WRP Technical Note WQ-SW-3.1
May 1994

Design of Constructed Wetlands Systems for Nonpoint Source Pollution Abatement

PURPOSE: This technical note describes some basic considerations for design of constructed wetlands for controlling nonpoint source (NPS) pollution. A design sequence for constructed pollution abatement wetlands systems for NPS pollution is presented. Critical elements in the design sequence are identified. This technical note should be used as a conceptual design guide and in conjunction with other guidance provided in WRP Tech Notes HS-EM-3.1, HY-EV-5.1, HY-IA-5.1, HY-RS-3.1, SG-RS-3.1, VN-EM-3.2, WQ-EV-2.1, and WG-RS-3.1.

BACKGROUND: NPS pollution originates from rainfall/runoff events on agricultural and urban areas. Because rainfall/runoff events are stochastic processes that can be highly episodic in character, hydraulic and pollutant mass loadings associated with nonpoint source pollution are extremely variable. Most treatment systems designed for point source discharges are ineffective for NPS pollution because they cannot handle wide fluctuations in hydraulic loading and perform poorly when there are large fluctuations in pollutant loadings. Wetlands, on the other hand, dampen extremes in flow and pollutant loadings by storing water. In addition, wetlands have intrinsic abilities to retain, transform, and degrade a wide spectrum of waterborne pollutants (Mitsch and Gosselink 1986; Hammer 1990). Constructed wetlands located to intercept runoff, therefore, have potential for reducing NPS pollution.

ENVIRONMENTAL ENGINEERING DESIGN: Constructed Pollution Abatement Wetlands Systems (CPAWS) are vegetated water retention facilities designed, constructed, and operated to treat pollutants using physical, chemical, and biological processes intrinsic to wetlands. Successful CPAWS design for NPS pollution abatement differs from CPAWS design for point source pollution in that average flows and pollutant concentrations do not provide a sound basis for design. The basic problem is to capture and spread high flow, high contaminant concentration runoff in a wetland and retain the water long enough for wetland biogeochemical processes to degrade or remove pollutants. A quasi-theoretical design approach that combines empiricism with simplified theory is recommended. This approach is based on first order process kinetics described by Reed (1990), Rogers and Dunn (1992) and Dortch (1993). The design sequence (Fig. 1) includes the following elements.

- Target Pollutants and Design Flows. Successful design of CPAWS requires development of the proper hydraulic and biogeochemical conditions to remove pollutants of concern. Therefore, the first step in the design process should be identification of pollutants to be treated and the design storm or flow. Pollutants can be targeted based on sampling inflow, review of available data on water quality problems in the receiving water body, or evaluation of land uses and probable constituents in runoff. Different pollutants may require different designs. For example, herbicides require a longer retention time for removal than suspended solids. The design flow can be selected or determined from the design storm event. Two types of events are important, the maximum event to be treated and the extreme event the wetland must survive. The maximum event determines the size of the wetland and associated control structures. The extreme event determines the size of emergency flow structures. Selection of the appropriate event will depend on the project. Costs, target treatment, and available land are some factors to be considered in the selection.

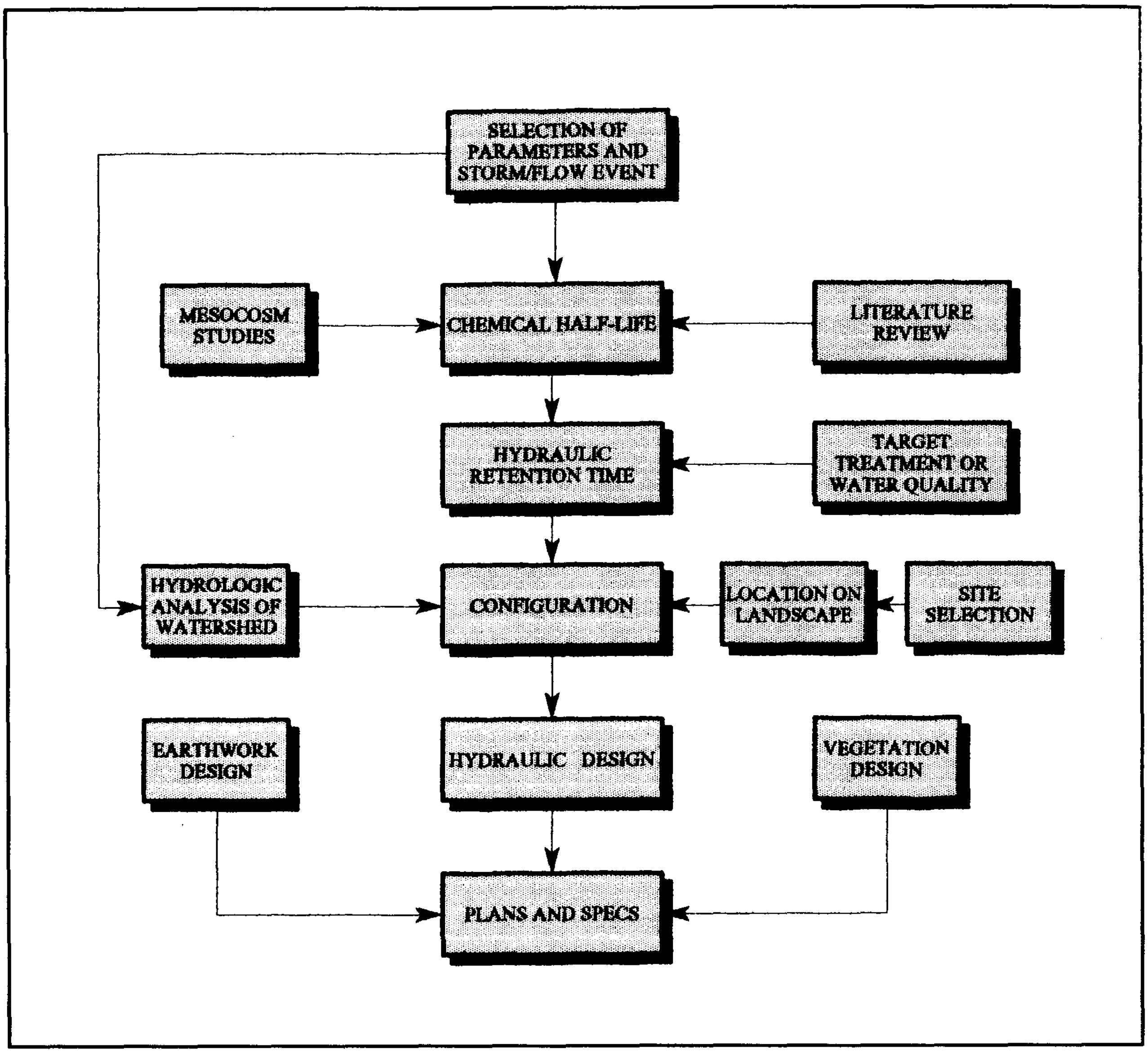

Figure 1. Design sequence for constructed pollution abatement wetland systems

- Chemical Half-life. Application of first order process kinetics to wetlands involves an overall disappearance coefficient. First order disappearance coefficients can be expressed as chemical half-lives. Thus, one of the first steps in design is to estimate the half-life applicable to wetlands. This half-life is chemical dependent and is anticipated to vary with wetlands characteristics, such as vegetative cover, vegetation type, climatological conditions, and other factors. Literature values for chemical half-lives can be unreliable for CPAWS design because few of the available data were developed from wetlands studies. Wetlands specific removal efficiencies are available for nutrients, metals, and some other water quality parameters, but in many cases the corresponding hydraulic retention times are not available (Phillips et al. 1993). Both parameters are needed to obtain disappearance coefficients. Experimental wetlands mesocosm studies can be conducted that provide half-lives for specific chemicals and wetlands characteristics (Doyle, Myers, and Adrian 1993).

- Hydraulic Residence Time (HRT). As indicated in Figure 1, chemical half-life determines the HRT required to meet a target level of treatment. The HRT then becomes the basis for hydraulic design. HRT is the average time required for a parcel of water to pass through a wetland. If the design HRT is not achieved, the design level of treatment will not be achieved. The theoretical HRT of an idealized system is defined as

$$HRT = \frac{V}{Q}$$

where V is the volume of the wetland and Q is flow. However, this definition implies that the entire cross-sectional area is included in the flow and each parcel of water remains in the system for the same amount of time. This is seldom true or even approximately true for wetlands. Irregularly shaped, vegetated wetlands subjected to a variety of flow conditions tend to form channels that reduce effective HRTs to values substantially less than theoretical HRTs. This is commonly referred to as "short-circuiting". Designing the system to reduce or eliminate channels and maximize vegetative cover will spread flow, reduce short-circuiting, and increase effective HRT. Kadlec (1989) and Reed (1990) proposed methods to calculate HRTs for CPAWS used to treat wastewater streams. These methods adjust the HRT to account for the effects of vegetation. Kadlec (1989) also described techniques to account for rainfall and evapotranspiration, which can be important when dealing with relatively small flows. Potentially more important considerations for CPAWS used for NPS pollution abatement are selecting an appropriate storm event and routing flow through the wetland. A detailed hydrologic and flow routing study should be conducted for any project which entails significant expenditures.

- Configuration. After the design HRT has been determined, a wetlands configuration is chosen. A variety of wetlands configurations ranging from a single wetland to several wetlands in parallel or series or distributed over a landscape are possible (Fig. 2). In many cases, configuration is primarily a matter of land availability. For distributed CPAWS, a HRT should be calculated for each wetland. Since wetlands are shallow, total wetlands area is usually the design parameter adjusted to provide the needed HRT.

- Hydrology. To determine the wetlands area, a design flow must be established. This is accomplished by hydrologic analysis of the watershed or catchment (Richards 1993a). Hydrologic analysis should provide storm hydrographs for routing water, establishing stage-storage relationships, sizing inlet and outlet structures, and sizing the wetlands. In addition, runoff models are available for some NPS pollutants, such as pesticides, that can be coupled with a hydrologic analysis to provide information on the distribution of hydraulic and pollutant mass loadings in space and time. Distributions of hydraulic and pollutant mass loadings in space and time are needed to design distributed CPAWS for large watersheds. The design HRT may require revision if the runoff quantity/quality estimated by runoff models differs from that used in the initial calculation of HRT.

- Vegetation. Vegetation is a key component of treatment process effectiveness. Vegetation provides resistance to flow, spreads water, and facilitates sedimentation. Vegetation is the primary source of detritus and also provides a substrate for the periphyton community. In a wetlands, periphyton surrounding plant stems is a region of intense energy (chemical) and materials transfer. It is in the periphyton community that pesticides and other toxic organics are most likely to disappear or be degraded. Basic considerations for vegetative design of wetlands were described

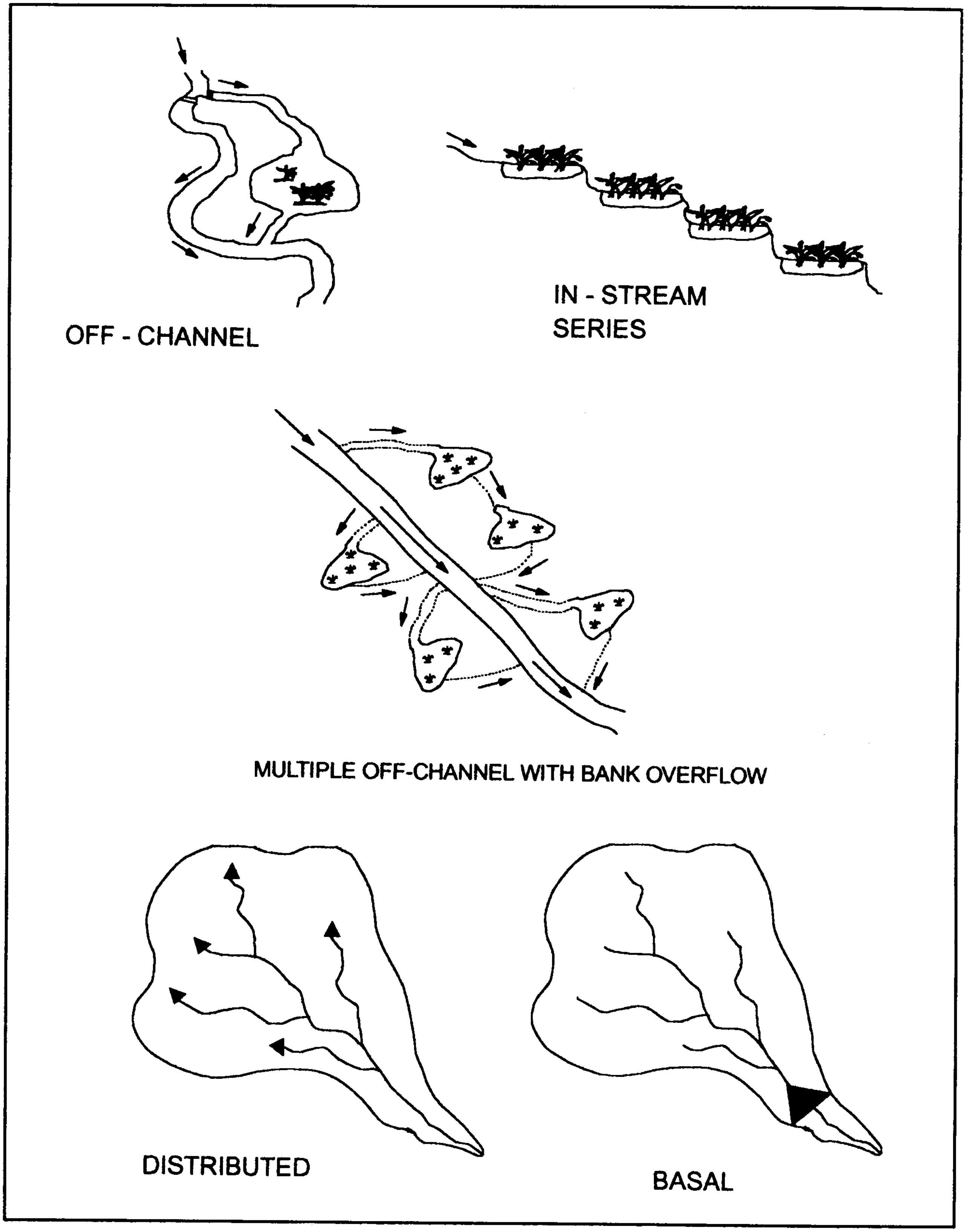

Figure 2. Selected Siting Alternatives for CPAWS

by Allen (1993). For CPAWS, development of the vegetation component to the maximum extent possible (consistent with hydraulic design) is an important design objective.

- Hydraulics and Earthwork. Hydraulic and earthwork design guidance for wetlands is available in Palermo (1992), Miller and Tate (1993), and Richards (1993b). Techniques for detention-pond analysis and design are also applicable to many aspects of hydraulic design for constructed wetlands, but the designer will need to consider factors specific to wetlands (Reed 1990; Palermo 1992).

- Operation and Maintenance (O&M). An O&M plan should be developed during design of CPAWS. O&M plans should address operation and cleaning of inlet and outlet structures, biomass harvesting, berm maintenance, and monitoring.

- Monitoring. Monitoring is an important element in the operation of CPAWS. Monitoring should focus on treatment effectiveness and effluent quality. Treatment effectiveness should be based on pollutant mass balances and as such will require monitoring inflow, influent pollutant concentrations, outflow, and effluent pollutant concentrations. Vegetation should also be monitored for coverage, health, and diversity.

SIMPLIFIED DESIGN EXAMPLE: The example given here is hypothetical and illustrates a simplistic analysis suitable for initial feasibility evaluation. More detailed analysis would be needed to proceed with planning and design.

Experimental wetland mesocosm studies showed a half-life of 8 days for atrazine (a herbicide) in a fully vegetated wetland. For an atrazine influent concentration of 20 $\mu g/\ell$ and a target effluent concentration of 3 $\mu g/\ell$, the calculated HRT is 22 days (see Fig. 3). Assuming an average depth of 3 ft and a design flow of 10 ft^3/sec, the needed wetlands area is about 146 acres. This acreage estimate is suitable for initial assessment of site availability and configuration alternatives.

CONCLUSIONS: The design sequence presented can be used for initial planning and feasibility assessments for nonpoint source pollution abatement using constructed wetlands. Chemical half-life and hydraulic retention time are key design parameters. Hydrologic analysis is essential in designing wetlands for nonpoint source pollution control.

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<u>First Order Process Equation</u> $C = C_0 e^{(-kt)}$

C = concentration, C_0 = influent concentration, k = first order disappearance coefficient, and t = time.

<u>Chemical Half-Life</u> From mesocosm studies, atrazine half-life is 8 days.

$$t_{..5} := 8 \cdot \mathrm{day}$$

<u>First Order Disappearance Coefficient</u> By definition $C/C_0 = 0.5$ when $t = t_{..5}$

Rearrangement of the First Order Process Equation yields

$$k := \frac{-1 \cdot \ln(0.5)}{t_{..5}} \qquad k = 0.087 \cdot \mathrm{day}^{-1}$$

<u>Hydraulic Residence Time (HRT)</u>

The HRT needed to reduce an influent concentration of 20 ug/L to 3 ug/L is obtained by substituting these values and the first order disappearance coefficient into the basic process equation and rearranging as follows:

$$C := 3 \qquad C_o := 20$$

$$t := \frac{\ln\left(\frac{C}{C_o}\right)}{-1 \cdot k} \qquad t = 21.9 \cdot \mathrm{day}$$

The needed HRT is about 22 days.

<u>Wetland Area</u> Area = [(Flow) (HRT)] / (Depth)

Flow: $Q := 10 \cdot \frac{\mathrm{ft}^3}{\mathrm{sec}}$ Depth: $D := 3 \cdot \mathrm{ft}$ HRT: $\mathrm{HRT} := 22 \cdot \mathrm{day}$

$$\mathrm{Area} := Q \cdot \frac{\mathrm{HRT}}{D} \qquad \mathrm{Area} = 145.5 \cdot \mathrm{acre}$$

Figure 3. Simplified Design Example

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