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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

$$U \frac{\partial C}{\partial X} = - KC \tag{2}$$

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),

$$\frac{dC}{dt} = - KC \tag{3}$$

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

$$C = C_i \, e^{-Kt} \tag{4}$$

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

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

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_t (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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