth and velocity as well as general capacity of the stream.

7. Restoration of riverbed construction with the use of hydrotechnic methods

21. In the case of larger and deeper riverbeds transporting peak flows, which would be inevitable, a reinforcement of the riverbeds is necessary in order to avoid damage of their bed and banks. Mixtures of natural and artificial materials as well as appropriate plant species are to be desired. Ripraps with in-situ soil on gravel filter layers and geotextile, micropiles, willow bundles and shrub above the maximum water level can be used (Pagliara and Chiavaccini 2004, Urbonas 2004).

22. Similar special construction reinforcements should be performed around sewer outlets. Further details are presented in the next entry.

8. Changing the straight watercourse segments into meandering ones

23. Straight channels are typical for previously regulated urban riverbeds but this option should be applied for some special situation only. Changing the riverbed into a meandering on creates a possibility to restore flow regime into a semi-natural ones and to purify the flowing stormwater. This makes it possible to attenuate the flow, too, since a meandering riverbed slows down the water velocity.

9. Flattening of the river longitudinal grade

24. Properly situated sills decrease the longitudal gradient, maximum velocity and possibility of erosion and should be applied in all cases of greater river gradients. A special attention should be paid to the proper construction of sills eliminating the possibility of bottom scouring (Adduce et al. 2004). Also a system of pool-riffle structures can be constructed (Dale 1996, Schwartz et al. 2002). This system is favourable for aquatic organisms creating refuge volumes (see the next entry).

10. Small architecture of engineer elements

25. Any interference unnatural elements like dams, culverts, sills, weirs, pipes and so on should be minimized by the use of hydrotechnic constructions resembling natural ones and use of natural materials exposed to the community (Geiger and Dreiseitl 1995, Stahre 2002, Urbonas 2004).

11. Easy access to the banks in the purpose of maintenance of the riverbed

26. The restored riverbed requires a temporal maintenance in order to keep its capacity – removal of wood debris and sediment, controlling invasive plant species and conducting construction renovation works. From the legal point of view, each water reservoir should have its banks kept free of buildings, fences and other artificial elements making difficult free access to it.

3.2. Upgrading of channel morphology - rebuilding of habitats heterogeneity

River restoration, even conducted in highly modified, urban areas has to consider that riverine habitats are organized hierarchically in a basin context (Fig.7)(Frissell et al., 1986).

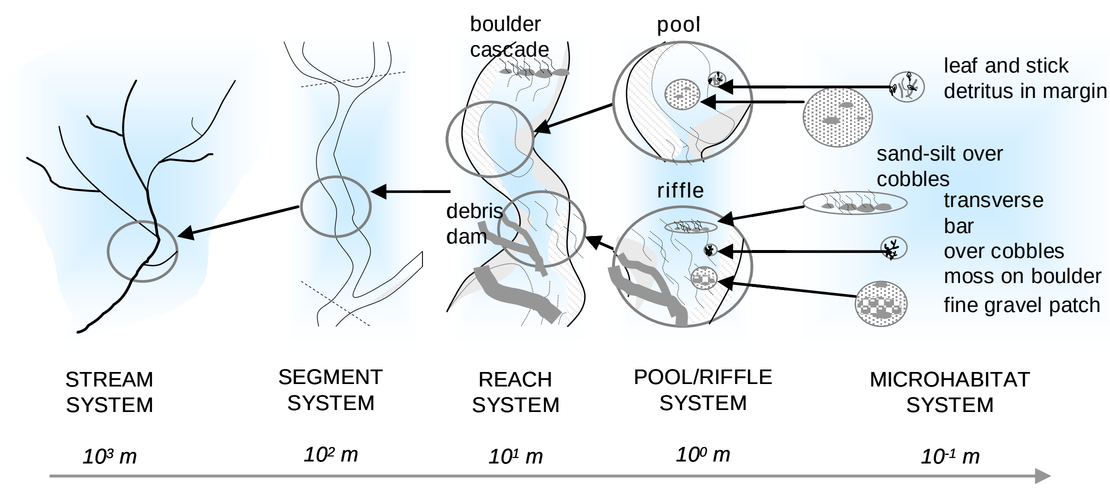


Fig.7. Hierarchical organization of a stream system and its subsystem habitats (modified from Frissell et al., 1986)

This hierarchical system is built with segments – parts of the stream system flowing through a single bedrock type and bounded by tributary junctions. A length of segment lying in between breaks in channel slope, local side-slopes, valley floor width, riparian vegetation, and bank materials forms reach system. Reach consists of subsystems having characteristic bed topography, water surface slope, depth, and velocity patterns and forming pool (deep zones) - riffle (shallow zones) mosaic. In a natural meandering watercourse riffles and pools lie in a regular pattern. However in rivers, habitats at this level can be more complex including also other forms like: rapids, runs, falls, side channels. The lowest level in hierarchy is a microhabitat system. Microhabitats are the patches within pool/riffle systems that have relatively homogenous substrate type, water depth and velocity (Fig.8)(Łapińska, 2004). The channel morphology has to be reconstruct with regard to the presented basin context and appropriate meso- and micro features in order to shape hydraulic properties and provide a template for physical (sedimentation, erosion), chemical (accumulation, sorption) and biological (self-purification, production, denitrification) processes typical for particular system. Without proper template recovery of the ecosystem, with its complexity and resilience, is not possible (Zalewski, Naiman, 1985).

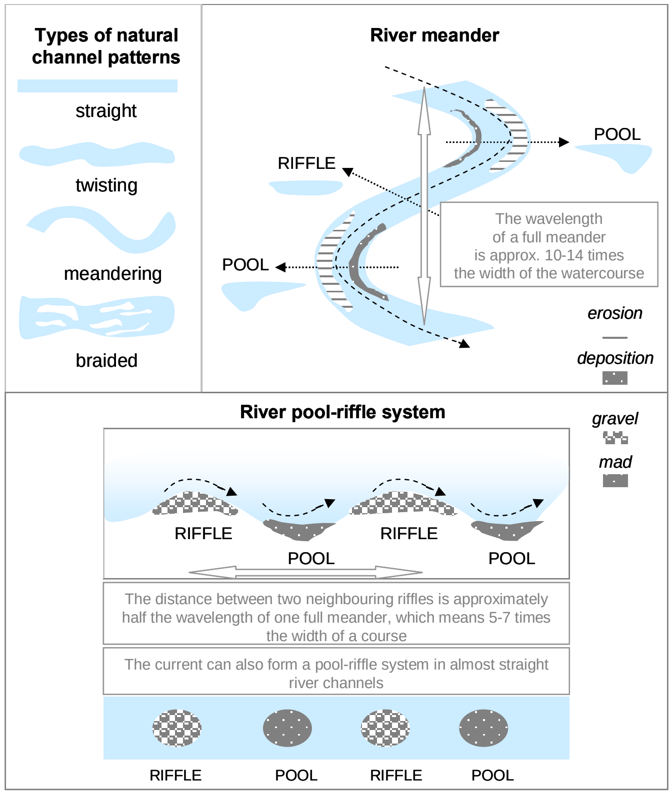


Fig.8. Basic river morphological structure: meanders and pool-riffle sequence (Łapińska, 2004; modified from Calow and Petts, 1992)

In channel reconstruction there are two key practices to be applied - maintenance of hydraulic connections and stream meander restoration. Maintenance of hydraulic connectivity allows movement of water and biota between the stream, abandoned channel reaches and adjacent areas. It prevents losses of aquatic habitat area and diversity. Slack water areas adjoining the main channel have potential for spawning and rearing areas for many fish species and are a key component of habitat for wildlife species that live in, or migrate through, the riparian corridor. Stream meander restoration is targeted at transformation of a straightened stream into a meandering one to reintroduce natural dynamics, improve channel stability, habitat quality, aesthetics, and other stream corridor functions or values. It enables creation of a more stable stream with more habitat diversity, but requires adequate area thus adjacent land uses may constrain this practice at some locations.

Stream bank treatment consists of numerous techniques, which are to protect river banks and simultaneously support some river ‘defense’ strategies: development of bank vegetation being filter for chemicals and stabilizers of soil, biomass interception, grazing, predator-prey interactions, etc. (Tab.8).

To create riffles, runs, flats, glides and open pools, being important components of mesohabitats, one can use boulder clusters, weirs and logs creating that structurally and hydraulically diversify channels (Tab.9.).

Tab.8. Techniques for restoring the physical structure of a river banks (Łapińska 2004, after FISRWG, 10/1998)

PRACTICE	**DESCRIPTION**	**APPLICATION**
Live Stakes	Live, woody cuttings tamped into the soil to root, grow and create a living root mat, that stabilizes the soil by reinforcing and binding soil particles together, and by extracting excess soil moisture.	Effective where site conditions are uncomplicated, construction time is limited, and an inexpensive method is needed. Appropriate for repair of small earth slips and slumps that are frequently wet. Can be used to stake down surface erosion control materials. Requires toe protection where toe scour is anticipated.
Live Fascines	Dormant branch cuttings bound together into long sausage-like, cylindrical bundles and placed in shallow trenches on slopes to reduce erosion and shallow sliding.	Can trap and hold soil on stream bank by creating small dam-like structures and reducing the slope length into a series of shorter slopes. Facilitate drainage when installed at an angle on a slope. Enhance conditions for colonization of native vegetation.
Log, Root Wad, and Boulder Revetments	Boulders and logs with root masses attached, placed in and on stream banks to provide stream bank erosion, trap sediment, and improve habitat diversity.	Will tolerate high boundary shear stress if logs and root wads are well anchored. Suited to streams where fish habitat deficiencies exist.
Riprap	A blanket of appropriately sized stones extending from the toe of slope to a height needed for long term durability.	Appropriate where long term durability is needed, design discharges are high, there is a significant threat to life or high value property, or there is no practical way to otherwise incorporate vegetation into the design. Can be vegetated (see joint plantings). Commonly used form of bank protection.
Stone Toe Protection	A ridge of quarried rock or stream cobble placed at the toe of a stream bank as armour to deflect flow from the bank, stabilize the slope and promote sediment deposition.	Should be used on streams where banks are being undermined by toe scour, and where vegetation cannot be used. Stone prevents removal of the failed stream bank material that collects at the toe, allows re-vegetation and stabilizes stream banks.

Tree Revetments	A row of interconnected trees attached to the toe of a stream bank or to dead heads in a stream bank to reduce flow velocities along eroding stream banks, trap sediment, and provide a substrate for plant establishment and erosion control.	Works best on streams with stream bank heights under 12 feet and bank-full velocities under 6 feet per second. Captures sediment and enhances conditions for colonization of native species particularly on streams with high bed material loads.
Vegetated Geogrids	Alternating layers of live branch cuttings and compacted soil with natural or synthetic geotextile materials wrapped around each soil lift to rebuild and vegetate eroded stream banks.	Quickly establishes riparian vegetation if properly designed and installed. Can be installed on a steeper and higher slope and has a higher initial tolerance of flow velocity than brush layering.

Tab. 9. Techniques of restoring the physical structure of a river bed (Łapińska 2004, after FISRWG, 10/1998).

PRACTICE	PRACTICE DESCRIPTION	APPLICATION
Boulder Clusters	Groups of boulders placed in the base flow channel to provide cover, create scour holes, or areas of reduced velocity.	Can be used in most stream habitat types including riffles, runs, flats, glides and open pools.
Weirs or Sills	Log, boulder, or quarry stone structures placed across the channel and anchored to the stream bank and/or bed to create pool habitat, control bed erosion, or collect and retain gravel.	Create structural and hydraulic diversity in uniform channels.
Fish Passages	Any one of a number of in-stream changes which enhance the opportunity for target fish species to freely move to upstream areas for spawning, habitat utilization, and other life functions.	Can be appropriate in streams where natural or human placed obstructions such as waterfalls, chutes, logs, debris accumulations, beaver dams, dams, sills, and culverts interfere with fish migration.
Log/Brush/Rock Shelters	Logs, brush, and rock structures installed in the lower portion of stream banks to enhance fish habitat, encourage food web dynamics, prevent stream bank erosion, and provide shading.	Most effective in low gradient stream bends and meanders where open pools are already present and overhead cover is needed.
Lunker Structures	Cells constructed of heavy wooden planks and blocks which are imbedded into the toe of stream banks at channel bed level to provide covered compartments for fish shelter, habitat, and prevention of stream bank erosion.	Appropriate along outside bends of streams where water depths can be maintained at or above the top of the structure.
Migration Barriers	Obstacles placed at strategic locations along streams to prevent undesirable species from accessing upstream areas.	Effective for specific fishery management needs such as separating species or controlling nuisance species by creating a barrier to migration.
Tree Cover	Felled trees placed along the stream bank to provide overhead cover, aquatic organism substrate and habitat, stream current deflection, scouring, deposition, and drift catchment.	Particularly advantageous in streams where the bed is unstable and felled trees can be secured from the top of a bank. Channels must be large enough to accommodate trees without threatening bank erosion and limiting needed channel flow capacity.
Wing Deflectors	Structures that protrude from either stream bank but do not extend entirely across a channel. They deflect flows away from the bank, and scour pools by constricting the channel and accelerating flow.	Can be installed in series on alternative stream banks to produce a meandering thalweg and associated structural diversity. Should be used in channels with low physical habitat diversity, particularly those with a lack of stable pool habitat.
Grade Control Measures	Rock, wood, earth, and other material structures placed across a channel and anchored in the stream banks to provide a "hard point" in the streambed that resists the erosional	Used to stop head cutting in degrading channels. Used to build bed of incised stream to higher elevation. Can improve bank stability in an incised

3.3. Reconstruction of biotic structure for improvement of water and habitat quality

Considering the role of vegetation in functioning of riverine system rebuilding of biotic structure should include 3 steps: 1) establishing of macrophyte communities in river bed, 2) structuring of plant cover on river banks and 3) development of plant vegetation in river valley (Tab.10.).

In urban catchment, due to spatial and land use constrains, re-establishing of biotic structure is usually limited to restoration of bank and in-channel vegetation. A partial recovery of valley functions can be however based on development or use of existing recreational/green areas, some other should be conveyed to engineering systems including sewerage systems, water supplies etc.

Tab.10. Role of vegetation in river – floodplain system.

VEGETATION IN RIVER CHANNEL	**BANK VEGETATION**	**VALLEY VEGETATION**
Dissipation of wave energy and decrease of flow velocity	Bank protection against erosion	Dissipation of wave energy during flood events
	Increase of infiltration of surface flow	
Stabilization of sediments and increase of channel roughness	Increase of channel roughness and regulation of coarse organic matter transport, decrease of surface flow velocity	Stabilization of river discharge, mitigation of the effects of floods and droughts
Influence on flow velocities distribution in a channel	Limiting the “active” cross-section of a channel	Providing a number of transitional land-water habitats and supporting development of biodiversity in an area.
Regulation of coarse and suspended matter transport	Providing a framework for biogeochemical processes taking part at land-water interface zones and enhancing matter retention and self-purification of a river (nutrient retention in soil and plant tissues)	Providing a framework for biogeochemical processes taking part at land-water interface zones and enhancing matter retention and self-purification of a river
Rising of water level within a channel and in adjacent areas	Rising water level within river channel	Woody debris and sediment trapping
Acceleration of ice-cover removal		

In-stream vegetation – use of aquatic plants

Role of aquatic plants is the most pronounced in small and medium size rivers, where depth does not exceed 2m during the highest discharges.

In urban rivers use of aquatic plants is especially recommended due to their role as moderators of channel hydraulics and characteristics of water flow and providers of refuges for biota. They also regulate sedimentation and biomass and nutrient interception. On the other hand one has to considered that use of aquatic vegetation can be restricted by habitat conditions: high peak discharges, high water turbidity (hydraulic tension, low light access) and demands imposed of a river as a component of water management system. Aquatic plants may handicap water flow leading to rising of water level and, due to decomposition and matter interception, they may cause decrease of channel volume for water transport. Thus proper introduction of vegetation for sustainable river management requires:

- precise calculation of water movement parameters;
- an understanding of channel hydraulics;
- knowledge about biomass distribution and
- ecology of dominant plant species (Krauze, 2004).

Plant growth and expansion rate are regulated by temperature, light access, flow distribution in a channel, nutrient concentrations and oxygen concentration. A careful planning of river channel morphology helps to define distribution of aquatic plants through distribution of flow. Temperature and light access can be regulated through composing of riparian structure and building up a canopy of shrubs and trees, wherever macrophyte growth is to be limited. However there are species difficult to control e.g., *Reynoutria japonica* (Japanese knotweed), *Stratiotes aloides* (water soldier), *Impatiens glandulifera* (Himalayan balam), *Nymphoides peltata* (fringed water lily). *Phragmites australis* (Norfolk reed), *Typha latifolia* (bullrush) require a lot of space thus they are suitable only for large rivers (NRA Severn-Trent Region), so should not be used for habitat improvement. Some of them may also present health hazards, e.g., *Heracleum mantegazzianum* (giant hogweed), *Conium maculatum* (hemlock).

Even when precisely planned, establishing of aquatic plants in urban streams requires application of special procedures and techniques to prevent plant damage and washing out in early stages of restoration. It includes creation of low flow, partially isolated zones within river bed and preparation of the substratum for planting, which will enhance plant potential (Fig.9).

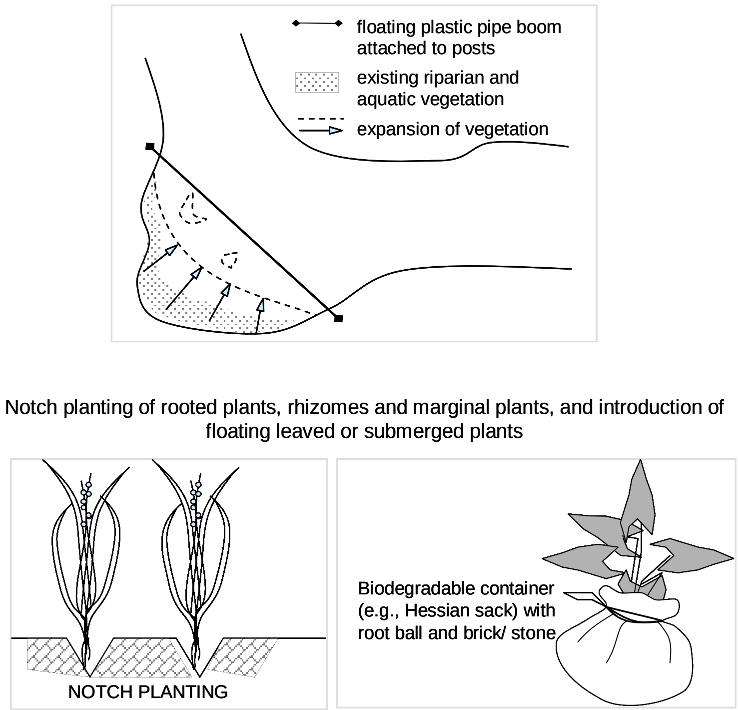


Fig.9. Enhancement of riparian and aquatic vegetation through protection from waves and current action (Krauze, 2004; modified from Cowx & Welcome, 1998 and NRA Severn- Trent Region)

In cases when some intervention in aquatic plant zones is necessary in order to protecting the functions of river ecosystems, it is important to consider:

- leaving, wherever possible, undisturbed sections of the river or at least parts of the middle and edge as they act as refuges for plants and animals and allow recolonization;
- timing of plant cutting;
- cutting and dredging operations should be conducted optimally every few years and all operations should be combined;
- aquatic plants, which have been disturbed during dredging, should be transplanted and a minimum amount of silt left in the channel to retain its profile; and
- fish and invertebrates should be protected during all maintenance operations and fish spawning seasons avoided.

Some alternative solutions maybe: partial shading of a river bed, change in the cross-section shape, and enhancing reproduction of herbivores (Krauze, 2004).

Riparian vegetation – role of land/water ecotones

The crucial role of land/water ecotones in protection of river systems and regulation of in-stream processes was pointed by Naiman et al. (1989). They underlined that riparian areas are major determinants of water and nutrient flows across riverine landscape. According to Petersen et al. (1992), the efficiency of wide ecotone zones (19-50 m) may reach even 78-98% removal for N in surface waters and 68-100% in ground waters. Other authors estimate reduction efficiency at a level of 50-90% for nitrogen and 25-98% for phosphorus (in ground water) depending on the initial concentrations, width of buffering zone, soil type and interactions between plants and other organisms. The most intense reduction occurs within the first 10 m of an ecotone zone.

However, influence of ecotone vegetation on water quality is possible only when the connection between terrestrial and water ecosystems is maintained. The basis for this connection is water circulation, therefore, the role of ecotones is significant only along unregulated river courses and natural shores of reservoirs.

Riparian areas are complex systems characterized by floral and faunal communities distinct from surrounding upland areas. There are many different types of riparian ecotones: swamp forests, bank vegetation, meadows, littoral zones, marshes, floating mats, oxbow lakes, etc. Their common feature is occasional flooding. The water regime modifies the rates of aerobic and anaerobic biochemical processes and hence seasonal releases and removal of phosphorus and nitrogen.
The generally features of riparian areas are:

- adjacency to the stream or river;
- role of transitional zone between water and terrestrial systems, having features of both;
- role of ecological corridors;
- they are covered with organic soils;
- have seasonally high groundwater level (0,6 m below the ground level);
- have hill slopes, with slopes greater than 15 %, which directly enclose a stream or river;
- include areas flooded with a 100-year flood, i.e., a flood with a 1% probability of recurring; and
- functioning as buffering zones.

Naturally occurring riparian communities in temperate climates are: alder forests (*Alnetea glutinosae*), mixed ash and alder forests (*Querco - Fagetea*), wet meadows (*Molinio - Arrhenatheretea*) and rushes (*Phragmitetea*). They may appear separately or form successive zones significantly reducing nutrient concentrations in ground waters and diminishing surface flow from agricultural areas (Klosowski, 1993). Zonation and species composition, together with hydrological and soil conditions, determine the physical structure of riparian habitats. This is important as plants themselves accumulate only 10-50% of nutrients

passing through the buffering zone (mostly during the growing season). The remaining pollutants are retained by other ecotone components.

Whenever natural communities are still present in city landscapes, it is recommended, for ecological, economic and aesthetic reasons, to preserve them and enhance. Such situation is usually rare although often there are remnants of natural plant cover in a form of scarce patches. They are important indicators of still existing connection between river and valley and hence should be considered during elaboration of restoration project. They are a source of information about the native plant composition, soil condition, and source of genetic material for design and construction of artificial land/water ecotones.

Using natural vegetation as sediment, nutrients, toxicants trap can threatened their healthy functioning and can have detrimental effect on wildlife and people. Thus under conditions of lack of natural buffering zones or high pollution loads it maybe necessary to create artificial riparian zones, which can remove much of chemicals and sediments from runoff before their reach a main water body or area of special ecological interest. The factors that have to be considered before preparation of an action plan are:

- 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.).

Constructing a system of biogeochemical barriers

One premise of the ecohydrological approach is the enhancement of ecosystem assimilative capacity in order to protect it from disturbance. At the landscape scale, the assimilative capacity of river system is a function of the catchment area occupied by biogeochemical barriers that create nutrient storage. In urban areas, a function of biogeochemical barriers should be conveyed to system of constructed wetlands and planted woodlands and grasslands. The components which can be combined at urban landscape scale are:

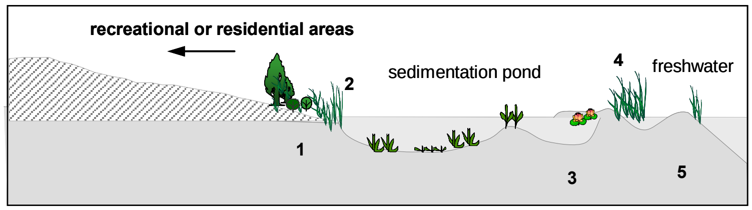
- sedimentation ponds;
- rainwater collectors;
- by-passes;
- ditches for surface flow collection;
- willow zones;
- tree and shrub zones;
- grassland areas

- floating macrophytes zones;
- submerged macrophytes zones; and
- embankments, etc. (Fig.10., Tab. 11.)

Tab.11. Factors to be considered in restoration of riparian zones in urban areas (Krauze, 2004).

FACTOR TO BE CONSIDERED	DESCRIPTION
Geomorphology	An 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. Another key feature is bank slope. It is also highly recommended to reduce the 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. The project has also to consider the ground structure and soil characteristics as they decide about sorption capacity of the zone and pattern of groundwater flow.
Species composition	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 able to store nutrients for longer times and do not require time-consuming conservation. They also regulate the dynamics of herbs, grasses shrubs (Boyt et al., 1977) and water plants. 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 planted 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 and places which for management, recreational or esthetic reasons have to be open. 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.
Macrophytes	The most popular species of macrophytes in reparian areas 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. 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.



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)*

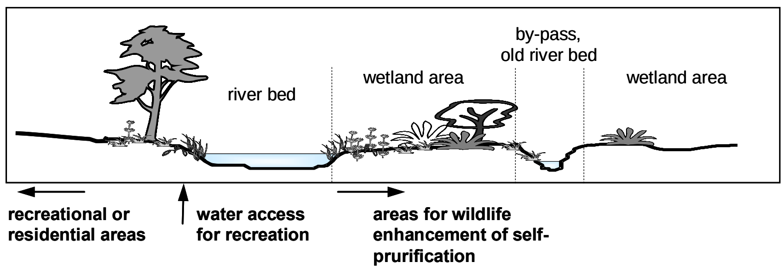


Fig.10. Proposed structure of urban river valley (Krauze, 2004)

The sequence of elements is dependent on local demands. The general rules however, results from properties of vegetation being key element of biogeochemical barriers. In order to achieve its high efficiency five major properties of planned system, as well as their spatio-temporal variability, have to be specified:

- type of plant community to be created and native species present in the area;
- mechanical and physical characteristics of individual species;
- substrate properties and species requirements;
- changes of river discharges and maximum water depth during flooding;
- seasonality of biological processes - usually plants are active for 200-225 days a year, but the vegetation of some communities can be continuous;
- types of stress imposed on the system (toxicity of chemicals, concentration of salt, extreme flows, seasonal drying, high sediment load, use by people, etc.).

There are two components of wetland assimilative capacity. The first is a hydrologic assimilative capacity, which is related to the retention and infiltration of surface water inputs. It is why wetland area has to be projected with regard to extreme hydrological conditions – stormflow inputs and eventual droughts. Wetlands have to be sufficient to retain certain volumes of water at depths and durations adjusted to hydroperiod tolerated by vegetation (Hammer, 1992; Taylor, 1992)(Tab.12.). On the other hand one has to consider that these are oxygen conditions which influence wetland trapping efficiency for different compounds. Almendinger (1999) demonstrated that the most permanent removal of phosphorus was favored in deeper wetlands and ponds where it is scavenged by algae and accumulated in organic form in sediments. Moreover wetlands should be permanently inundated to maintain anaerobic conditions and hence minimize decay of organic matter and favor denitrification.

Tab.12. Tolerance of some typical land/water ecotone species to hydrological conditions (Krauze 2004, modified from Kadlec and Knight, 1996 and 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

The second component of assimilative capacity is chemical assimilative capacity, which consists of: macrophyte uptake, microbial transformation and sorption of chemicals by bed sediments. It results from hydrological regime, but also depends on dynamics of biota. According to Devito and Dillon (1993) assimilation is low when chemical input exceeds metabolic rates of organisms, thus it is inversely

correlated to runoff and coincides with high biotic assimilation rates during growing season. In consequence significant differences in wetlands efficiency maybe observed (Tab. 13.).

Tab. 13. Retention of nitrate and phosphorus in different types of wetlands and reduction of nutrient content by a grassland buffer strips (Vought et al. 1995)

Retention per wetland type				
Wetland type	Retention NO_3-N		Retention tot P	
	%	in detail (kg $ha^{-1}month^{-1}$)	%	in detail (kg $ha^{-1}month^{-1)}$
Lacustrine reedswamp	54-65	40 – 230	-	-0,8 – 23
Irrigated riparian meadow	99	80	93	14
Irrigated riparian wetland	70-77	95-280	-17-100	-1
Natural riparian wetland	29-85	20-50	100	0,1
Irrigated riparian meadow	20-100	6-100	40	0,2
Artificial flooded meadow	0-16	0-10	20-50	3-3,6
Pond	-	6-570	-	1-2
Percent reduction in NO_3-N and PO_4-P in grassland strips of given width				
5m	40-50	out of 8 mg tot N l^{-1} initial load	65-85	out of 2 mg P l^{-1} initial load
5m	10-15	out of 12,3 mg tot N l^{-1} initial load	40-45	out of 6,4 mg P l^{-1} initial load
10m	50	out of 7 mg N l^{-1} initial load	70-80	out of 0,3 mg P l^{-1} initial load
10m	75	out of 8 mg N l^{-1} initial load	95	out of 2 mg P l^{-1} initial load
10m	25-30	out of 12,3 mg N l^{-1} initial load	65-70	out of 6,4 mg P l^{-1} initial load
15m	40-45	out of 12,3 mg N l^{-1} initial load	85-90	out of 6,4 mg P l^{-1} initial load

Although benefits of using of constructed wetlands to reduce chemicals load of municipal waste waters are well documented, it is important to underline that their construction has to be preceded with detailed analysis of composition and concentration of contaminants in supplying waters. It is also inevitable to understand pattern of physical and chemical processes occurring in wetland of planned parameters. As wetland ability to reduce river pollution with anthropogenic contaminants results from complex redox reactions and microbial processes, eventually transformations may lead to more toxic and bioavailable forms of some chemicals (Shiaris, 1985). It is especially true for areas exposed to mixtures of chemicals,

what often occur in industrial cities. Forstner and Wittman (1981) showed that anoxic conditions led to reduction of arsenic and chromium to more toxic states. Helfield and Diamond (1997) provided evidences that alternating oxygen conditions, due to periodic inundation and drying of wetland, may enhance the bioavailability of metals sorbed to hydrous oxides of iron and manganese. Oxygen conditions may also influence the effects of metals on biota through enhancement of methylation. In this case high levels of microbial activity in wetlands result in net methylation and subsequent biomagnification of mercury (Helfield and Diamond, 1997 after Portier and Palmer 1989 and Wood et al. 1968).

Phytoremediation

Considering the problems with prediction of metabolic pathways and transformation of chemical compounds carried with waste and storm waters, in some cases establishing of wetlands is not advisable. Alternatively the structure of urban river valley maybe planned toward implementation of phytoremediation techniques. Phytoremediation is a variety of cost-effective soil remediation methods using plants. It concerns the upper 50 -centimeter -deep layer of soil when herbaceous plants are used (Kucharski et al., 1998; Raskin and Ensley, 2000) or deeper when deep-rooting trees are being used to extract organic solvents from deep aquifers (Negri et al., 1996). In this surface level of soil most of biological processes take place. From the user point of view, soil from this zone is responsible for dust resuspension, involuntary pollutant ingestion by children and grazing animals (Thornton, 1982) and contamination of surface runoff.

There are several methods of phytoremediation differentiated on the basis of biochemical processes involved, application method and type of plant used (Tab.12.).

Tab. 12. Characteristics of three commonly applied phytoremediation methods (Kucharski, 2004, modified).

METHOD	**PROCESS DESCRIPTION**	**SUGGESTED APPLICATION**	**PLANT USED**	**APPLICATION METHOD**

Phytoextraction	- based on the ability of some plants to take up significant amounts of contaminants from soils by their roots and transport them to aerial parts, e.g., leaves; Contaminants are removed from the environment by harvesting and carefully disposing the plants.	- moderately contaminated land	- species with high biomass production, good accumulation properties in above-ground parts, tolerance to the local climate; the most commonly used species for metal phytoextraction come from Brassicaceae family, e.g., Indian mustard.	- the efficiency of this technology depends on biomass production and contaminant concentration; they in turn are dependent upon complex interactions among plant physiology, soil chemistry, hydrogeology and climate; the effectiveness maybe enhanced through the use of soil and plant amendments. - the role of soil amendments is to facilitate the uptake of metals from soils to plants, usually various chelators are used for that purpose (EDTA, DTPA, HEDTA) followed by organic (citric or acetic) acids.
Phytostabilization	- conversion of soil contaminants into inert, immobile elements using metal tolerating plants through: absorption, adsorption, accumulation, precipitation or physical stabilization of contaminants in the root zone - plants with well-developed root systems prevent contaminant migration via wind and runoff through the soil profile; plant root biochemical activities can change soil pH as well as convert metals from a soluble to insoluble form.	- applicable to large areas of contaminated soil, sludge and sediments that are not amenable to alternative forms of treatment; and - remediation of heavily polluted sites.	- indigenous species of grass and shrubs, which develop a dense and strong root system, e.g., Deschampsia caespitosa, in the case of heavily metal-polluted soils.	- the upper layer of soil is treated first with chemicals (e.g., lime, commercial fertilizers as needed) to adjust soil pH, fertilize, and to transform metal compounds into nonsoluble forms; - the next step is to develop a robust plant cover to reinforce the soil surface, to maintain the desired soil chemical conditions and to minimize soil transport processes (e.g., erosion and wind transport) (Vangronsveld et al., 1995, Kucharski & Nowosielska, 2002).
Rhizofiltration	- the mechanism is based on adsorption or precipitation of contaminants onto plant root surfaces or bioaccumulation in plant tissues. Contaminants are then removed by physically removing and disposing of the plants (US EPA, 1997).	- applicable to surface water, wastewater and (extracted) ground water contaminated with low concentrations of contaminants	- aquatic plants or terrestrial plants (grown hydroponically)	

Phytoremediation appears to be a „natural technology", relatively simple and uncomplicated. There are, however some important factors that should be observed carefully in order to achieve the expected results and to avoid disappointments:

- plant species used for phytoremediation should be selected according to the purpose;

- it is desirable to use an indigenous species that locally adapted and resistant to the substances polluting the soil;
- optimally, the selected plant should not require special care, should be tolerant to naturally
- variable weather conditions and should grow well on the type of soil to be remediated;
- for optimal performance, regular watering and fertilizing is necessary; and
- the use of exotic plant species should be avoided, because cultivation procedures will need to be developed specifically for the plant/environment (Kucharski et al.,1998), what is time consuming and expensive.

3.4. Diminishing risk in restoration projects

In order to achieving long-term success, restoration of urban river system has to address both the symptoms and the causes of ecological disturbance. The source of disturbances is often removed in space and time from the target system as urban rivers constitute part integral part of complex waste water, storm water and sewage systems established and developed in the past. There are four main stages in restoration project:

1. establishing a vision
2. development of plan
3. implementation of plan
4. monitoring and review.

They realization should involve learning-by-doing procedure of adaptive management (Fig.11). To avoid failure a restoration project should start with specification of mission, goals and objectives explicit enough to become a basis for a project evaluation checklist at the end, and in post-restoration period. According to Committee on Restoration of Aquatic Ecosystems: Science, Technology, and Public Policy, U.S. National Research Council (1992) such a checklist for project planning and design should include:

- definition of problem that requires treatment
- consensus of all involved parties on restoration program goals,
- capacity building plan for required expertise and scope,
- formulation of midcourse correction point in-lined to adaptive management plan,
- specified performance indicators being measurable biological, physical and chemical parameters appropriately linked to the objectives,
- planning of adequate monitoring, surveillance, management and maintenance programs which should be developed along with the project, including anticipated costs, operational details, and monitoring results being input to techniques improvement,

- defined reference systems for evaluation of project performance,
- specification of base-line data that will be sufficient to facilitate before-and-after system comparisons,
- specified critical procedures already tested experimentally,
- elaborated parts of design which make restored system as self-sustained as possible to minimize maintenance requirements,
- elaborated plan of long-term system monitoring,
- analysis of uncertainties related to project realization.

The key issue in pre-restoration period is proper scale planning. The project should cover area large enough to: decrease boundary effects, cover at least some sources of disturbances to the system, what allows control them in more efficient way, the area should enable proper monitoring of restoration results. On the other hands the scale has to be affordable.

During the restoration project the critical step is careful monitoring if intermediate objectives are achieved. In case of failure the necessary actions should be planned to correct the problems. The evaluation should include also verification of performance indicators and monitoring program if they appear to be insufficient or inappropriate considering the goals of the project.

Finally in post-restoration period it is inevitable to confront achievements with planned objectives. The important criteria are:

- similarity of the restored system to target one,
- its sustainability,
- assessment if all critical components of the system were restored,
- clarification of ecological, economic and social benefits achieved by realization of project,
- knowledge sharing with parties of interest,
- assessment of cost-effectiveness of the project.

The important issue at this stage is establishing of project schedule, which enables to check restoration results against some unusual environmental conditions e.g. floods and droughts.

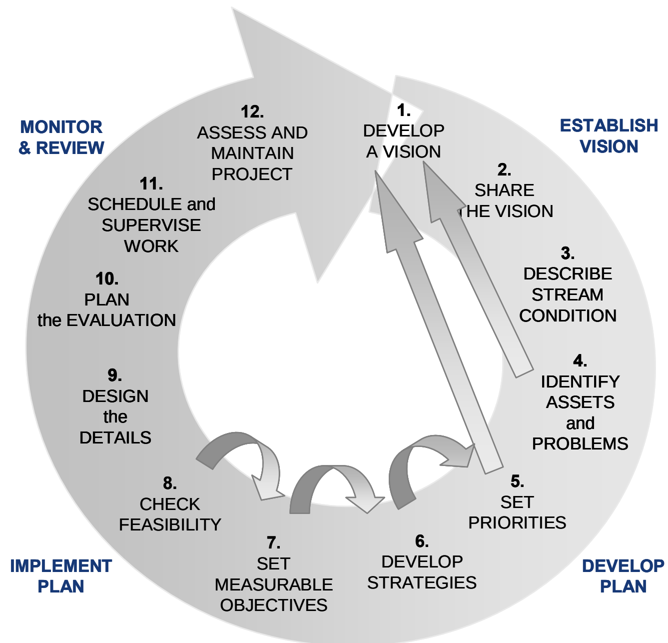


Fig.11. A 12-Step rehabilitation procedure (modified from Rutherfurd et al., 1999)

There are several main causes of failure of restoration project. First is related with lack of institutional agreements and consensus of parties of interest on restoration goals. This can jeopardise the execution of action plan or impose constraints on some necessary actions. The second one concerns improper implementation of the project often resulting from lack of sufficient data base or using of inadequate techniques, and/or lack of mid-term assessment and improvement procedures. The third common reason of failures is improper formulation of objectives and goals, what causes that restoration project neither meets ecological nor social expectations.

4. Literature

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