The WRP Notebook

CONTENTS

Screening-Level Assessment of Water Quality Improvement from Wetlands

PURPOSE: One of the objectives of the Critical Processes work unit on water quality within the Wetlands Research Program (WRP) is to recommend techniques for assessing the functional ability of wetlands to improve water quality. This technical note provides initial guidance on the use of a screen-level approach for estimating the amount of water quality improvement provided by wetlands.

BACKGROUND: Water quality improvement is potentially an important function of wetlands. Mechanisms that occur in wetlands, such as sedimentation, filtration, adsorption, precipitation, decomposition, and uptake and metabolism, can act to reduce concentrations of problematic water quality constituents flowing into wetlands. Similarly, streams, ponds, and lakes can act as natural treatment systems, but wetlands seem to be especially effective because of the abundance of plants that help filter and remove constituents and the shallow depths which increase contact with bottom sediments that can adsorb and decompose substances. Therefore, wetlands, whether natural or constructed, have been recognized as a potentially cost-effective means of water quality treatment.

Quantitative techniques are needed for assessing the ability of wetlands to enhance water quality. There is a need to know how much improvement or treatment wetlands provide. These questions are difficult to answer because the degree of improvement depends on many site-specific factors, such as the concentration and loading rate of inflowing constituent, the hydraulics (e.g., residence time and depth) of the system, water and sediment chemistry, and system biological conditions (including microbes, macrophytes, and phytoplankton). Even with these complexities, it is possible to develop estimates of water quality improvement, as discussed below.

APPROACH: Removal efficacy (RE) is introduced as a convenient means to quantify the amount of water quality improvement. RE (percent) is defined as

$$RE = 100 \times \frac{C_i - C_o}{C_i} \qquad (1)$$

where C_i and C_o are the inflowing and outflowing concentrations of a particular water quality constituent. Therefore, if the total concentration of a problem water constituent is removed by a wetland (i.e., C_o is zero), RE = 100%.

A simplified approach for estimating the effects of wetlands on removal of problem water quality constituents is developed as follows. The approach is discussed in general terms (i.e., for a generic water quality variable), but could be applied for any specific water quality variable in a similar manner. Through several assumptions, an analytical model is derived that can be easily applied (without the need for numerical solutions and computer simulations). These assumptions, which pertain primarily to time and space, are

- The system is at steady state (i.e., flow, inflow, or wastewater loadings, and constituent concentrations are constant in time).
- Concentration gradients can be described by the one-dimensional (longitudinal) mass transport equation (thus, vertical and lateral gradients are neglected).
- Longitudinal dispersion is much smaller than advection due to flow, thus negligible.
- Uniform flow is assumed (i.e., velocity and depth of flow are spatially uniform).

It is also assumed that kinetic rate/loss coefficients are first-order and are uniform throughout the system.

With the above assumptions, the one-dimensional, steady-state transport equation for a water quality constituent, C, is written as

$$U \frac{\partial C}{\partial X} = - KC \qquad (2)$$

where

U = average stream velocity along the X coordinate (L/T)
X = distance coordinate along main flow path of the wetland (L)
K = bulk loss or removal rate (1/T) for the constituent

Equation 2 is for a fixed coordinate view point (i.e., an Eulerian view), but by recognizing that U = dX/dt, it can be transformed into a Lagrangian description (i.e., following a parcel of water),

$$\frac{dC}{dt} = - KC \qquad (3)$$

where t is time. With the boundary condition for influent concentration, C_i, specified, Equation 2 can be solved analytically for C at time t (i.e., elapsed time after entering the wetland), yielding

$$C = C_i \, e^{-Kt} \qquad (4)$$

Thus, if C is interpreted as the effluent concentration (C_o), t is the travel time (or retention time) through the wetland. Equation 4 is also referred to as a plug flow reactor model or a first-order decay model. Equations 1 and 4 can be combined to yield

$$RE = \left(1.0 - e^{-Kt} \right) \times 100 \qquad (5)$$

The bulk removal rate, K, can result from a number of processes, such as microbial metabolism (decay), plant uptake, adsorption, volatilization, nitrification, denitrification, and settling). Additionally, these processes can be site specific and can depend on ambient conditions, such as temperature, pH, etc. Thus, obtaining a representative value for K can be problematic. Empirical estimates can be obtained from field data, but these estimates can be site and time specific and costly to obtain. However, if a dominant removal mechanism is fairly well understood for a particular water quality variable, such as die-off rate of coliform bacteria or decay of organic matter (e.g., biochemical oxygen demand, BOD), then it is possible to estimate K from the literature without site-specific data. When the major removal mechanism involves a physical mass transfer mechanism, such as volatilization to the atmosphere, solids settling, or diffusion into the bottom sediments, a mass transfer rate, V_s (L/T), can be estimated and divided by the water depth, H, to obtain K. Bowie et al. (1985) is a good reference for selecting various process rates (e.g., coliform bacteria die-off, BOD decay, suspended solids settling, nitrification, denitrification, etc.). Lyman, Reehl, and Rosenblatt (1982) is an excellent reference for estimating volatilization rates; and references by Boudreau and Guinasso (1982), Gantzer, Rittman, and Herricks (1988), and Hammer and Kadlec (1983) can be used to obtain estimates of flowing water-sediment mass transfer rates.

The two hydraulic variables, H and t, must be estimated. The depth, H, is needed only for converting a mass transfer rate into K, and can be estimated from the wetland water volume divided by the surface area. The retention time, t, can be estimated from either the wetland volume divided by the flow rate or the wetland longitudinal (i.e., streamwise) length, L, divided by U, the average velocity of flow. Average velocity is obtained by dividing the flow by the average cross-sectional area. Cross-sectional area can be estimated as the product of H and a representative width of flow, W. Longterm, average (e.g., annual average) quantities for flow, surface and cross-sectional areas, and volume are recommended. Actual travel times can be different from these simple estimates because of temporal and spatial variations and short-circuiting of flow. There is always a trade-off in accuracy for the simplicity associated with screening-level analyses.

EXAMPLE APPLICATION: An example is given here to illustrate how this simplistic model can be used to estimate RE. A wetland downstream from pastureland is being assessed for the functional ability to remove nitrate and total coliform bacteria (TCB). Suppose that the mean annual retention time of the wetland is estimated to be 10 days (i.e., t = 10 days). The die-off rate for TCB is estimated to be 1.0 day^{-1} (Thomann and Mueller 1987). Additionally, long-term nitrate removal is assumed to occur primarily through denitrification at a rate of 0.1 day^{-1}. This value is consistent with denitrification measurements of 0.04 day^{-1} to 0.19 day^{-1} obtained by Graetz et al. (1980) for 15 Florida wetland soils. Similarly, Bavor et al. (1989) computed nitrogen removal rates for seven constructed wetland systems that varied between 0.072 and 0.189 day^{-1}. Substituting into Equation 5, with $t = 10$, $K = 1.0$ for TCB, and $K = 0.1$ for nitrate, gives RE = 99.995% and RE = 63.2% for TCB and nitrate, respectively.

FUTURE DIRECTION: Work will continue toward developing a screening-level method for estimating wetland removal efficacy for problem water quality constituents using the concept discussed above. This method will remain simplistic for rapid application with little input data. Presently, the greatest difficulty in using this approach is the specification of K. There is an ongoing effort in the WRP to analyze removal rates and provide future guidance on estimating K for various constituents and conditions. Wetland performance results reported in the literature (e.g., wetland study sites reported by the Water Pollution Control Federation, 1990) and results from WRP study sites (e.g., Cache River) are being used for these analyses and recommendations. For some constituents, such as the ones used in the example above, removal rates can be defined relatively well. For some others, such as phosphorus, prescribing removal rates will be much more difficult.

CONCLUSION: The simplified model presented here is best suited for constructed wetlands and natural wetlands with well-defined and rather constant inflows and outflows, such as small, permanently flooded depressional wetlands. In contrast, natural riverine wetlands such as the Cache River can experience highly variable flows and periods without standing water. These highly variable conditions do not preclude the use of the simplified model. For example, this approach may still be used as a screening-level assessment of long-term, average conditions. However, application of the model to highly variable, natural wetlands should proceed with caution and the results viewed with discretion.

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Screening-Level Techniques for Estimating Pollutant Removal by Wetlands

PURPOSE: This technical note gives a basic overview of screening-level techniques for estimating the amount of pollutant removal by wetlands. Such estimates are useful for evaluating water quality functions of existing wetlands or for designing constructed wetlands for pollution abatement (see WRP Technical Note WQ-SW-3.1).

BACKGROUND: Since water quality improvement is potentially an important function of wetlands, quantitative techniques are needed to assess this function. WRP Technical Note WQ-EV-2.1 should be used in conjunction with this technical note since it provides background information on the use of a screening-level approach for estimating the amount of water quality improvement provided by wetlands. A technical report by Dortch and Gerald (1995) provides the detailed model formulations and guidelines for computer program implementation.

A screening-level assessment refers to the use of simplified quantitative methods that minimize time and effort for implementation. Simplification is achieved by making assumptions that reduce complexity of the mathematical formulations and input data requirements. These techniques have been programmed into an interactive, user-friendly, PC-based computer program.

APPROACH: The objective is to estimate removal efficiency (*RE*) for a specific pollutant given a limited amount of basic information about the wetland. *RE* (percent) is defined as

$$RE = 100 \times \frac{W_L - QC}{W_L} \tag{1}$$

where

W_L = total loading of pollutant entering the wetland (that is, $\Sigma\, Q_iC_i$)
Q_i = water flow rate entering the wetland at point i
C_i = pollutant concentration of flow entering at point i
Q = total water flow rate exiting the wetland
C = pollutant concentration of flow exiting the wetland

Thus, RE = 100 percent denotes total removal of a pollutant. Equation 1 is applicable to both point and nonpoint source loadings since $W_L = \Sigma Q_iC_i$. That is, the total load (mass/time) entering can be considered. If the outflow from the wetland occurs at more than one location, then QC would also be summed for all outflow points since *RE* should be a measure of the total mass flux removed by the wetland.

The primary assumption made with this model to achieve simplicity is that the wetland is at steady state (that is, flow and concentrations are constant in time). With this assumption, the analysis is most valid for determining long-term, average values of *RE*. Mean annual input conditions (for example, flows, depth, etc.) are consistent with this assumption.

Either of two conditions is assumed for spatial gradients in concentration: 1) fully mixed (that is, no gradients) or 2) gradients along the main flow axis (longitudinal gradients, but well mixed laterally and vertically). The mass balance equation for the first spatial assumption is stated as

$$\frac{d(VC)}{dt} = W_L - QC - KVC \tag{2}$$

where

V = volume of the wetland

C = pollutant concentration in the wetland and flowing out of the wetland for the fully mixed assumption

t = time

K = bulk loss or removal rate of the pollutant due to physical, chemical, or biological processes

For the steady-state assumption, Equation 2 reduces to

$$QC = \frac{W_L}{1 + K\tau} \tag{3}$$

where τ is the hydraulic residence time, V/Q. Rearranging Equation 3 and substituting Equation 1 results in

$$RE = \left(\frac{K\tau}{1 + K\tau} \right) \times 100 \tag{4}$$

The relationship for *RE* with the second spatial assumption (that is, existence of longitudinal gradients or plug flow) and steady-state conditions is derived from the one-dimensional mass transport equation (neglecting dispersion), as shown in WRP Technical Note WQ-EV-2.1, and is stated as

$$RE = \left(1 - e^{-K\tau}\right) \times 100 \tag{5}$$

Now, *RE* can now be estimated from either Equation 4 (fully mixed) or Equation 5 (plug flow) given K and τ. Values for K depend upon the pollutant of concern and the wetland characteristics, as discussed below. The choice of Equation 4 or 5 depends on wetland mixing characteristics. A bowl-shaped wetland with little sheltering from the wind would be expected to exhibit relatively uniform concentrations; thus, Equation 4 should be used. Well-mixed conditions also tend to be associated with wetlands having small hydraulic residence times (V/Q) and small length-to-width ratios (for example, $L/W \approx 1.0$). A long, narrow wetland would tend to exhibit longitudinal gradients, requiring the use of Equation 5. The plug flow condition is expected with large L/W ratios ($L/W > 10.0$) and large residence times. In most cases, Equation 5 should be used.

HYDRAULIC VARIABLES: Hydraulic residence time is defined as the theoretical maximum detention time, V/Q, where V and Q are mean annual values for wetland volume and flow, respectively. However, the true detention time of water parcels can be less than V/Q due to dominant flow paths that result in dead zones and short-circuiting. Additionally, the location where the pollutant is introduced in the wetland (a point source load) affects the detention time. The detention time, τ (days), as affected by L/W, can be estimated from (Thackston and others 1987)

$$\tau = 0.84 \frac{V}{Q} \left(1 - e^{-0.59 \frac{L}{W}} \right) \tag{6}$$

where L/W is the ratio of wetland length to width. If a wetland is considered to be well mixed, then Equation 4 should be used, and τ should be approximated as V/Q. For plug flow conditions, Equation 5 is recommended, and τ should be estimated from Equation 6 or set equal to V/Q for large L/W ($L/W > 10$).

Other hydraulic variables needed by the model include flow velocity, hydraulic depth, and the water surface area. The wetland hydraulic depth, H (m), is defined as V/A, where A (m^2) is the water surface area, and V (m^3) is the volume. Thus, with an estimate of two of the three variables (V, A, and H), the third variable can be computed. The mean velocity of the flow, U, is either input by the user or estimated from L/τ or Q/WH.

WATER QUALITY CONSTITUENTS: The model contains algorithms for the following water quality constituents:

- Total suspended solids.
- Total coliform bacteria.
- Biochemical oxygen demand.
- Total nitrogen.
- Total phosphorus.
- Contaminants.

The RE for each constituent depends on the removal rate, K, for the constituent via Equation 4 or 5. The removal rates depend on a number of processes, such as microbial metabolism, adsorption, volatilization, denitrification, settling, etc. Additionally, these processes are dependent on ambient conditions, such as water temperature, so obtaining a representative K value can be problematic. The approach here is to focus on the dominant long-term removal mechanisms, making use of literature values or formulations for those mechanisms. Presentation of formulations for estimating K values is beyond the scope of this technical note, but these are presented by Dortch and Gerald (1995). The computer model includes the formulations for estimating K rates for each water quality constituent.

MODEL IMPLEMENTATION: Formulations for estimating pollutant removal have been coded into a user-friendly, interactive computer program operational on PCs. The program is called PREWet, which is an acronym for Pollutant Removal Estimates for Wetlands. The equations and logic are programmed in C. The graphical user interface was developed with Zinc, a commercially available interface library. PREWet displays menus for selection of variables and parameters. Wherever applicable, default values for parameters are also provided. The model is designed to be self-explanatory, but on-line help features are available if necessary. PREWet can soon be downloaded through the Internet via FTP. Point of contact for information on model retrieval is Ms. Toni Schneider, (601) 634-3670, e-mail: *schneil@ex1.wes.army.mil.*

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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.

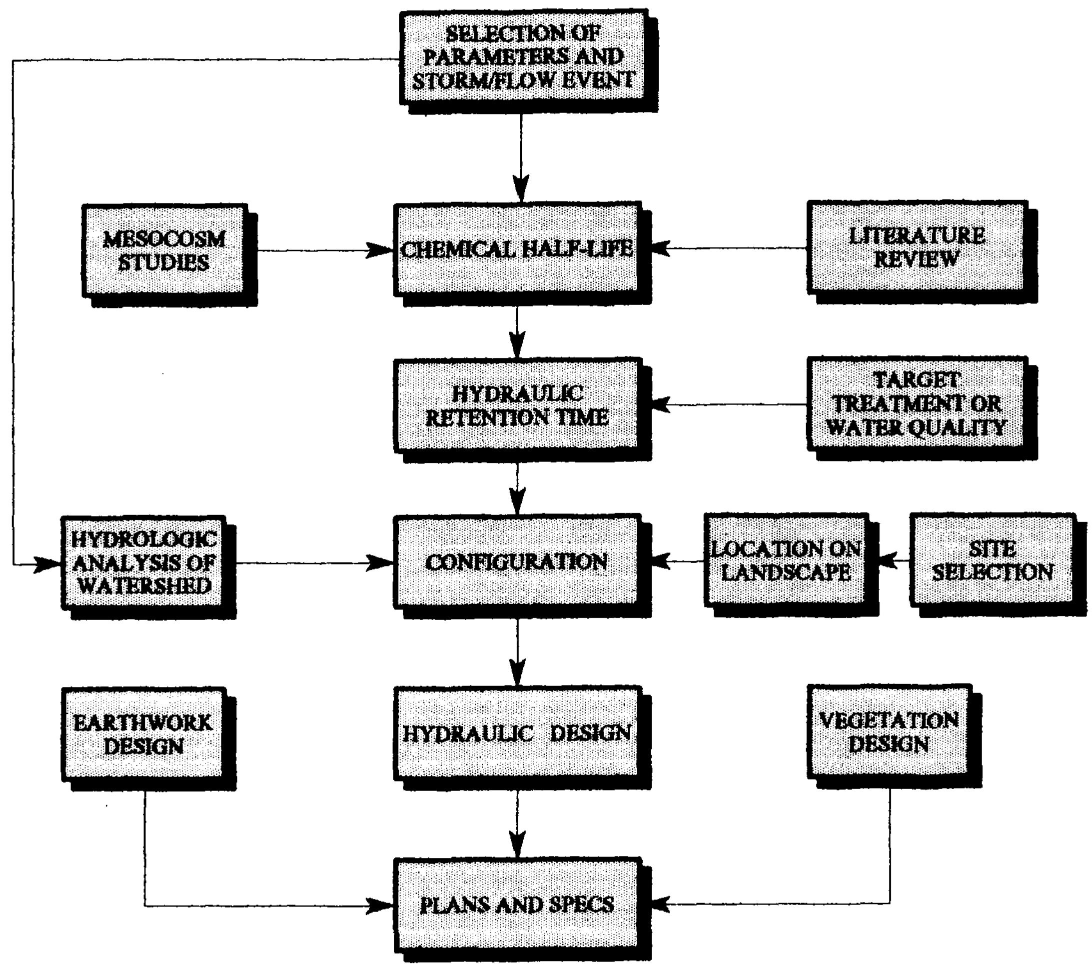

Figure 1. Design sequence for constructed pollution abatement wetland systems

- 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

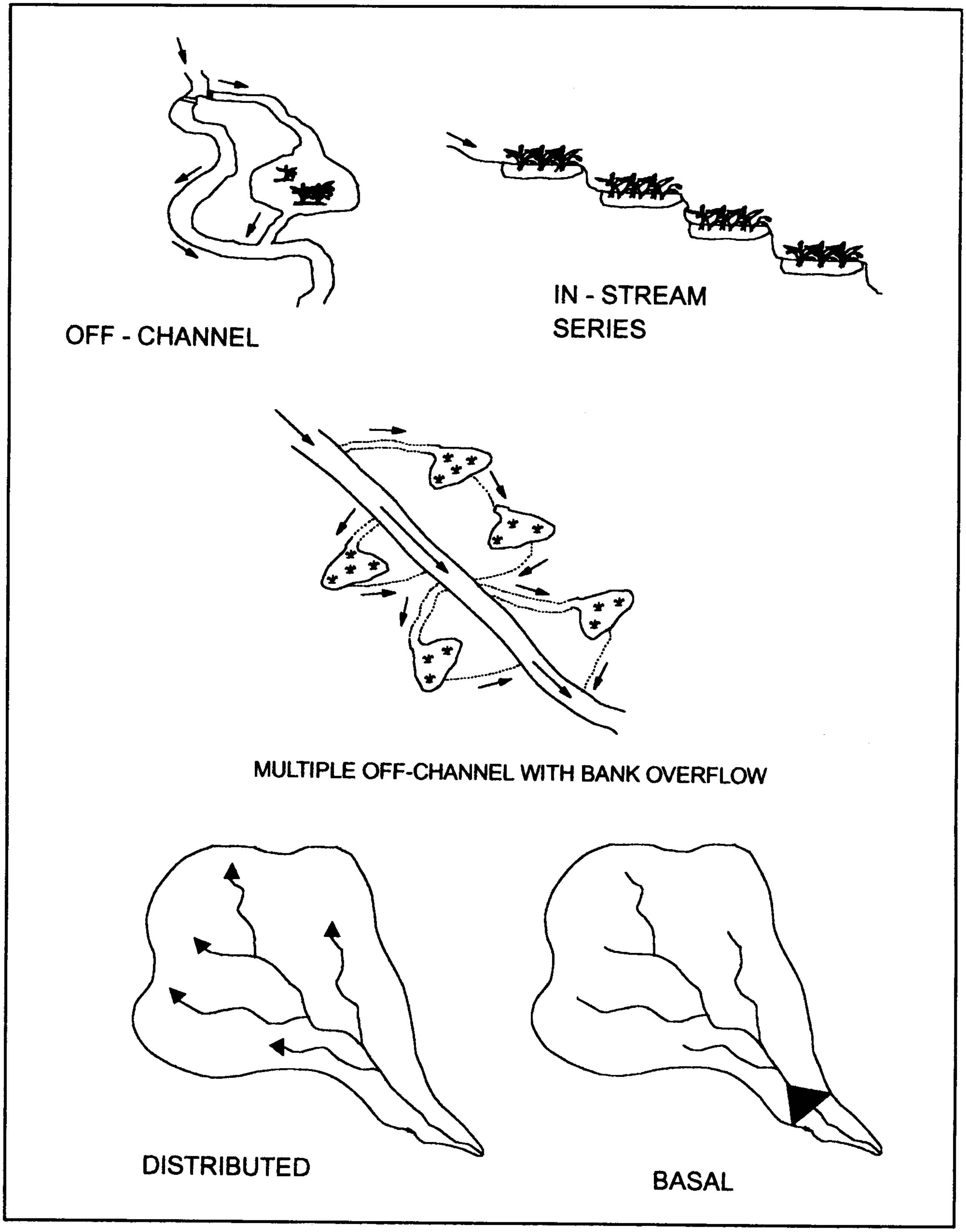

Figure 2. Selected Siting Alternatives for CPAWS

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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First Order Process Equation $C = C_o e^{(-kt)}$

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

Chemical Half-Life From mesocosm studies, atrazine half-life is 8 days.

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

First Order Disappearance Coefficient By definition $C/C_o = 0.5$ when $t = t_{..5}$

Rearrangement of the First Order Process Equation yields

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

Hydraulic Residence Time (HRT)

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:

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

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

The needed HRT is about 22 days.

Wetland Area Area = [(Flow) (HRT)] / (Depth)

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

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

Figure 3. Simplified Design Example

Kadlec, R. H. 1990. "Hydrologic Factors in Wetland Water Treatment," in Hammer, D.A. (ed), *Constructed Wetlands for Wastewater Treatment*, Lewis Publishers, Inc., Chelesa, MI.

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