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Guidelines for free water surface wetland design

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1 Introduction

The spectrum of wetland types is very wide; it ranges from constructed wetlands in a greenhouse (living machine), to natural wetland systems passing through constructed wetlands for treatment purposes, polishing wetlands, combined sewers overflow ponds, reconstructed wetlands, and so on. The technology usually applied to these different types of wetlands is decreasing with naturalness of wetland, while the “greenness “ is increasing (BRIX 1998).

Wetlands constructed with the purpose to treat civil and industrial waste waters are usually very sophisticated. They can be constructed even on dry soil where a wetland could never be imagined. For this reason constructed wetlands are substantially a treatment plant facility. They compete in costs and performances with the traditional and technological Activated Sludges Treatment Plants (ASTP).

The differences between constructed wetlands and treatment plants are mostly related to the processes adopted. The quantity of technical know-how do not differ greatly; imagine, for instance, how compact a constructed wetland can be and which care has to be invested in building the soil bed for aquatic plants.

In spite of this high technological level applied, constructed wetlands cannot reach the water quality standard of activated sludges treatment plants. Constructed wetlands are, in fact, suffering and profiting from the natural cycles imposed by forcing functions to the system processes (KADLEC 1998).

Constructed wetlands and treatment plants are competing and all the advantages presently offered by the constructed wetlands in treating wastewaters of small communities more cheaply and more easily could very quickly be outdated by the appearance of compact activated sludge treatment plants on the market. Activated sludges treatment plants combine indeed the reliability of mature technology, the low and easy maintenance and the advances in treating processes. In such a case the future survival of constructed wetlands could be very hard and/or restricted to a few applications, produced that the water quality standards admit a certain flexibility in the concentration discharge.

Nevertheless, the huge scientific and technical effort in the field of application of wetlands to treat waste waters has provided a wide selection of technologies.

These can be used as well as to restore and protect natural wetlands. In this context reconstructed wetlands represent the future of wetlands technology for the following reasons:

- they do not compete with the activated sludges treatment plants;
- reconstructed wetlands can be integrated with activated sludgs treatment plants, downstream of their point of discharge, to polish the discharged water and to store storm waters from combined sewer overflow;
- reconstructed wetlands are very suitable to abate residual pollution loads, to treat surface waters polluted both by diffuse and treated point sources;
- reconstructed wetlands are an appropriate tool to restore the self purification capacity of the receiving water bodies.
- reconstructed wetlands have peculiar requirements:
    - to perfectly fit a landscape where wetlands were previously present;
    - to be under-engineered and over-sized compared to constructed wetlands;
    - to look like a natural wetland;
    - to reconstruct a natural habitat
    - to provide the benefits of natural wetlands when used as recreational areas.
- reconstructed wetlands need an optimum management that respects both the needs of pollution abatement and those of the natural environment;
- reconstructed wetlands usually deal with waters that have already reached the standard imposed by law or they have no standard to respect (diffuse sources).

They must to accept respect the natural “standard” of receiving water bodies. In this case the natural cycles of their forcing functions are not a limiting factor of their potential application but a value.

In order to provide a better design of reconstructed wetlands that matches as much as possible the needs of nature, a pronounced know-how of the natural processes of wetlands has to be provided as well as the technique of the reconstruction of natural wetlands.

Up to the actual state of knowledge, it is possible to propose some guidelines for reconstructed wetland design. The following pages present the design characteristics of a typical free water surface re/constructed wetland intended to remove pollutants from surface waters. The reconstruction of a wetland is proposed as a final remedation of the water quality. It is clear that all the preventive actions and point source treatments have to be carried out to treat the water in the wetland.

2 Multifunctional design

Wetlands can be designed to meet many different objectives. Some of these objectives can be simultaneously fulfilled. Objectives of most wetland projects include:

- water quality enhancement through assimilation and transformation of sediments, nutrients and other pollutants,
- water storage and flood attenuation,
- recharging of groundwater,
- primary production and food web support design,
  - photosynthetic production,
  - wildlife production,
  - food web and habitat diversity,
  - export to adjacent ecosystems,
- human uses
  - aesthetic uses,
  - recreational uses,
  - commercial uses,
  - educational uses.

Water quality enhancement

Wetlands are mainly used to restore the self-purification capacity of river-net ecosystems. Wetlands facilitate the reduction of concentrations of suspended solids, biochemical oxygen demand, nitrogen, phosphorous, pathogens and other substances. The treatment efficiency depends on water residence time, temperature, incoming concentration of pollutants, depth, vegetation distribution, hydraulic efficiency and light.

Water storage and flood attenuation

The use of wetlands as water storages and high flow buffering zones requires design according to the best hydrological engineering practice.

Recharging of groundwater

Wetlands can also be used to recharge groundwater. This is possible by holding surface water in the wetland long enough to allow water percolation into the underlying sediments and/or bedrock aquifers, encouraged by a permeable soil.

Human uses

Humans appreciate wetlands for their commercial values (plant harvesting, livestock grazing, hunting and aquaculture) and non-consumptive values (aesthetics, recreation, education, research) (REIMOLD & HARDISKY 1978; SATHER & SMITH 1984; KADLEC & KNIGHT 1996).

For non-consumptive uses, wetlands have incorporated attractive and informative park-like areas for field trips and other educational purposes. Adequate structures should be designed for bird-watching, walking, jogging and cycling.

These human uses of wetlands, including the satisfaction of having a wetland and wildlife reserve at the edge of town, for example, may be important factors behind public support for the protection and enhancement of existing wetlands (KADLEC &KNIGHT 1996).

Primary production and food web support design

When project goals include the generation of organic matter as the basis of a food web leading to an animal population, then system design and operational control can be used to supply the factors limiting the growth. For example, light can limit algae production. If reduction of algae suspended solids is a goal, then wetlands can be designed with a densely vegetated emergent zone downstream of the wetland. If algae productivity is desired to enhance an aquatic food web then open water zones should be included in design.

Highest net primary production is usually measured in shallow (< 0.3 m), regularly flooded, emergent marshes (BROWN et al. 1979). In such shallow systems, high primary production may result from the availability of water combined with higher sediment dissolved oxygen levels and light availability. More fluctuating water levels generally result in lower net primary production: if, for example, prolonged flood events occur several times each year, with dry periods interspersed, the plant community will be stressed and is likely to have low annual net primary production.

3 Design data

Site characteristics

Conditions that should be evaluated when planning a wetland include climate, geography, groundwater, soils and geology, rainfall and runoff water chemistry and environmental impact.

Climate

Climate is important during project planning and site selection because it affects type and size of the wetland that will be used. Latitude is the most critical parameter affecting the climate as it determines seasonal temperature ranges. Other climatic factors that are important during project planning include rainfall, evaporation, evapotranspiration, insolation and wind velocity.

The long-term average temperature during the coldest month of the year has been found to be a good estimator of the critical low water temperature that will be experienced in a wetland system (KADLEC & KNIGHT 1996). For areas where the minimum annual average monthly temperature is less than zero, it can be assumed that the minimum wetland operational temperature will be slightly above zero under an ice cover (KADLEC & KNIGHT 1996).

Geography

Geography studies are very important when deciding where to re/construct a wetland (siting = site selection). Knowledge of elements including topography (characterisation of highlands and lowlands, natural depressions, slopes), proximity to the river system, land use, and population density are essential for siting.

Soils and geology

For planning purposes, the soils of the site should be characterised. Soils are classified based on a complex array of physical and chemical characteristics. Soil information that may be important during project design include depth of seasonal high groundwater, depth of confining layers of clays, soil textures and chemical composition particularly for bank construction or for leakage into the groundwater. In some cases, the sorption potential of the soils will be a design variable, for example for removal of metals.

Groundwater

Infiltration of water affects the wetland water balance and could pose management problems of the water table under some conditions. Soil infiltration rates published in soil surveys typically overestimate the actual infiltration rates under saturated soil conditions. Surface infiltometer tests or slug tests provide better estimates of the groundwater leakage that can be expected in a wetland.

Wetlands can be designed for groundwater recharge as a specific project goal (EWEL & ODUM 1984; KNIGHT & FERDA 1989).

Groundwater infiltration can be eliminated as a project concern by using a clay or plastic impervious liner.

Characterisation of inlet water flow and quality

Flows

The amount and timing of the water that passes through the wetland is the first and foremost item in the design plan. This information should include the possible seasonality of flows and the pattern of past flows at least as long as the life of the designed wetland. Wetlands can continue to function for very long periods, for example there are receiving wetlands that have been in operation for periods of 70 and 90 years (Great Meadows and Brillion). Projecting flow estimates far into the future is risky, so it is necessary to be explicit about flow capacity at the time of design.

Well designed wetlands can handle even extreme events, in that case it is accepted that the removal efficiency of the system can be lower for a certain recover period.

Quality

The concentrations of the pollutants in the water flowing into the wetland are critical to the size of the wetland and to predict its removal performance. A clear definition of the incoming water quality is essential, including the previous temporal distribution of concentrations. There are often seasonal fluctuations for point and diffuse sources and variability of concentrations for stormwater flows.

The output concentrations may be predicted by design models: in fact there are several possibilities of hydraulic and water quality models that can be used for design and for management.

Chemical substances to be analysed must be chosen according to the treatment objectives. Initially the substances described by the 91/271/EEC directive for discharge in water bodies can be used, specific pollutants to be removed can be added later.

4 Table of contents for designing procedure

The following table of contents shows the structure of the output usually requested in a free water wetland designing procedure. This list is not intended to be exhaustive and is suggested for the preliminary design only.

GENERAL REPORT: *general aspects of the wetland reconstruction study:*

- **analysis of the current situation**: general description of the present situation of the watershed, water bodies, flora and fauna;
- **reasons why the intervention is to be undertaken**: environmental reasons, why the wetland has to be reconstructed (e.g. to protect the final water body from eutrophication, to polish the wastewater to comply with environmental standards, etc.);
- **legislation in force**: laws and local regulations, financial sources for construction and maintenance;
- **description of the site**: description of the main features of landscape geography and morphology, summary of geological report;
- **siting**: (site selection) why was that particular wetland location chosen;
- **analysis of available data** on: water quality, precipitation, river discharges, river water levels, land-uses, temperature, solar radiation…missing data, planning of monitoring surveys for data collection;
- **analysis of data collected;**
- **dimensions of the wetland;**
- **description of the wetland**: how is the wetland composed (numbers of compartments, where/how is the wetland receiving water, where/how is the wetland discharging, etc.);
- **alternative solutions**: other solutions considered and reason of the choice;
- **hydrologic balance**: (= precipitation + inflow - evapotranspiration - infiltration - outflow) average and extreme situations, summary of hydrologic and hydraulic report;
- **efficiency of pollutant removal**: e.g. evaluation of the pollutant removal using water quality modelling;
- **ancillary benefit values**: for public use (recreational and educational benefits) and ecological state improvement (wildlife, vegetation);
- **earthworks, banks, hydraulic engineering works**;
- **environmental and landscape reconstruction**;
- **management:** operation and maintenance plan; construction and ordinary management; water level operation; plant maintenance; monitoring
- **erosion and fill up control plan**

TECHNICAL REPORTS

- **hydrological report**: (site oriented) precipitation, infiltration, flood and drought events;
- **hydraulic report**: (wetland oriented) discharges, flow velocity, water levels, re-suspension, detention times, fetch, pumping, etc. - rough estimations and modelling;
- **geological report**: including groundwater level and hydrogeology;

- **data collected**: presentation of the data collected for the wetland design;
- **evaluation of pollutants removal** through modelling;
- **cost and benefit evaluation** through modelling;
- **naturalistic evaluation:** identifies existing and expected terrestrial and aquatic vegetation and fauna

ENVIRONMENTAL IMPACT ASSESSMENT

- **basic studies to undertake**
- **the environment**
- **legislation in force and territorial planning**
- **methodologies of analysis and criteria for a comprehensive estimation and evaluation of impacts**
- **frame phase**: all the information is arranged through a specific information system
  - **programmatic reference table**: characterisation of existent relationships between the project and the territorial planning tools
  - **plan reference table**: characterisation of project components for the definition of potential critical elements connected to the project
  - **environmental reference table**: characterisation of environment showing critical components connected to the project
- **phase of point out of potential interference of the work on the environment**
  - **disaggregation**: point out of perturber factors and significant environment compartments
  - **point out of potential impacts**: point out of environment compartments potentially alterable by the actions of the project
  - **characterisation of the impacts**: a classification of potential impacts based on their nature, duration…
  - **selection of significant impacts**: every impact is to be tested and classified as significant or insignificant
- **analysis phase**: of the significant impacts
  - **definition of reference environmental indicators**: point out of one or more indicators suitable to describe the impact evolution
  - **procedural schemes for the main environmental compartments**: the analysis procedures are subdivided for environmental compartments
- **estimate phase and total valuation of the impacts**
  - **application of impact scales**: in order to allow comparison of the analysis matrices
  - **aggregation in columns**: every alternative is represented by a vector
  - **generation of the valuation matrix**: is the result of the aggregation
  - **attribution of weights**: attribution of an influence degree to each decision
  - **ordering** the alternatives
- **phase of definition of the interventions**: the negative effects on the environment can be mitigated by project precautions

LIST OF UNIT PRICES according to local regulations;

***BILL OF QUANTITIES*:** quantities and technical specifications for materials and workmanship;

PRICED BILL OF QUANTITIES according to local regulations;

COST-BENEFIT ANALYSIS:

- **land acquisition;**
- **construction costs;**
- **operation costs;**
- **maintenance costs;**
- **pests (mosquitoes and biting insects, dangerous reptiles, odours, etc.)**
- **annual total costs;**
- **change of land-use costs;**
- **hydrological benefits;**
- **pollutants removal benefits;**
- **recreational benefits (aesthetics, public use);**
- **educational benefits;**
- **ecological improvement (biodiversity, rare species);**
- **'greenness' (sustainability);**
- **evaluation of pollutants removal unit costs.**

DESIGN PLANS

- **Current situation:**

- **Plan of the catchment**;
- **Plan of local land-use planning**;
- **Properties identification maps**;
- **Planimetry** showing dimensions and accurate contour lines;
- **Planimetry** showing cross sections location;
- **Cross sections**;
- **Monograph of bench marks**;
- **Planimetry** with vegetation state and land-use;
- **Photographic documentation**;
- **Services map**: locates existing overhead and underground services including water supply, storm-water, sewer, electricity, gas and telecommunications;

- **Project Design:**

- **Wetland planimetry** illustrating dimensions and accurate contour lines
- **Planimetry** illustrating cross sections location
- **Cross sections**
- **Hydraulic profile**
- **Earth works**:
    - planimetry of the embankments;
    - cross-sections;
- **Engineering works**:
    - Intake works;
    - Inlet works;
    - Outlet works;

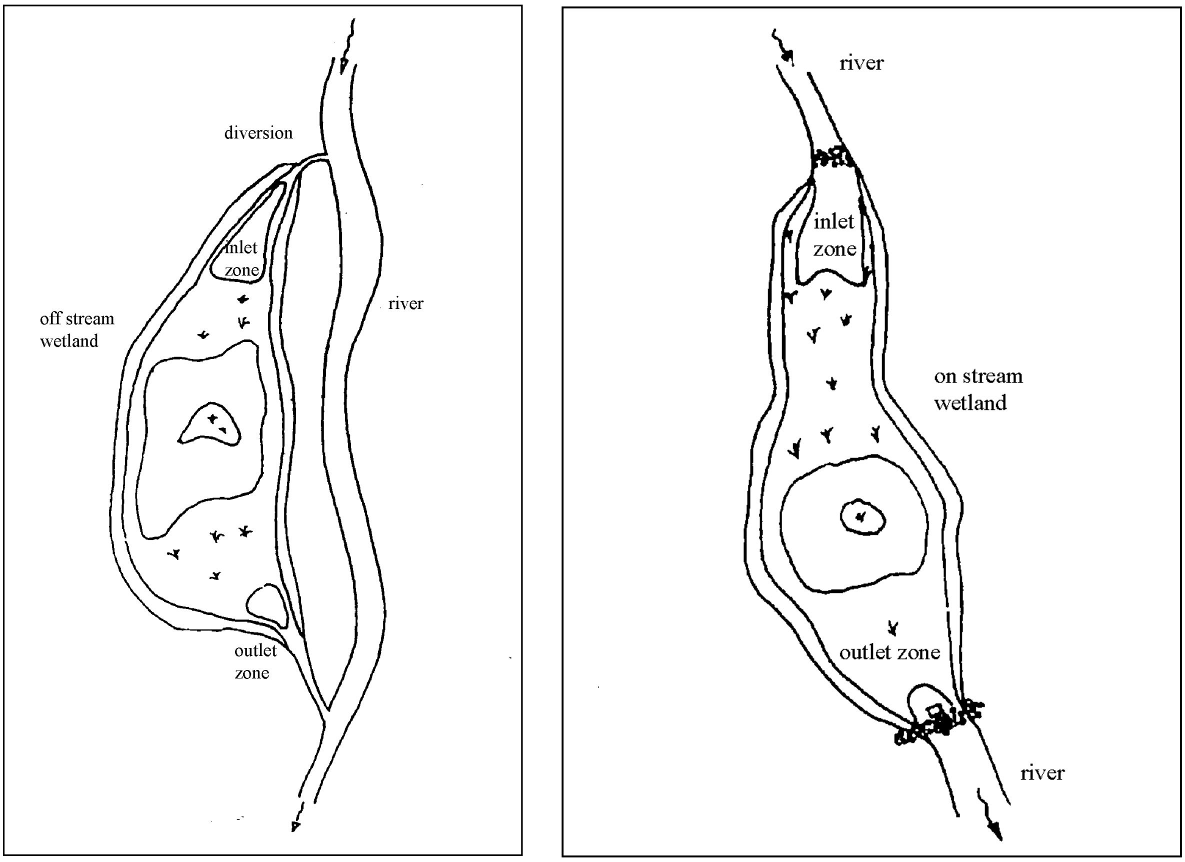
- Floodgates;
- Electromechanical works;
- Services plan: locates proposed overhead and underground services including water supply, storm-water, sewer, electricity, gas and telecommunications;
- Buildings for electromechanical equipment, for drive control and utilities;
- Weather and automatic data survey station;

- **Layout and environmental works**:
  - Access;
  - Reception and sanitary services;
  - Naturalistic and didactic equipment: bridges; foot path (e.g. pile-work, etc.); observatory; landing sites, piers; vegetation general planimetry; vegetation typical sections.

5 Planimetry

Off-stream and on-stream wetlands

An off-stream wetland is constructed adjacent to the stream where only a portion of the flow enters the wetland (the inflow can be regulated by pumping or with natural flow). An on-stream wetland is constructed in the river bed and all flows enter the wetland (apart from the possibility of a by-pass) (Figure 1).



A: off-stream wetland b: on stream wetland

Fig. 1: Off stream wetland and on stream wetland

An off stream wetland assures an exclusion from the stream conditions, allows the possibility of hydraulic regulation, minimises hydraulic risk problems, permits reversibility of the wetland system. It is recommended that the portion of stream that does not pass through the wetland reaches at least the minimum flow needed for the survival of flora and fauna.

Cell size and configuration

Multiple cells have the advantages of providing greater flexibility in design and operation, and of enhancing the performance of the system overall by decreasing the potential for short-circuiting.

Wetland cell size depends primarily on water quality treatment needs and cost considerations. Large cells require less berm construction per unit area and fewer inlets and outlets, so project costs per area are reduced. Although cell size may influence the use of wetlands by larger wildlife, it has minimal affect on plant productivity or secondary production of most wetland animals (SATHER & SMITH 1984). A higher berm-to-cell area ratio, typical of smaller wetland cells, may result in increased beneficial edge effects (more nesting and feeding habitat).

Berms

Earthworks

A general earthwork aim is to balance excavations and fills, in order to avoid buying supplement soil or discarding superfluous soil: if possible the soil should only be moved inside the wetland yard. Selection of the bottom elevation of the wetland, together with proper positioning on the site with respect to its topography, generally allow balancing of cut and fill, avoiding import/export costs and greater environment impact.

Exterior berms

Berm design is based on hydraulic and geotechnical considerations. The purpose of berms is to regulate and contain water within specific flow paths.

Exterior wetland berms should be kept as small as possible for aesthetic reasons, but at the same time providing an adequate freeboard to prevent flow releases. Exterior berm freeboards should be sufficiently adequate to prevent overtopping during storm events (based on a storm event frequency of 10, 25 or more years) and allow overflow of less frequent storm events through controlled and protected emergency overflow points. Berm freeboards should also consider berm soil consolidation and subsidence, and also that the wetland can gradually fill with vegetation and with sediments which increase flow resistance and decrease freeboard during wetland life.

Berm height should equal the sum of the maximum desired normal water level, the return storm rainfall amount, the lifetime loss of freeboard due to sediment and plant accumulation, berm soil consolidation and subsidence.

Compaction, the immediate increase in soil density effected by the displacement of air, should not be confused with consolidation, which is a slow increase in density due to the gradual rearrangement of soil particles over time.

Compaction affects the future behaviour of any earth structure. Poor compaction results in low strength, high permeability, susceptibility of tunnelling in dispersible clay, risk of erosion and risk of slip failure.

Motorised rollers are usually used to compact soil. The movement of ordinary machinery during construction may provide sufficient compaction, however this technique should be used with caution.

Berms should be constructed on the basis of standard geotechnical considerations. The materials that are available dictate how berms will be designed. Internal clay plugs may be required to minimise berm seepage if permeable materials are used for berm construction. External seepage collection channels may be necessary if soils are unconsolidated.

Berms are used also for access, by walking or driving. A vehicle access berm needs at least to be more than 3m wide at the top, a foot access berm needs to be at least 1m wide. Berms greater than about 5m in width are less likely to be fully penetrated by muskrats or nutrias.

Furthermore, water containment berms are subject to local dam safety regulations.

Interior berms

Interior berms may be used for flow distribution inside the wetland, but do not have to control offsite water releases. For this reason they can be smaller than exterior berms. Interior berms designed for pedestrians access may be at least 1m wide at the top.

Flow diversion banks

Small embankments may be utilised to divert water through the wetland, creating a longer flow path. This increases the efficiency of the system by increasing the hydraulic residence time. The top of the banks may be below or above water level. Flow diversion banks are usually submerged at nominal operating level.

Design factors

The principal design factors for reconstructed wetlands are detention time, organic loading rate, water depth, aspect ratio and shape. Typical ranges of design criteria are presented in Table 1 (REED et al. 1988; WATSON et al. 1989; WATSON & HOBSON 1989; HAMMER 1989; CRITES 1994; KADLEC & KNIGHT 1996).

Tab. 1: Ranges of design criteria from literature

Factor	Literature suggested ranges
Detention time (for soluble pollutants removal), d	5 to 14
Detention time (for suspended pollutants removal), d	0.5 to 3
Maximum BOD5 loading rate, kg/ha.d	80 to 112
Hydraulic loading rate, m/d	0.01 to 0.05
Area requirement, ha/m3.d	0.002 to 0.014
Aspect ratio	2:1 to 10:1
Water depth - average condition, m	0.1 to 0.5
Bottom slope, %	0 to 0.5

detention time and pollutants removal

Detention times for significant nutrient removal (40-50%) need to be longer than the 5 to 10 days needed for BOD (Biochemical Oxygen Demand) and TSS (Total Suspended Solids). For the removal of ammonia and total dissolved nitrogen both minimum temperature and detention time are important. Detention times for significant dissolved nitrogen removal should be 8 to 14 days, or more (CRITES 1994). Nitrogen removal and nitrification will be reduced when temperatures fall below 10°C.

An example of correlation between detention time and total nitrogen removal efficiency can be seen in Figure 2 and 3, on the basis of k-C* model (KADLEC & KNIGHT 1996).

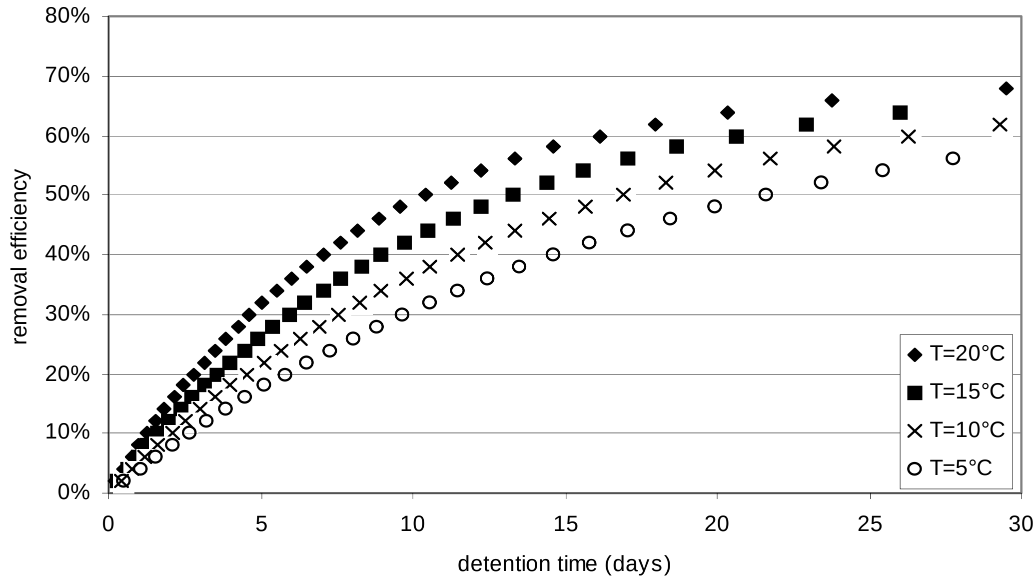


Fig. 2: Total Dissolved Nitrogen (TDN) removal efficiency according to k-C* model (KADLEC & KNIGHT 1996) for TDNin=5mg/l and h=0.5m, T variable.

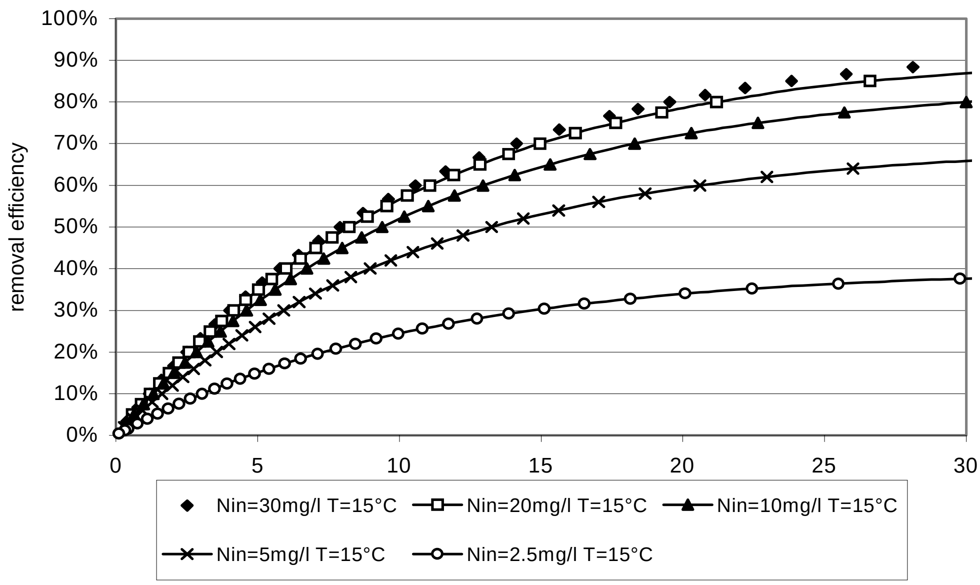


Fig. 3: Total Dissolved Nitrogen removal efficiency according to k-C* model (KADLEC & KNIGHT 1996) for T=15°C and h=0.5m, C variable.

Plant uptake of dissolved phosphorous is rapid, and after plant death, phosphorous may be quickly recycled to the water column or deposited in the sediments (WPCF 1990). The only major sink for phosphorous in most wetlands is in the sediment. Significant dissolved phosphorous removal requires long detention times (15 to 25 days) and low phosphorous loading rates (less than 0.3 kg/ha.d) (CRITES 1994).

Appropriate design can accomplish low concentrations for NH4+ and total nitrogen. Wetland systems designed for low effluent NH4+ concentrations (<2mg/l, annual average) should: 1) use a loading rate of < 3 kg N/ha/d for total Kjeldahl Nitrogen or NH4+ (HAMMER & KNIGHT 1994) and 2) provide for alternating aerobic and anaerobic zones within the wetland system.

hydroperiod and water regime

In all wetlands, the frequency, depth and duration of the water's influence determine the vegetation presence and the functions that the wetland provides. In order to create a wetland system which provides specific functions, one specific hydroperiod or range of hydroperiods is often most effective or desirable. A hydroperiod can be defined as the number of days per year of surface water at a given wetland location (KADLEC & KNIGHT 1996).

This factor in wetland systems design and operation is very important, as incorrect understanding of the hydroperiod and water regime limitations of wetland plant species is the most frequent cause of vegetation problems in natural and constructed wetlands (KADLEC & KNIGHT 1996).

While hydroperiod refers to the duration of flooding, the term water regime refers to hydroperiod as well as to the combination of water depth and flooding duration. The duration and depth of flooding affect plant physiology because of soil oxygen concentration, soil pH, nutrients and toxic chemical concentrations. For any specific location within the wetland, a depth-duration curve can be prepared to summarise the water regime and hydroperiod. A summary of typical hydroperiod tolerance ranges for different wetland plant species are presented, for example, in KADLEC and KNIGHT (1996).

It is suggested for wetland channel-zone a hydroperiod of at least 360 days per year, for reed bed area an hydroperiod of at least 300 days per year, for shrubs and trees a hydroperiod range from 0 to 60 days per year.

hydraulic preferential ways

Open water areas and nonvegetated channels should be meandered and obviously avoid short circuiting and dead zones (Figure 4).

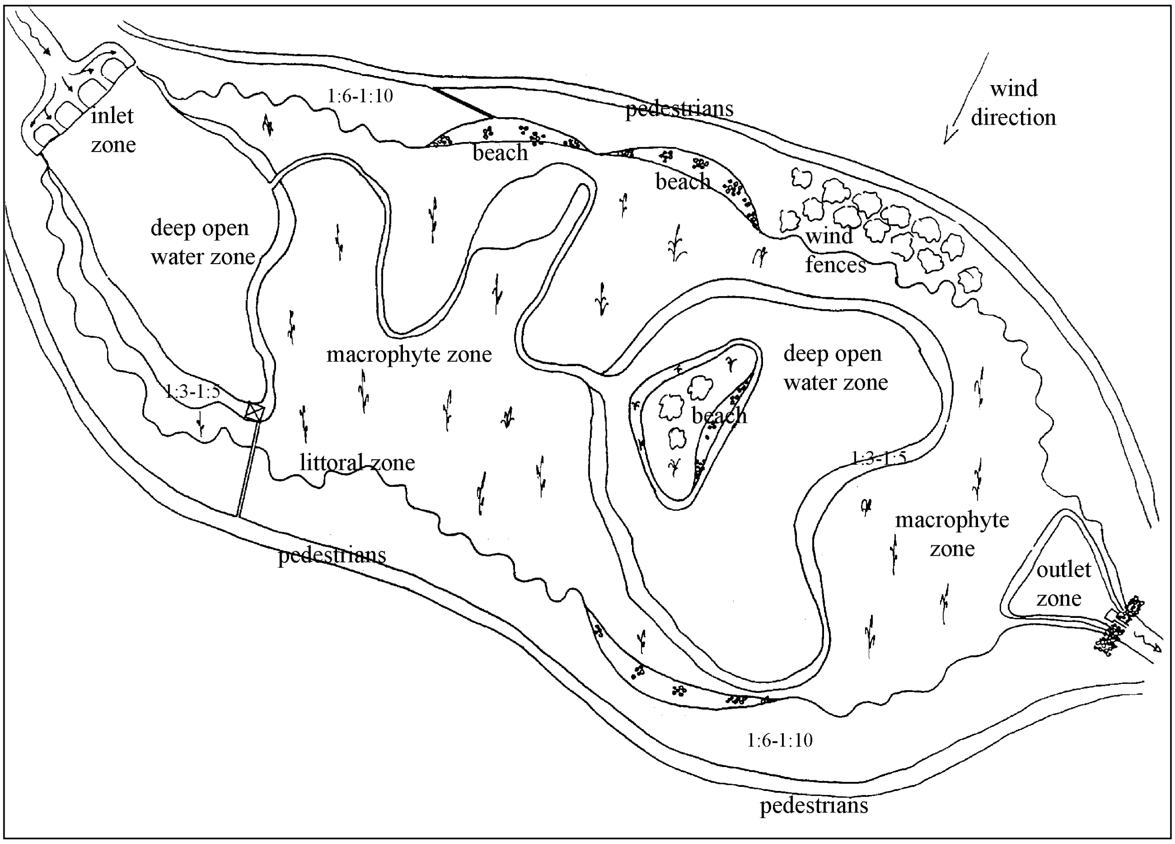


Fig. 4: A design scheme for a free water surface wetland

To prevent hydraulic short circuiting, the flow path connecting open water areas should be reduced; in some cases even be removed and open water areas interspersed with densely vegetated shallow marsh habitat (KADLEC & KNIGHT 1996).

To minimise short circuiting a uniform longitudinal bottom slope from inlet to outlet should range from 0 to 0.5% (HAMMER 1989). Care must be taken to degrade any pre-existing ditches, roads, or berms on the site, because these will exert possibly undesirable flow control in the wetland.

Length to width ratio

Length to width ratio is very important in wetland design, because of its effect on flow distribution and on hydraulic short circuiting. A good hydraulic performance[1] obtained through a good design of the shape and of the hydraulic structures increases pollutant removal efficiency.

[1] A common method to study hydraulic performance is the use of a tracer. By injecting a tracer instantaneously in the inlet and then measuring the outlet concentration, different water systems will produce different residence time distribution functions (RTD). For an impulse input of tracer into a steadily flowing system, the function *f(t)* is

$$f(t) = \frac{QC(t)}{\int_0^\infty QC(t)dt} = \frac{C(t)}{\int_0^\infty C(t)dt}$$

where C(t) is exit tracer concentration and Q is the water flow rate.

The mean detention time (i.e. mean residence time), t_{mean}, which is the average time that a tracer particle spends in the water system, is defined as the centroid of the RTD:

A high length to width ratio is suggested by the necessity to minimise short circuiting and maximise water contact with biofilm substrate for biological removing of nutrients.

In contrast, high length to width ratios lead to large bank surfaces, and, as a consequence, high costs and non-natural layouts. The minimum length to width ratio recommended for an economical point of view (best combination between flow distribution and banks earthworks costs) is 2:1 (KNIGHT 1987). Some studies show that for the removal of nutrients, the optimum length/width ratio is 10:1 (HAMMER 1989). Other methods for maintaining effective flow distribution, such as adequate inlet, deep zones, islands, etc., are recommended to reduce the need for high length to width ratio. Wetland shape, inlet/outlet locations, inlet/outlet type, island influence the hydrodynamics of the system. In a study of hypothetical water quality ponds (PERSSON 1999) a clear correlation was shown between the pond layout and the hydraulic efficiency (Figure 5).

$$t_{mean} = \frac{\int_0^\infty t f(t)dt}{\int_0^\infty f(t)dt}$$

Another fundamental expression is the variance, σ^2, which is a measure of the spread of the RTD. A plug flow condition will induce a RTD with a variance equalling 0 (i.e. no dispersion other than the advection).

$$\sigma^2 = \frac{\int_0^\infty (t_{mean} - t)^2 f(t)dt}{\int_0^\infty f(t)dt}$$

A common measure of the degree of plug flow is the number of stirred tanks (N) used in a tank-in-series model (Fogler, 1992). The higher N, the more plug-flow-like the flow is and also less mixed. Measures of N are

$$N = \frac{t_n^2}{\sigma^2} \qquad N = \frac{t_n}{t_n - t_p}$$

where t_n is the nominal detention time (which is defined by the ratio between volume and flow)and t_p is the peak time of the RDT.

However, to consider only the degree of plug flow is not sufficient, since the effective volume differs considerably between ponds; i.e. the mean detention time, t_{mean}, is less than the nominal detention time, t_n. The effective volume ratio, e, is defined by (Thackston et al., 1987)

$$e = \frac{t_{mean}}{t_n} = \frac{V_{effective}}{V_{total}}$$

where V_{total} is the total volume of the water system and $V_{effective}$ is the total volume minus the dead volume (i.e. volume of water that has no interaction with the water flowing through the system).

The factor hydraulic efficiency, λ, is sometime used as a total measurement of the hydraulic performance, varying from 0-1. It is a combination of the amount of mixing and the effective volume ratio (Persson et al., 1999). The efficiency is high when: a) the degree of mixing is low, which is preferable since all fluid elements reside around the nominal residence time and secondly since the removal rate of BOD and TN increases with the loading rate, and b) the effective volume ratio is high, since this gives a longer detention time for a given volume.

$$\lambda = e \left(1 - \frac{1}{N}\right) = \frac{t_p}{t_n}$$

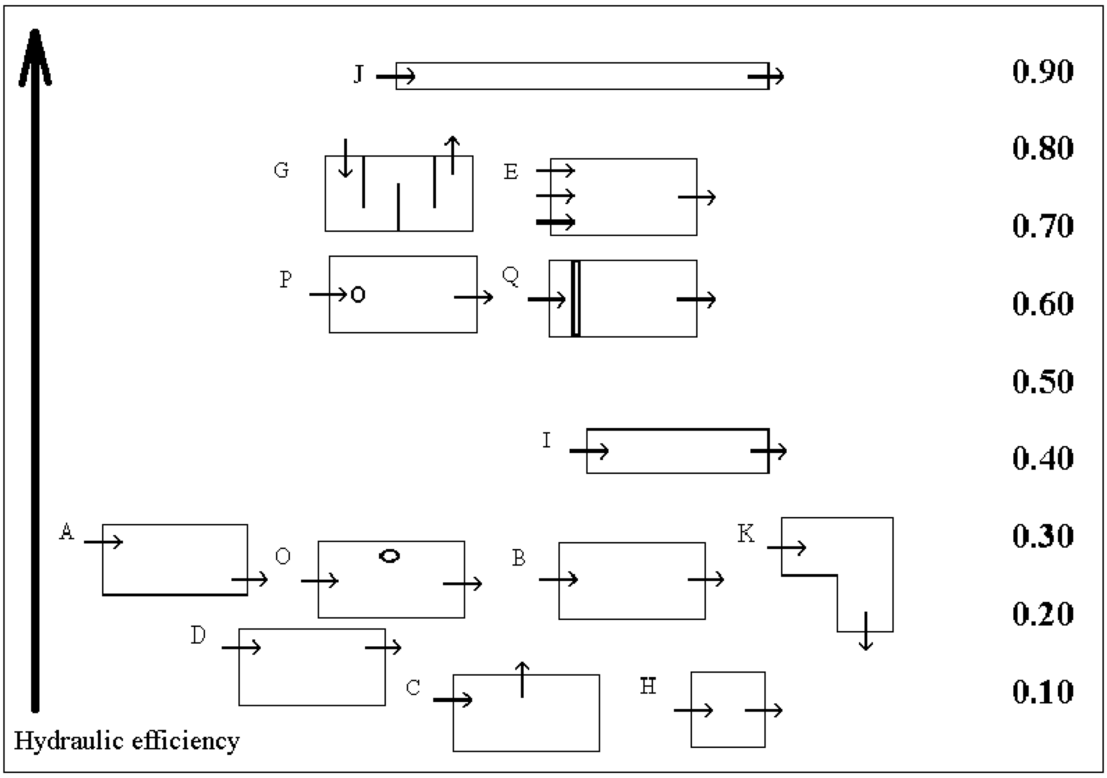


Fig. 5: Hydraulic efficiency for different shapes of wetlands

The aspect ratio of the macrophyte zone should range from 4:1 (length : width) to 10:1 (DLWC-NEW SOUTH WALES 1998).

Flow velocity

Flow linear velocity is another important design parameter. For instance TSS removal efficiency depends on sedimentation and trapping within the wetland. Excessive velocities can lead to large values of shear stress and to resuspension. It is recommended that velocity w be kept below a value which would resuspend 15 μm particles that settle at w=0.1 m/d in a 0.3 m deep flow of Manning's coefficient of 0.1 s/m$^{1/3}$ (KADLEC & KNIGHT 1996). This value is approximately u=1000 m/d, even if existing wetlands operate at a very safe velocity lower than this, mostly below 100 m/d. The presence of some higher velocity areas creates habitat diversity.

Drainage

Draining of the wetland can be important for many reasons: it aids establishment after planting, it allows supplementary planting if initial planting results in poor survival rates, it can be used to control weeds, particularly floating species; it can help in mosquito and fish management; it facilitates the reduction of erosion and solves other structural problems.

Drainage must be considered during design, and deep open water zones must be designed to provide a refuge for fish, invertebrates and frogs during draining periods and winter time.

Inlet zone

Inlet may consist of either a pipe structure or a channel and serve to provide a controlled entry of water to the wetland.

Inlet zone has to provide an effective flow distribution across the full width of the wetland entrance, in order to minimise short-circuiting and dead zones and maximise frictional resistance. In fact frictional resistance is higher when water spreads out over a large area, rather than being confined to a channel. When frictional resistance is high, velocity and potential erosiveness are lower. Water velocities less than 10 cm/s are recommended for wetland entrance zones if the bottom is not protected (MARBLE 1992). High water velocities also discourage plant growth.

Energy dissipation may be required for the incoming water to provide protection for the wetland inlet. Energy dissipation can be caused by gravity using riser pipe inlet or by resistance using rock energy dissipator and, in situation of low velocities, by vegetation.

There is a potential problem of algae growth on distribution system, so it is necessary to minimise light contact with the incoming water (e.g. use of riser pipes) and to design openings large enough to avoid obstruction by algae growth.

If the incoming water is not well oxygenated and contains a high level of organic nitrogen and ammonia, a zone of the wetland is necessary which allows oxygenation (open water, no vegetation, waves) to enhance nitrification before the macrophyte zone.

Inlet zones should provide access for sampling and flow monitoring. In the case of freezing, inlet water distribution must be kept below the ice layer. The slope of the bottom of the wetland in the inlet zone should be practically zero, thus assuring an equal water distribution.

If the inlet consists of a pipe structure, the header pipe material should be selected on the basis of required system life and cost. Inlet pipes have been made from a variety of materials including aluminium pipe, PVC pipe and ductile iron. The header pipe may be exposed to temperature extremes and ultraviolet radiation, so that PVC may have a limited life expectancy and may break. Aluminium pipe may dent and break. Ductile iron is strong and has a long life, but corrodes. Examples of wetland system inlet pipe configurations are shown in Figure 6.

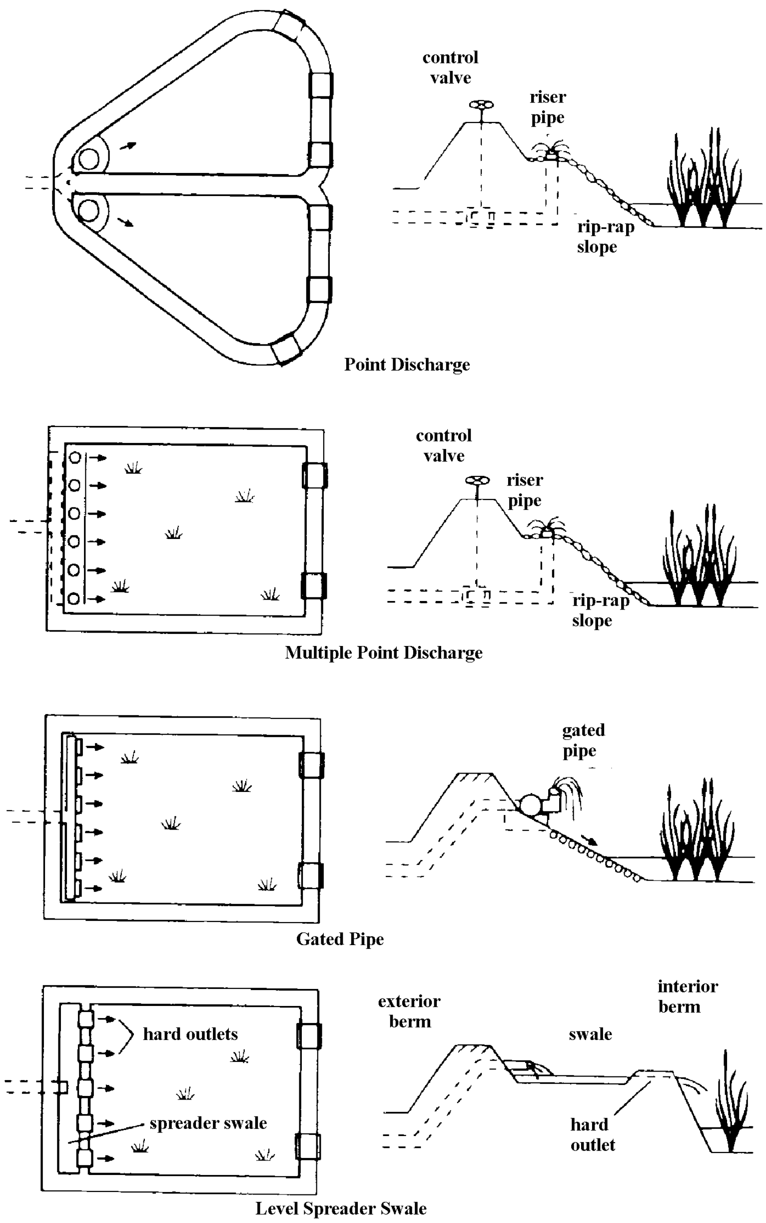


Fig. 6: Wetland treatment system inlet configuration alternatives (from KADLEC & KNIGHT 1996)

Islands

Islands can enhance hydraulic efficiency by diversion of the flow and in open water also provide visual and habitat variety. The size and shape of the island should be determined by the following (DLWC-NEW SOUTH WALES 1998):

- the flow conditions and characteristic of the wetland;
- the visual impact;
- according to the use of island as a flow diversion or wave energy dissipator.

The island should be greater than 25 square meters in size, and separated from the wetland's shoreline by permanent deep water (MARBLE 1992).

The islands surface should be 30 cm higher than usual water level, but if there are trees greater heights are recommended.

Islands can be expected to benefit waterfowl which can use the island for nesting, loafing and cover. In general, islands give protection to the wildlife from predators and humans.

Control of erosion will be critical; it is important that good vegetative cover is established right to the water's edge.

Habitat islands may have a beach area on at least one side to provide walk access for water fowl. It has to be morphologically protected by flow erosion and partially free from vegetation (using for example cobblestones as substrate).

Littoral zone

The littoral zone provides unique habitat within the wetland, as it is the interface between terrestrial and aquatic habitats. When constructed with gentle slopes, this zone provides excellent littoral habitat for plants, birds, macroinvertebrates and amphibians; there are some species of water birds that will only nest at the edge of wetlands. Littoral vegetation will protect the batters from water erosion through the binding action of the plant's root system on the soil. The littoral vegetation also serves to break up wave action, reducing its impact on the embankments.

The opportunities for habitat can be maximised by:

- constructing gentle slope;
- planting with diverse littoral species;
- incorporating sinuous edges to maximise the length of the littoral habitat. A constructed wetland designed to have an irregular upland/wetland edge can generally be expected to attract a greater abundance of waterfowl (more irregular upland/wetland edge means more territories for male waterfowl defence and so maximisation of waterfowls utilisation of space) and fish: an irregular edge provides more microhabitat and access to the marsh surface than a regular edge. Some authors (URESK & SEVERSON 1988) recommended a shoreline irregularity index[2] greater than 2, but it depends on the targeted wildlife species;
- keeping pathways and other pedestrian access points away from parts of the littoral area to provide safe wildlife habitat;
- creating beach areas which:
    - allow safe and stable access to the water's edge for recreational purposes;
    - break continuity of the edge;
    - provide feeding grounds for water birds.

Interspersion of vegetation and water and the length of shoreline are correlated directly with bird species diversity. Contact zones between water and vegetation provide cover for breeding waterfowls.

A well constructed littoral zone adds significantly to visual amenity and habitat potential.

[2] Shoreline irregularity index I is the shoreline length divided by the circumference of a circle with an area equal that of the wetland (WETZEL 1975) - for example a circle has I=1, a square has I= $\frac{2}{\sqrt{\pi}}$

Fetch and resuspension

Fetch is the maximum length of exposed water surface, in the direction of the wind, over which wind can blow unimpeded to generate waves. One of the most critical causes of erosion and sediment release is wind borne waves.

It is necessary to avoid a constructed wetland where fetch is long enough to generate a wave climate that will erode the bank. The wetland open water zones have to be located perpendicular to the dominant wind direction.

Resuspension is the process that takes a particle from the sediment and moves it in the water body.

The mechanism of resuspension in a wetland depends on several factors:

- energy delivered by the wind to the water surface depending on wind velocity U and on the fetch;
- waves, whose significant wave height H_s and significant wave period T_s depend on wind velocity and fetch;
- energy in the water, caused by circular eddies, which dissipates with depth: it exerts a shear stress τ at the bottom;
- type of sediment described by grain size and consolidation state that determine the critical shear stress τ_c.

In general, the greater the wind velocity and fetch, the greater the height and period of the resulting waves[3].

Minimal fetch and minimal exposure of the wetland to wind and wave action will discourage the resuspention and transport of sediments out of the wetland, acting to retain sediments for long period of time or indefinitely.

If selected site is exposed to a long fetch, the wetland should be located so that adjacent topographic relief or adjacent vegetation is sufficient to shelter the wetland from wind.

Vegetation

For role of vegetation, wetland morphology, biodiversity, hydraulic efficiency, shoreline stabilisation, primary production, organic carbon source for denitrification, water depth and irregular topography, plant species and planting see Vegetation Chapter.

In the design phase it is necessary to consider providing an access to vegetation that can be required for maintenance.

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[3]The amount of sediments ε scoured from the bottom can be calculated with $\varepsilon = 0$ if $\tau \leq \tau_c$. or $\varepsilon = (\alpha_0/t_d^2)(\tau - \tau_c)^3$ if $\tau > \tau_c$. where usual values for the costants are $\alpha_0=0.008$ and $t_d=7$. For shallow waters, where resuspension can easily mobilise sediments and pollutants, the shear stress can be approximated by $\tau = 0.003\ u^2$ where u is the velocity created by waves at the bottom (15 cm over the bottom). It can be generated by wind and also by currents in river bed. If we consider the first case, we can use the following formula to calculate it $u = (\pi H_s/T_s)/(100/\sinh(2\pi H_s/L)$ where L is wavelength. H_s, T_s, L can be estimated or calculated by complex formulas that can be found in specialised texts (CHAPRA 1997).

Ratio open water area/reed bed area

The ratio of open water area to reed bed area depends on objectives of water quality, habitat diversity and aesthetics/recreation.

Tab. 2: Objectives and considerations for wetland design.

Objective	Considerations
Water quality	reed beds are necessary for filtration, nutrient abatement and enhance sedimentation deep open water allows pathogen kill deep open water increases detention time and provide mixing: this can enhance removal processes open water allows oxygenation
Habitat diversity	open water areas are required for waterfowl landing open deep water areas are required for fish protection in dry and cold periods small meandered channels are required for fish movements into the wetland open water around islands are required for protection of fauna from predators and human disturbance reed beds provide macroinvertebrate habitat a balance of open water areas for waterfowls and reed bed areas for macroinvertebrates creates habitat diversity
Aesthetics/recreation	open water zones are good for viewing some reed beds are necessary for visual balance

The ratio of open water area to reed bed area is determined not only by defining objectives, but also by the importance of each objective relative to one other.

A ratio of 1 open water area to 3 reed bed is suggested to achieve a multi-objective design. But, if the most important objective is water quality, then a high ratio of open water to reed bed area (i.e. 1:5) should be selected. However, if habitat diversity is considered an important objective, then a lower ratio (i.e. 1:1) is required (table 3).

Tab. 3: Optimum ratio open water/reed bed for various water quality - habitat diversity - aesthetics/recreation objectives.

ratio	encouraged process	encouraged habitat	encouraged aesthetics/recreation aspect
1:6	filtration, nutrient transformation		
1:4		macroinvertebrate	
1:2	settling		
1:1	pathogen kill, reareation	waterfowl species	visual balance, viewing, passive recreation

Outlet zone

Wetland outlet design is important in avoiding potential dead zones (Figure 7), in controlling water level, for avoiding blocking and for monitoring flow and water quality.

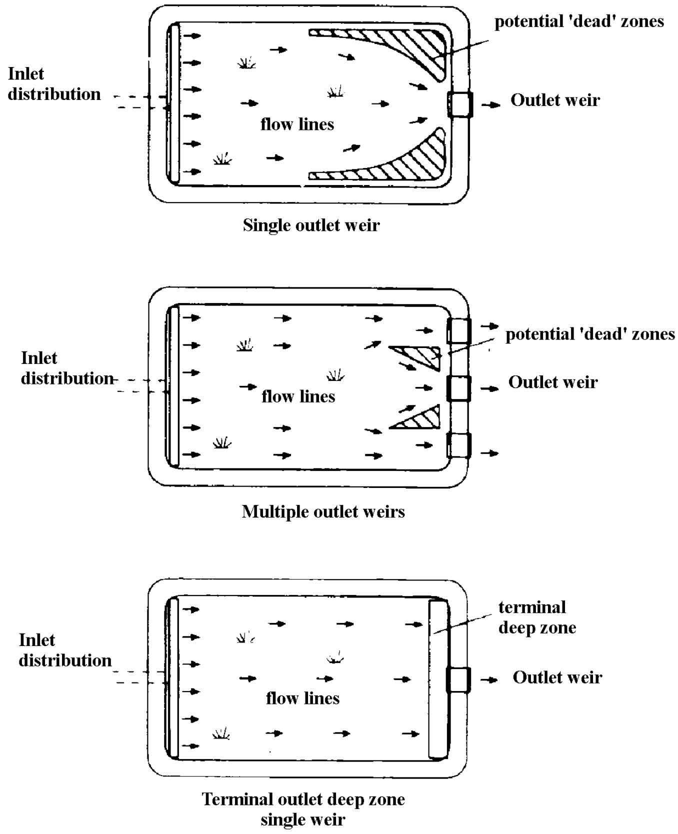

Fig. 7: Illustration of the effect of outlet design on flow distribution in constructed wetlands (from KADLEC & KNIGHT 1996)

A deep open water zone should be designed to collect and route flows to an outlet weir. This terminal deep zone must be kept as small as possible to discourage a long residence time and subsequent algae growth.

Outlet structures are sensitive to accumulation of debris, so a final filtering of algae biomass produced in the wetland is desirable to reduce biomass export: system configuration should include final filtration by aquatic plants. Other possibilities that can alleviate this problem are the use of a rock filter or of a large-mesh debris fence placed a meter or two from the outlet structure. The algae biomass has then to be removed and not to be left on the shoreline zone where overland flow can bring nutrients back into wetland water.

There are different types of structures that should be used to control water level within the wetland. The use of these structures depending upon the applicability of each structure to different situations and the objectives of the wetland (Figure 8, 9, 10, 11).

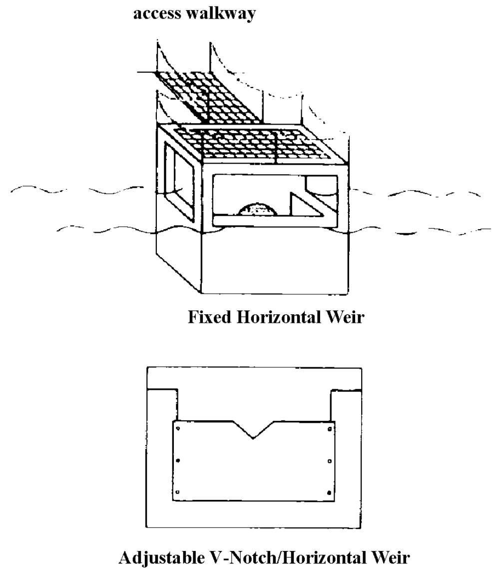

Fig. 8: Examples of wetland outlet weir designs (from KADLEC & KNIGHT 1996)

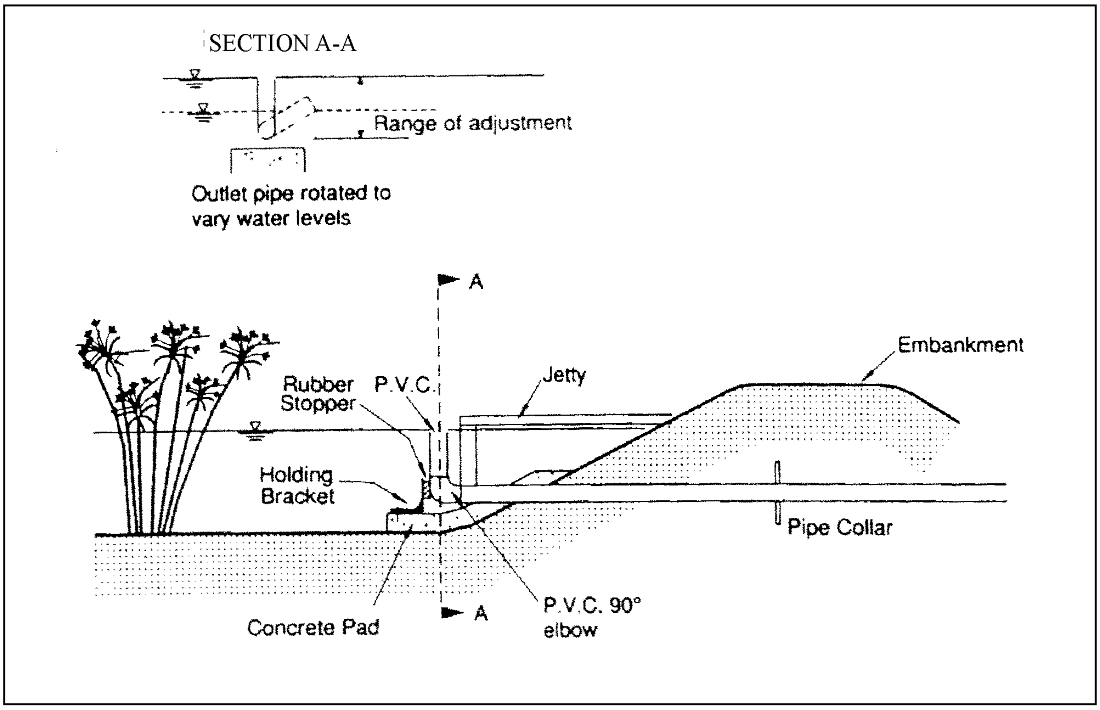

Fig. 9: Water level control structure - water level varied by swinging the PVC pipe (from DLWC - NEW SOUTH WALES 1998)

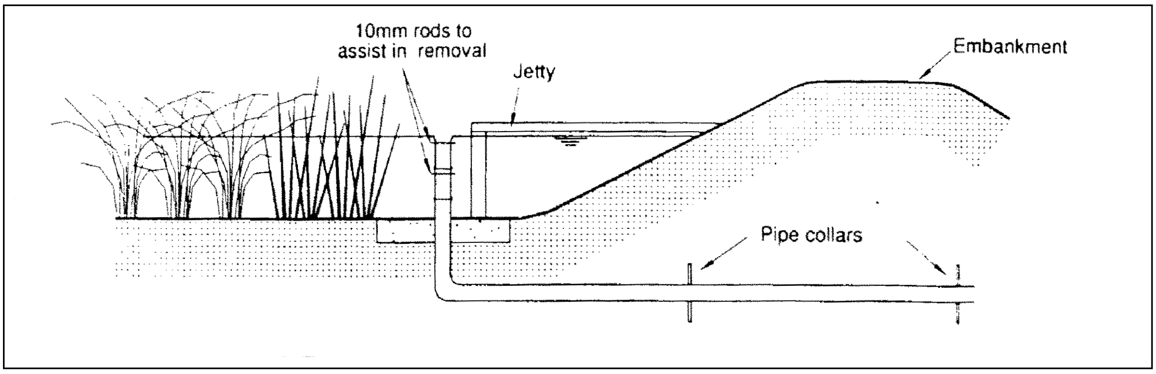

Fig. 10: Water level control structure - a number of individual pipes that fit together in a combination to obtain the desired water level (from DLWC - NEW SOUTH WALES 1998)

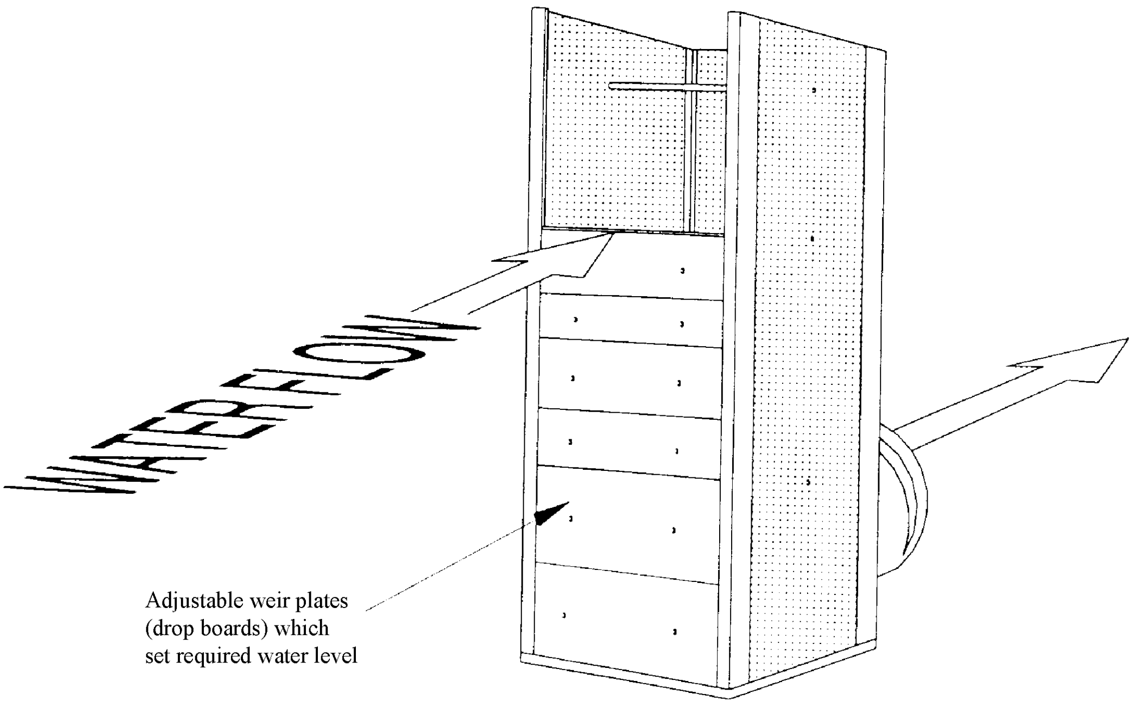

Fig. 11: Drop board water level control structure (from DLWC - NEW SOUTH WALES 1998)

The water level structure should be constructed in a weir or embankment. The embankment needs to be constructed with an impervious core to reduce seepage and to ensure stability.

6 Vertical profile

Stability of the bank

It is important to note that there is no standard slope which can be used as a guideline for determining stability. A determination of adequate slope for stability depends upon several factors (soil composition, soil erosivity, type of bank, wave climate and current velocity) and must be made based upon local site conditions.

The bank should not be perceived as an insuperable barrier: an environmental impact assessment has to be carried out.

Steep of water-land interface

The steeper the slope is, the more vulnerable the shore is to erosion.

- If the design includes a steep slope, the planned wetland could be ineffective at providing shoreline bank erosion control. It depends on the soil type, wave energy, water velocity, shoreline morphology, soil drainage system, and on presence and type of vegetation.
- Steep slopes can be used to provide open deep water and to encourage waterfowl to areas where they are most likely to be seen by people.
- The reed beds should have very gentle edge slopes ranging between 1V:6H and 1V:8H to provide shallow water for wetland processes (DLWC-NEW SOUTH WALES 1998); these slopes are also conducive to public safety.
- A gradual slope permits free movement for many waterfowl species which nest in and/or obtain food from adjacent upland areas (e.g. 1V:4H - 1V:6H (GREEN & SALTER 1987; PROCTOR et al. 1983; BARTOLDUS et al. 1994)).
- A gradual slope also maximises the amount of available shallow water habitat which is desirable for foraging and as habitat for potential food sources; e.g. invertebrates, fish, snails.
- A variety of slopes from the shoreline will provide a variety of habitats for water plants and animals.

Recommended minimum water/land slope is 1V:6H-1V:10H.

Variety of substrates

Where possible, a variety of substrates (e.g. sand, pebbles, clay) can be used to create variety along the shoreline, thereby providing different habitats for plants, aquatic macroinvertebrates and other animals.

Debris such as rocks, tree limbs, hollow logs should be placed in and around the wetland and on islands. These materials provide shelter for fish, aquatic invertebrates, insect, frogs, etc.

Shoreline vegetation

Shorelines are protected from erosion by the ability of wetland plants to reduce wave energy, bind the substrate, enhance slope stability and increase deposition by slowing the current; these plants also provide shading and cover for fish, are the source of detritus for invertebrates (fish food source), help regulate stream water temperature, minimise solar heating (algae blooms) and dry the bank.

For erosion protection rooted vascular aquatic beds, plant height, root structure and vegetation persistence are also important.

Macrophyte zone

The reed bed needs to be planted appropriately to maximise the performance of the wetland, increase its habitat value and enhance its visual amenity. The depth in the reed beds may vary from a minimum depth of 0.1 to a maximum of 0.5 m, with the optimum depth being 0.4 m (DLWC-NEW SOUTH WALES 1998). Different soil layers will increase vegetation layers and avian diversity, a good management of hydraulic level will also increase nitrification/denitrification processes. It is important that changes in bed elevation be constructed perpendicular to the flow to prevent channelisation. It is preferable for the reed bed to be flat.

Water flow and depth control

Water depth and flow rate are important factors affecting dissolved oxygen in wetlands. Higher flow rates in shallow water tend to result in higher dissolved oxygen concentration caused by atmospheric reaeration. These higher dissolved oxygen levels generally result in a higher presence of aquatic invertebrates and vertebrates.

Water depth is one of the main factors that affects wetland plant growth. High water levels will stress growth of emergent macrophytes and encourage dominance by floating or submerged plants or algae. Ideal design should allow water levels to be varied from zero to the maximum depth tolerance of desired plant communities.

Deep open water zone

Open water areas within constructed wetlands are necessary to enhance many of the natural processes that occur, including:

- reduction of stagnant areas by mixing by wind and temperature change in the water column;
- reduction of short circuiting by re-orienting flow paths,
- UV disinfection of bacteria and pathogens by sunlight,
- providing deep water habitat for birds, fish, invertebrates, frogs, etc.,
- creating a refuge during dry or drought times and during freezing periods,
- providing landing and safe areas for waterfowl,
- providing sedimentation of finer particles,
- improving the visual and recreational potential of the wetland system.

The depth of open water can be between 1.3 to 2.5 m (DLWC-NEW SOUTH WALES 1998).

The slopes for open water areas can be relatively steep, i.e. 1V:3H - 1V:5H (DLWC-NEW SOUTH WALES 1998). However if the open water component is placed directly adjoining a habitat island the slope can be gentler, i.e. 1V:5H - 1V:8H. This will enhance the habitat value of the islands by creating shallow waters for birds and macroinvertebrates.

Irregular topography and biodiversity

Irregular topography attracts more species because the diverse depths create different conditions that are compatible with the preferred feeding modes of a variety of bird species.

Some tables connect water depths with vertebrate species; they can provide a general guide for design, but it is recommended to consult local experts.

In Table 4 you can find an example of some habitat conditions that attract vertebrates to moist-soil impoundments and reclaimed gravel pits (BARTOLDUS et al. 1994).

Tab. 4: Habitat conditions that attract vertebrates to moist-soil impoundments and reclaimed gravel pits (from BARTOLDUS et al. 1994)

Moist-soil impoundments[a]												Reclaimed gravel pits[b]
	Foods					Openings		Vegetative cover				
Vertebrate group	Vertebrates	Invertebrates	Seeds	Browse	Water depth (cm)[c]	Water	Mudflat	Rank	Short	Dense	Sparse	Water depth (cm)
Amphibians		✓			0-20	✓	✓		✓		✓	
Reptiles	✓	✓			0-50	✓		✓	✓	✓	✓	
Grebes	✓				25+	✓			✓		✓	
Geese			✓	✓	0-10	✓	✓		✓	✓	✓	
Dabbling ducks		✓	✓		5-25	✓	✓	✓				30-200 with 30-70% of pit<60 cm deep
Diving ducks		✓	✓		25+	✓						60-240; average 100
Hawks	✓				NA				✓	✓	✓	
Galliforms		✓	✓		D-M			✓	✓	✓	✓	
Herons	✓	✓			7-12	✓			✓		✓	
Rails		✓	✓		5-30			✓	✓	✓		
Coots			✓	✓	28-33	✓			✓		✓	
Puddle ducks												30-180; average 45
Shorebirds		✓			0-7	✓	✓		✓		✓	<30 for 20% of pond when full
Owls	✓				D-M				✓	✓	✓	
Swallows		✓			NA	✓			✓		✓	
Sedge wrens		✓			NA			✓		✓		
Nesting passerines		✓	✓		NA			✓	✓	✓	✓	
Winter fringillids			✓		NA			✓	✓	✓	✓	
Rabbit				✓	0			✓		✓		
Racoon	✓	✓	✓		0-10	✓	✓	✓	✓	✓	✓	
Deer				✓	0			✓				
Muskrats and nutria												20-45

[a] source: FREDRICKS & TAYLOR 1982
[b] source: PAYNE 1992
[c] D-M = range dry to moist; NA = not applicable (use is not dependent on flooding or specific water depths)

It is always desirable to ensure that some areas of shallow water and some areas of deeper water are provided into the wetland. Landscapes with a diversity or complexity of components have a better visual impact and general appeal.

Access to the site

According to local safety laws, landscape design should include a diversity of open spaces which invite multiple use and experience of the site. Access should be provided for both able and the physically impaired people. Wheelchair access requirements include the incorporation of access at grades less than 1:10 (paths).

Suitable access shall be provided for maintenance machinery. It is recommended to create only one access track, to prevent machinery from accessing the site at a number of points and causing further disturbance. This track must have a stable surface in all weather conditions, be well-drained and have measures to control erosion. An access ramp must be at least 3.7 m wide and have slopes no steeper than 1:6 (DLWC-NEW SOUTH WALES 1998). Transitions shall be provided at the crest and toe of the ramp. Adequate space to manoeuvre machinery on and off the ramp shall also be provided.

Banks accessible to machinery should be at least 3 m wide.

Boardwalks can greatly enhance the recreational and educational benefits of a reconstructed wetland. Although public access to a created wetland might disturb wildlife populations, disturbances can be minimised with controlled access to certain areas and with design features such as islands for nesting (Figure 12)

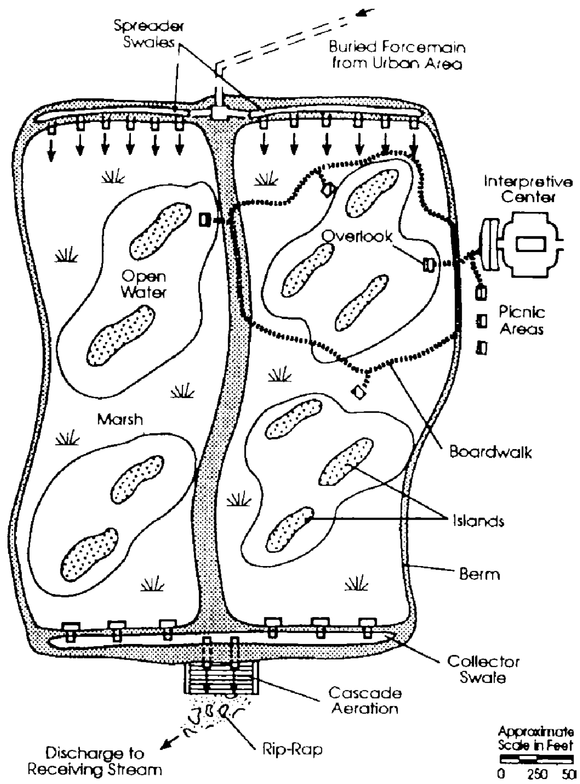

Fig. 12: Conceptual plan for treatment wetlands with ancillary benefits (from KNIGHT 1989)

Water level fluctuation

Severe fluctuation will have a negative effect: maximum daily water level changes of 30 cm do not seem to affect benthic communities (SMITH et al. 1981) but fluctuations grater than 90 cm will have adverse effects (FISHER & LAVOY 1972).

Water level management depends on the objectives of the wetland (water quality, flood control, wildlife, etc.).

7 Vegetation

Role of vegetation

Role of vegetation in re/constructed wetlands:

- roots and rhizomes provide oxygen to sediments; for *Phragmites* there are many values calculated with different techniques: 4.3 $gm^{-2}d^{-1}$ (LAWSON 1985), 0.02 $gm^{-2}d^{-1}$ (BRIX 1990), 1-2 $gm^{-2}d^{-1}$ (GRIES et al. 1990), 5-12 $gm^{-2}d^{-1}$ (ARMSTRONG et al. 1990);
- submerged parts of the plants provide support for biofilms which facilitate nutrient transformations and organic flocculation, provide filtration of pollutants, enhance sedimentation;
- emergent parts of the plants provide protection from the wind and shading which decreases water temperature and algae growth;
- vegetation increases biodiversity;
- provides a range of habitats for macro- and microfauna;
- provides visual contrast through different textures, sizes, shapes and colours.

The reed bed needs to be planted appropriately to maximise the performance of the wetland, to increase its habitat value and to enhance its visual amenity.

Wetland morphology

Wetland morphology is a major factor which determines the ability of macrophytes to exist. The wetland must be shallow, sheltered, soft-bottomed and unshaded to maximise macrophyte growth.

Wetland soil

With regard to vegetation propagation, soils with high humic and sand components are easier for the tuber runners to grow through, plant colonisation and growth are more rapid.

Vegetation diversity

In general policoltures are preferable to monocoltures. Monocoltures have a greater probability of weed invasion, destruction by parasites and incidence of disease.

Several forms of vegetation in a wetland are desirable, as they are a form of physical habitat, they provide diversity of food sources and consequently increase diversity of aquatic organism. A diversity of habitat conditions within the wetland will also create a diversity of wetland dependent birds.

Moderate shading enhances aquatic diversity in riverine wetlands. A moderate amount of shade should be provided to the wetland by partial vegetated cover on its banks.

Interspersion of vegetation and water and the length of shoreline are correlated directly with bird species diversity. Contact zones between water and vegetation provide cover for breeding waterfowls. Several vegetation classes are often required for food, shelter, nesting, lodging and predator protection by many species: integrated patches of different vegetation classes should be established.

The diversity of birds occupying a wetland is also related to the number of vertical layers in the wetland. Complexity of vegetation on the vertical axis generally increases the number of niches available for bird breeding, feeding and cover. Vegetation preferred by a desired waterfowl species should be included in a percentage of at least 10% of the wetland, with a minimum extension of approx. 1/2 ha.

Wetland vegetation provides fish a source of nutrients, protective habitat and temperature moderation through shading; but vegetation can also be detrimental when too dense: unvegetated channels, pools or other open water areas are needed for fish movement.

High temperature is a limiting factor for many aquatic organisms, it can be controlled by providing shade from overhanging vegetation, and also by deep pools and flowing water. These open water areas and unvegetated channels should be meandered and obviously avoid short circuiting and dead zones. The presence of some higher velocity areas creates habitat diversity.

Hydraulic considerations

The vegetation should not be so dense that it inhibits water circulation, but rather have a sufficient density high enough to be productive and capable of retaining drifting organic material. Mature wetlands have a reed density that range from 80 to 120 plants/m^2. These climax values are generally constant in all reed wetlands; differences in biomass between wetlands are due to single plant growth.

Dense wetland vegetation will act to slow water velocity, to force water to flow through a longer course, and act to retain it longer in the basin.

Extensive stands of vegetation offer frictional resistance to water flow enhancing sedimentation. The wider the stand of vegetation is, the greater the potential to encourage sedimentation. Dense vegetation also decreases the probability of sediment resuspention by wind or wave action.

Wetlands with dense stands of vegetation and with little open water are more capable of slowing flood water than open water alone. Increasing vegetation density increases channel roughness and the ability to retain floodwater.

Densely vegetated areas are more effective in treating pollutants than sparsely vegetated areas.

The aspect ratio of the macrophyte zone should range from 4:1 (length : width) to 10:1. Ratios less than 4:1 may cause short circuiting.

Bands of the same species of macrophyte should be planted in the perpendicular direction of water flow: this will reduce the risk of preferential flow paths. In fact, different aquatic plants may have different resistance to water flow.

Shoreline stabilisation

Persistent emergent vegetation will provide shoreline stabilisation by offering frictional resistance to waves and by binding the soil within its roots.

Trees planted in a bank may cause future bank failures. The weight of trees may offset any advantage provided by root system.

Trees and vegetation can be used as wind fences if the fetch is too long.

Primary production

Wetlands are highly productive biological systems because of their export of large amounts of organic material.

Primary productivity is higher in wetlands with flowing water and sheet flow; however, high water velocities discourage plant growth. Primary productivity is higher in water with a pH between 6 and 8.5; surface waters usually range in this interval of pH.

The range of net production rates in natural wetlands which are not subject to anthropogenic nutrient enrichments vary from 50 g/m^2/year in arctic tundra to 3500 g/m^2/year in southern marshes. Most temperate freshwater marshes have net primary production rates of 600 to 3000 g/m^2/year (KADLEC & KNIGHT 1996).

As wetland plants mature and die, they form organic detritus. This is a source of organic carbon that is used as substrate by microorganisms whose activities influences many of the water quality treatment functions. The organic detritus that is typical of a mature wetland requires from 1 to more than 5 years to develop (KADLEC & KNIGHT 1996).

Organic carbon source for denitrification

Bulrush is a poor choice for denitrification wetlands. The physical structure of the bulrush hinders its rate of transfer to the water column. Floating and submersed plants will provide a more readily available organic carbon source to denitrifiers. Cattail plants appear to overcome their slow decomposition rates by being highly productive and introducing litter into the water column rapidly.

We recommend that a mixture of floating, submergent and emergent macrophytes and grasses be promoted and maintained in free-surface wetlands for nitrate removal.

Water depth and irregular topography

Various management tools can be used in wetlands to encourage or maintain vegetation types. Water depth manipulations and irregular topography in the bed surface can be used to moderate or encourage colonisation rates and select for specific vegetation communities.

Water depth should never exceed 50% of plant height in the growing period.

Plant species

Wetland plant species selection should consider: expected water quality, normal and extreme water depths, climate, latitude, maintenance requirements and objectives of the wetland. There is no evidence that treatment performance is different among the common emergent wetland plant species (KADLEC & KNIGHT 1996). Decisive selection criteria are growth potential, survivability, cost of planting, cost of maintenance. Plant species that provide structure for the whole year perform better than species that die below the water line for cold temperature. For these reasons, fast-growing emergent species that have high lignin contents and that are adapted to variable water depths are the most ideal for re/constructed wetland. Wetland plants which more successfully meet these criteria include *Phragmites*, *Typha* and *Scirpus* (KADLEC & KNIGHT 1996).

Planting

The establishment of vegetation is crucial to the success of the wetland. Planting itself may not be required, when natural re-vegetation and colonisation of plant establishment can be relied upon.

If the wetland is to be planted, the cost and availability of plant materials must be considered early in the design process. The possibility of establishing an onsite wetland plant nursery must be decided very early, as mature 1- to 2-years-old plants are preferred (KADLEC & KNIGHT 1996). These have the energy reserves to survive the transplanting operation. Consequently, the establishment of the nursery must be completed before other construction operations begin.

Another option is to allow natural regrowth of the wetland basins. In warm-tropical climates, this process is complete within one growing season; two or more seasons in cold-temperate climates maybe required. In all cases, the option of transplanting will accelerate the establishment of vegetation.

The provision of a suitable substrate follows basic horticultural principles, i.e. plants need support, ability for downward root growth and nutrients. Usually, the base of the wetland is too well compacted to allow plant root growth and may also lack nutrients. Therefore substrates (minimum depth should be 25 cm) need to be provided for planting. The most convenient option is if the substrate can be used from the wetland construction site: the substrate material should be stockpiled and protected against erosion for later replacement in the wetland.

Substrates imported to the site should be tested for their ability to support plant growth, for the presence of contaminants and their ability to adsorb nutrients. The use of substrate material with weed seeds should be avoided. The placed substrate should be levelled, but not be compacted. A pre-flooding phase should be managed to allow the substrate to settle, and then re-grade. The wetland should be drained in order to avoid mosquito habitats.

The least time intensive method of planting is to place young plants into damp or dry soil and irrigate after planting. Sometimes, however, planting into wet mud or shallow water may be the only practical way.

Wetland vegetation establishment is most rapid when plants are closely spaced, less than 1 m on centres, and planted during the growing season (LEWIS & BUNCE; 1980; BROOME 1990)

In dry conditions the plants need to be irrigated within a few hours of planting. Subsequent irrigation will vary according to each site. If planting takes several days or weeks, plants will need to be irrigated frequently.

Shallow planted areas of the wetland should be constructed so that they can drain completely. Draining of the wetland can be important for many reasons: it facilitates for plant establishment after planting; it allows supplementary planting if initial planting gives poor survival rates; it can be applied as a form of weed control, particularly floating species; it can assist mosquito and fish management; it facilitates erosion control and other structural problems.

For water management following planting, see the management chapter.

8 Management

Mosquito control

Mosquito control provisions include use of biological controls, encouragement of predators, stocking with mosquitofish, maintenance of aerobic conditions, and avoidance of dead zones.

Mosquito problems in wetland systems are primarily caused by excessive organic loading (STOWELL et al. 1985; WILSON et al. 1987; MARTIN & ELDRIDGE 1989; WIEDER et al. 1989). High organic loading reduce dissolved oxygen levels, limiting the effectiveness of natural aquatic predators such as mosquitofish (*Gambusia affinis*) and aquatic insects (dragonfly and damselfly larvae and beetles). Thick stands of surface vegetation may also limit the access of predatory fish to mosquito larvae.

Using mosquitofish to control mosquito populations is relatively easy in reconstructed wetlands as long as perennial flooded areas exists and highly anoxic conditions are avoided (STEINER & FREEMAN 1989; MARTIN & ELDIDRGE 1989; DILL 1989). Deep water zones provide refuge for fish and other aquatic organisms during fluctuating level conditions and cold weather (KNIGHT & IVERSON 1990).

Mosquito larvae and mosquitofish populations in wetlands should be monitored regularly to determine the need for restocking or other operational controls.

Odours

Wetland systems typically operate without problematic odour levels (KADLEC & KNIGHT 1996). Compounds producing odours are typically associated with anaerobic conditions. The extents of these anaerobic areas is largely dependant upon BOD and ammonia nitrogen loading and the hydrogen sulphide produced. The potential for nuisance odour conditions can be reduced by reducing loading of these oxygen-demanding constituents and by interspersing aerobic pools or channels between wetland components. Cascade outfall structures and channels provide an opportunity to dissipate residual odours before they reach nuisance conditions.

Monitoring

Monitoring is one of the most important aspects for wetland operation and provides much important information (DAVIDSSON et al. 2000). Monitoring of inflow and outflow water quality provides an indication of wetland health and performance; monitoring of the internal wetland structure provides a reference for correlating changes in water quality performance with system structure; monitoring of wildlife and vegetation provides an indication of wetland ecosystem. Routine monitoring and data analysis are essential in reaching decisions concerning control of operational variables such as water depth and hydraulic loading. Additional monitoring may be performed to accomplish specific operational goals.

Typically, the only system controls available are variation of inflow hydraulic loading and control over water levels within the wetland. They have influence on detention time, water velocity, inundated areas, vegetation state; these variables have influence in turn on water quality and ecosystem health.

Hydraulic detention time

Of great importance in the monitoring and in the analysis of wetland processes are hydraulic nominal detention time and hydraulic detention - or residence - time distribution (RTD).

Hydraulic nominal detention time at steady state is defined by

$$\tau = \frac{V}{Q} = \frac{\varepsilon A h}{Q}$$

where:

τ = nominal detention time, d,
V = wetland water volume, m^3;
Q = water flow rate, m^3/d;
A = wetland area (wetted land area), m^2;
h = mean water depth, m;
ε = water volume fraction in the water column (wetland porosity), m^3/ m^3.

There is obviously a possible ambiguity that results from the choice of the flow rate that is used in this equation. The inlet flow rate is often used when there are no measurements or estimates of the outlet flow rate. Given the exit flow, some authors base the calculation on the average flow rate (inlet + outlet divided by 2). When there are local variation in total flow and water volume, the correct procedure must involve integration of transit times from inlet to outlet (KADLEC & KNIGHT 1996).

The porosity of the wetland (ε) is the fraction of the volume available for water to flow through. Wetland porosity has proven difficult to be accurately measured in the field. As a result, wetland porosity values reported in literature are highly variable. REED et al. (1995) and CRITES and TCHOBANOGLOUS (1996) suggest wetland porosity values ranging from 0.65 to 0.75 for vegetated wetlands, with lower numbers for dense, mature wetlands. KADLEC and KNIGHT (1996) report that average wetland porosity values are usually greater than 0.95, and ε=1.0 can be used as a good approximation. GAERHEART (1997) found porosity values in the range of 0.75 in dense mature portions of the Arcata wetland. For design a porosity value should be used which is based on a weighted value of open water zones to vegetated zones.

Nominal detention time is not necessarily indicative of the actual detention time because it is based on the assumption that the entire volume of water in the wetland is involved in the flow. This can be an error, and result in measured detention times that are much smaller than the nominal value.

The RTD represent the time that various fractions of water spend in the wetland; hence it is the contact time distribution for the system. RTD is the probability density function for residence times in the wetland. This time function is defined by:

$f(t)\Delta t$ = fraction of the incoming water which stays in the wetland for a length of time between t and $t+\Delta t$

where f = RTD function, 1/d and t = time, d.

The RTD function may be measured by injecting an impulse of dissolved inert tracer material (LiCl for example) into the wetland inlet and then measuring the tracer concentration as a function of time at the wetland outlet.

As the residence time distribution RTD is the probability density function for residence times in the wetland, the tracer detention time (τ) is the average time that a tracer particle spends in the wetland and is the first moment of the RTD.

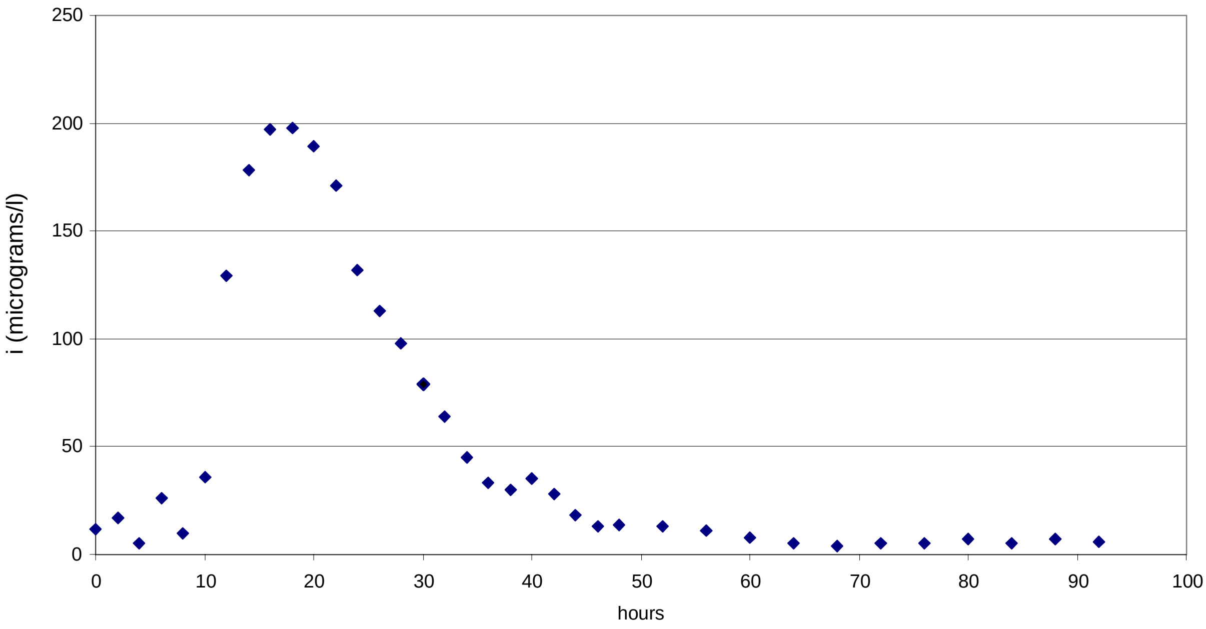

Fig. 13: Example of results of a tracer study (Castelnovo Bariano pilot wetland, Italy, January 2000)

Wetland hydrology

Water enters natural wetlands via streamflow, runoff, groundwater discharge and precipitation (Fig. 14). Wetlands lose water via streamflow, groundwater recharge and evapotranspiration.

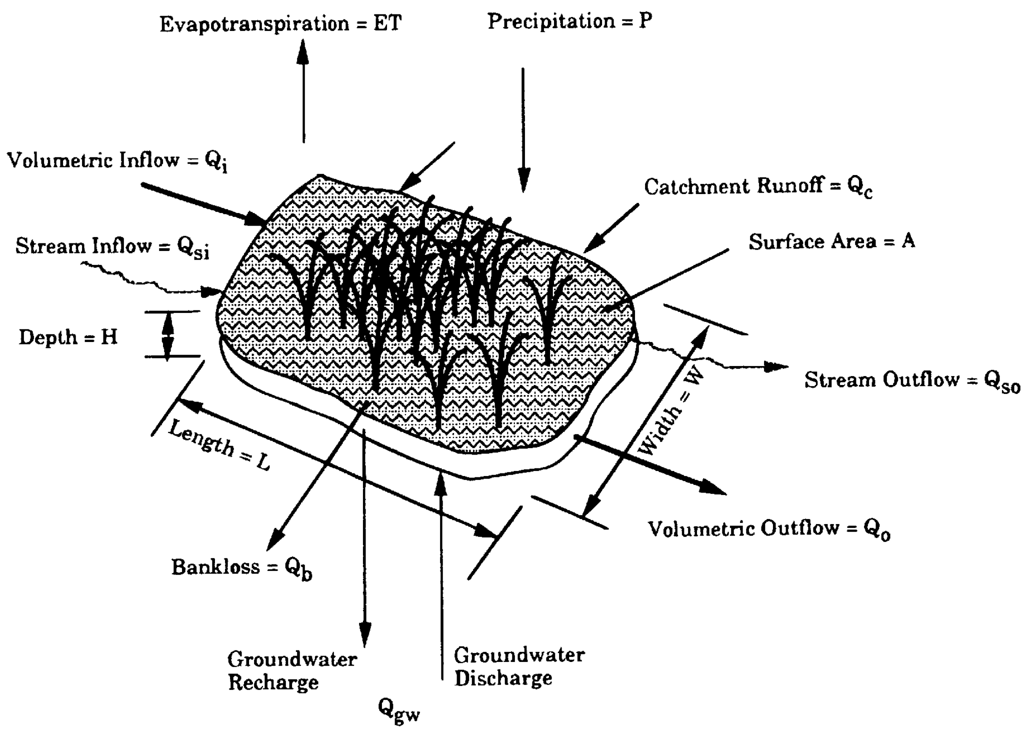

Fig. 14: Components of the water budget and associated terminology (from KADLEC & KNIGHT 1996)

The dynamic water budget for a wetland is:

$$Q_i - Q_o + Q_c - Q_b - Q_{gw} + Q_{sm} + PA - ETA_v - E(A - A_v) = \frac{dV}{dt}$$

where:

A = wetland surface area, m^2;

A_V = wetland vegetated surface area, m^2;

ET = evapotranspiration rate, m/d;

E = evaporation rate, m/d;

P = precipitation rate, m/d;

Q_b = bank loss rate, m^3/d;

Q_c = catchment runoff rate, m^3/d;

Q_{gw} = infiltration to groundwater, m^3/d;

Q_i = input flow rate, m^3/d;

Q_o = output flow rate, m^3/d;

Q_{sm} = snowmelt rate, m^3/d;

t = time, d;

V = water storage volume in wetland, m^3.

Water level and flow control

Water level and flow control is often the only significant operational variable available to influence the performance of pollutants removal in the wetland.

Water level affects hydraulic residence time, atmospheric oxygen diffusion, plant cover, water temperature, light diffusion, sedimentation processes, wetted areas.

Water flow rate affects hydraulic loading, pollutants loading, hydraulic residence time, water velocity, longitudinal gradients in water elevation.

During summer periods when water temperatures are elevated, possible oxygen saturation is lower and plant productivity is at its highest, water levels should be lowered to promote better oxygen diffusion to the sediments, plant roots and treatment microbial communities.

During freezing periods water levels should be reduced by lowering the downstream water level control structure so that water will flow freely under the insulating cover of ice and snow.

Waterfowl usually use islands for nesting: at the beginning of the nesting period the water level has to be kept high, so that birds build their nests in higher positions. This allows future water level fluctuation possibilities, even during the nesting period, without the hazard of submerging nests.

Shallow planted areas of the wetland should be constructed so that they can drain completely. Fluctuating water levels create more ecological niches and result in higher wildlife species diversity. Because many wildlife species are attracted to wetlands with perennial water, less frequently flooded areas generally will have lower populations of wetland wildlife.

Drastic water level fluctuations can cause severe erosion and should be avoided. The velocity of level fluctuation has to be slow enough as to permit migration for the benthic fauna.

Deposits of mineral sediments entering a wetland through erosion can smother plant roots, especially wetland tree species. Dense clay soil may also contribute to severely reduced oxygen diffusion rates at the root zone.

Water level management after planting

Following planting the wetland water level will need to be controlled to prevent young plants from being desiccated due to lack of water, or suffocated by excessive water levels (table 5).

Tab. 5: Water level management after planting (DLWC-NEW SOUTH WALES 1998)

Time frame	Water level management activities
Initial months	Once planting is completed and the soil saturated, the reed bed should be drained completely and left like this for two weeks to one month, ensuring that there is always adequate sub-surface moisture by occasional flooding.
First year	Water depth should generally not exceed 20 cm in the deepest planted section during the first year. It may be that in irregular or sloping wetlands some areas of the reed-bed may be no more than 5 cm deep.
Second year	During the second year of growth, water depths should be increased to 20-40 cm, interspersed with weeks of shallower depths and a few weeks of complete draining. Therefore, water levels can be maintained up to 400 mm in the deeper planted parts. Water levels can be deeper for short periods when combined with a draining phase during the year.

Managing water depths this way will increase diversity and improve establishment success. During plant establishment the wetland should be checked regularly for plant health and weed invasion.

Vegetation harvesting

The usefulness of plant harvesting in wetlands depends on several factors, including climate, plant species and the water quality objectives. Many authors agree upon the fact that harvesting is not important in nutrient removal (KELMAN WIEDER et al. 1989; BRIX 1994) and is not recommended (REED et al. 1988; CRITES 1994).

The uptake capacity of emergent macrophytes, and thus the amount that can be removed if the biomass is harvested, is roughly in the range 50 to 150 kg P ha^{-1} $year^{-1}$ and 1000 to 2500 kg N ha^{-1} $year^{-1}$ (BRIX 1994). However, the amounts of nutrients that can be removed by harvesting is generally insignificant compared to the loading into the constructed wetland with the incoming water (BRIX 1994).

Harvesting of the emergent vegetation is only required to maintain hydraulic capacity, to promote active growth and to avoid mosquito outbreak.

Storm and flood management

Wetlands should be inspected as soon as practicable after a storm or flood event. Repairs of damage to wetland should be carried out and litter removed.

During flood periods most mature plants will be able to survive for a 1-2 weeks period of inundation (DLWC-NEW SOUTH WALES 1998). If areas of plants are lost, re-establishment should be carried out. Small areas will generally recover naturally, larger areas may require re-planting. If erosion has occurred, the wetland substrate may require replacing before re-planting.

Litter management

Debris may accumulate on grates or throughout the wetland. If optimum hydraulic and water-quality performance is to be maintained, the debris should be removed periodically and immediately after storm events. Litter removal will also enhance the wildlife habitat and scenic amenity.

Animal pests

Some fishes, e.g. carp, can cause high turbidity and affect wetland performance. Draining of the wetland can facilitate the collection of carp. Some birds can cause problems by foraging on seedlings. This can lead to problems during plant establishment. Nutrias and muskrats, which can form tunnels on the banks, can cause problems to the stability and hydraulic impermeability of the banks.

9 Suggested books

- U.S. Environmental Protection Agency, **Design Manual: Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment**, EPA, 1988, pp.83. It is one of the first wetland design manuals.
- Donald A. Hammer, **Constructed Wetlands for Wastewater Treatment**, Lewis Publishers, 1989, pp. 831. The volume consists of the proceedings from the first International Conference on Constructed Wetlands for Wastewater Treatment held in Chattanooga in 1988.
- IAWPRC, **Constructed Wetlands in Water Pollution Control**, Pergamon Press, 1990, pp. 605. The volume consists of the proceedings from the International Conference on the Use of Constructed Wetlands in Water Pollution Control, held in Cambridge in 1990.
- Anne D. Marble, **A Guide to Wetland Functional Design**, Lewis Publishers, 1992, pp. 222. It is a conceptual approach to wetland design from a functional standpoint based on the Wetland Evaluation Technique (WET) which is used to determine the relative values of existing wetland functions. Site selection and site design features for wetland replacement are described for nutrient removal/transformation, sediment/toxicant retention, shoreline stabilisation, floodflow alteration, ground water recharge, production export, aquatic diversity/abundance, and wetland dependent bird habitat diversity. The design of multiple functions is also discussed.
- Gerald A. Moshiri, **Constructed Wetlands for Water Quality Improvement**, Lewis Publishers, 1993, pp. 632. The volume consist on the proceedings from the Constructed Wetlands Conference held in Pensacola, Florida in 1993.
- U.S. Environmental Protection Agency, **Created and Natural Wetlands for Controlling Non-point Source Pollution**, EPA, 1993, pp. 216. It is a collection of 11 papers on this topic.
- Candy C. Bartoldus, Edgar W. Garbisch and Mark L. Kraus, **Evaluation for Planned Wetlands**, Environmental Concern Inc., 1994. It provides a wetland assessment procedure

that can be used in wetland creation, restoration, mitigation banking, impact analysis and watershed planning.

- Carl Hawke and Paul José, **Reedbed Management for Commercial and Wildlife Interests**, The Royal Society for the Protection of Birds, 1996. It is an exhaustive and complete book about reeds and reedbeds: planning for management and creation, management and rehabilitation, reedbed creation, case studies.
- H. Kadlec and R. L. Knight, **Treatment Wetlands**, Lewis Publishers 1996, pp.893. It is an exhaustive and complete book about wetland treatment systems (WTS), the first book that collected together all information about WTS: wetland structure and function (landform and occurrence, wetland soils, hydrology and water quality, microbial and plant communities, wildlife), water quality processes (hydraulic and chemical design tools, temperature, oxygen and pH, suspended solids, BOD, Nitrogen, phosphorous, other substances, organic compounds, pathogens), wetland project planning and design (wastewater source characterisation, wetland alternative analysis, surface-flow wetland design, subsurface-flow wetland design, natural wetland systems, ancillary benefits of wetland treatment systems), WTS establishment, operation and maintenance, wetland data case histories (WTS inventory, treatment wetland case histories).
- Department of Land and Water Conservation New South Wales, **The Constructed Wetlands Manual,** DLWC - New South Wales, 1998, pp. 222. It is a complete manual about constructed wetlands (CW) made by Australian researchers. **Volume 1**: background (systems approach to CW, chemical, biological and physical processes in CW), planning (planning considerations, legislative framework, community involvement), investigation and management issues (site and catchment investigations, soils for plants and construction, wetland plants, surface water quantity and quality, groundwater and hydrogeology, public health and safety, mosquito risk assessment and management, blue-green algae and its control). **Volume 2**: design (concept development and detailed concept design, design of urban stormwater wetlands, design of wastewater wetlands, design of habitat wetlands, wetland rehabilitation, design of farm dam wetlands, design of wetlands for recreation and visual amenity, detailed component design), construction (construction planning and management, planting, erosion and sediment control), operation and maintenance (operation, maintenance and monitoring, weeds and noxious plants).
- R. H Kadlec, R L Knight, J Vymazal, H Brix, P Cooper, R Haberl, **Constructed Wetlands for Pollution Control - Process, Performance, Design and Operation,** IWA Publishing, Alliance House, London UK, 2000, pp. 164. This book presents a comprehensive up-to-date survey of wetland design techniques and operational experience from treatment wetlands. It is a synthesis of information related to constructed treatment wetlands. Types of constructed wetlands, major design parameters, role of vegetation, hydraulic patterns, loading, treatment efficiency, construction, operation and maintenance costs are discussed. History of the use of constructed wetlands and case studies from various parts of the world are also included.

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