CONCEPTUAL MODELS FOR WETLAND ASSESSMENT

Water Storage and Water Quality Functions

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Introduction

It has long been recognized that wetlands have the capacity to improve water quality and provide storage and desynchronization of floodwaters. The inherent capacity to perform these functions is dependent on the physical, biological, and chemical characteristics of the wetland. Coastal Prairie Freshwater Wetlands (CPFWs) are an integral part of the Galveston Bay ecosystem, yet their water quality and flood storage functions have not been evaluated. This report presents five conceptual models that predict a CPFW's capacity for (1) water storage, (2) nitrogen removal, (3) phosphorus removal, (4) heavy metal removal, and (5) removal of organic compounds. The models are derived from literature reviews of site specific research studies and functional assessment models (primarily hydrogeomorphic models) developed for other classes of wetlands. This literature was used in conjunction with the project team's professional judgment and what is known about hydrology and biogeochemical processes in CPFWs.

Methods

The models presented in this document were based largely on three HGM models for depressional wetlands (Gilbert et al. 2006, Lin 2006, Stutheit et al. 2004) and one similar model developed for wetland in south Florida (Zahina et al. 2001). Our approach to model development also incorporates some of the general guidelines presented by Smith et al. (1995). Most functional assessment approaches relate a wetland's potential for performing a given function to the wetlands' characteristics such as its position in the landscape, morphology, hydrology, soils, vegetation, etc. The resulting predictive models *do not measure* whether the function is actually being performed and such verifications are rarely attempted. Instead, functional models provide a relative estimate of functional capacity. They typically provide qualitative values (low, medium or high) or indexed values (0.0 – 1.0) relative to a "fully functional" reference wetland. Some models (e.g. WET 2.0) include variables that account for the opportunity the wetland has to perform the function and social significance. Other approaches (e.g. HGM) do not include opportunity or social significance variables. The CPFW functional models presented in this document do not include opportunity or social significance variables. They are also indexed to provide a relative estimate of function known as the Functional Capacity Index (FCI). The FCI can range from 0.0 – 1.0, where 0.0 indicates that the functional capacity is absent and a 1.0 indicating that the wetland functions at a level similar to the selected reference wetlands.

One important difference between the CPFW models and existing hydrogeomorphic (HGM) models is the use of reference wetlands. Development of an HGM approach for a regional class of wetlands requires extensive data collection in reference wetlands, which are wetlands believed to be performing at a high functional capacity (Smith et al. 1995). Data collected in reference wetlands are used to define the range of functionality and the range of values for predictor variables. Because this level of effort is beyond the scope of this project, our sampling will characterize three relatively unimpacted wetlands and supplement those data with information from the regional literature. For example, soil organic matter has been identified as a variable in several water quality models. We will rely on soil surveys within the study area to evaluate the possible range of soil organic matter.

Variables used in HGM models characterize land use, hydrology, soils, and vegetation. They are assigned values that range from 0.0 to 1.0 scaled to the range of expected values for the type of wetland. Variables selected for CPFW models were defined so as to allow them to be quantified in the field either by direct measurement or by field indicators. A second selection criterion for variables was that they be applicable using GIS tools. These field measurements will be correlated with measured functions in selected wetlands. GIS methods will be utilized to apply the models to CPFWs in the study area. The conceptual models presented in this document will be modified as results of field sampling and additional data collection. Methods and supporting information for assigning values to model variables are included in Appendix A.

The final step in conceptualizing the assessment model is to develop an aggregation equation that combines model variables and derives the FCI. We used the approach developed by Smith and Wakeley (2001) for HGM development. In this approach, the types of interactions between model variables (Table 1) may be additive, where either variable alone or both in combination contribute to functional capacity. If the sum exceeds 1.0, the FCI is taken to be 1.0. A *limiting* relationship is one in which a low value for any one variable lowers the function. This type of relationship is defined by the minimum of the two variables. It is commonly used in habitat indices, where factors such as food, cover, or nesting sites are all necessary for survival. A *compensatory* relationship occurs when a high value for one variable compensates for a lower value of another variable. This type of relationship is defined by the maximum value of the two variables. A *partially compensatory* relationship occurs when two or more variables contribute equally and independently to the level of function. It is calculated as either the arithmetic mean or the geometric mean, with the former being more sensitive to low values. Another important difference between the arithmetic mean and the geometric mean is that with the geometric mean, if *any* variable is equal to zero, the resulting FCI is zero. A *controlling* (one feature is critical to the performance of a function). For example, a model for organic carbon export might contain the following equation: $FCI = V_{FREQ} \times (V_{LITTER} + V_{CSD})/2$. Carbon export is affected by the abundance of leaf litter V_{LITTER} and coarse woody debris V_{CSD}, which are grouped and averaged because they contribute equally and independently to the availability of material for export. However the export cannot occur unless floodwaters scour the site regularly. Thus the product relationship allows V_{FREQ} to drive the FCI to zero at sites where no flooding occurs, despite high values of the other variables. Finally, variables may also be weighted if their contribution to the function is believed to be more important than other variables.

Table 1. Types of interactions between model variables and their mathematical expression for developing HGM assessment models (adapted from Smith and Wakeley 2001).

Type of Interaction	Mathematical Operation	Example
Cumulative	Addition	FCI = $V_A + V_B + V_C$; if sum > 1.0 then FCI = 1.0
Limiting	Minimum	FCI = MIN (V_A, V_B)
Fully compensatory	Maximum	FCI = MAX (V_A, V_B)
Partially compensatory	Arithmetic mean	FCI = $(V_A + V_B + V_C)/3$
	Geometric mean	FCI = $(V_A \times V_B \times V_C)^{1/3}$
Controlling	Product	FCI = $V_A \times (V_B + V_C)/2$
Weighted	Coefficient	FCI = $2V_A + V_B + V_C)/4$

Surface Water Storage Model

Surface water storage is defined as the capacity of a wetland to temporarily store and convey surface water during rainfall or flood events. The primary source of surface water is from direct precipitation and overland runoff. This function is often referred to as flood attenuation or flood peak desynchronization. The water budget of depressional wetlands is influenced by precipitation within the catchment, groundwater recharge and discharge, evapotranspiration, and the configuration of the wetland outlet. In wetlands with flow-through, density and rigidity of emergent vegetation can retard water velocities by providing hydraulic roughness. At any given moment, the water level in the wetland is a balance of these factors.

In general, the underlying geology and soils of the coastal plain area promote slow rates of ground water – surface water exchange. In CPFWs, therefore, precipitation and evapotranspiration (EVPT) are believed to play the largest role in determining fluctuations in the wetland water level (Smeins et al. 1992). Evapotranspiration may be the most important pathway for water losses in depressional wetlands; annual lake evaporation in the Galveston Bay Area is approximately 53 inches and annual class A pan evaporation is 70 to 75 inches (Dunne and Leopold 1978). Rates of EVPT have been shown to be higher in systems with abundant emergent vegetation. For example, wetlands dominated by broadleaf cattail (*Typha latifolia*) were demonstrated to have double or triple EVPT rates of an unvegetated area (Towler et al. 2004). Wetlands with larger surface areas would also have greater potential for total EVPT.

A wetland’s capacity for flood attenuation is dependent upon the storage volume available at the onset of precipitation events. Thus overall wetland size and volume are important characteristics for predicting flood storage. The ratio of the wetland surface area to the surface area of its catchment (V_{catch}) has been proposed as an important characteristic for evaluating water storage function (Bradshaw 1991, Fennessy et al. 2004, Lin 2006). Wetlands that can store at least 25% of the catchment runoff from a 24-hr two-year rain event have been assigned a high water storage function (Simon et al. 1987, Bradshaw 1991). Water storage and flood attenuation tend to be greater in wetlands with substantial water level fluctuations, such as those with large wet meadow zones (Gilbert et al. 2006), or with intermittent, seasonal, temporary, or semi-permanent hydrologic regimes. Hydrological modifications or modifications to wetland outlets typically reduce their effective storage volumes.

The conceptual model for water storage (Eq. 1) contains variables for wetland volume (V_{vol}), ratio of wetland size to catchment size (V_{catch}), modifications to the wetland outlet, and percent of wetland area that is vegetated with macrophytes (V_{mac}). The wetland volume variable can be zero if the wetland has been filled or modified to drain completely.

$$FCI_{WS} = V_{vol} \times \left(\frac{V_{catch} + V_{out} + V_{mac}}{3} \right) \qquad \text{(Eq. 1)}$$

Water Quality Models

It has been well documented that wetlands have the ability to remove, reduce, degrade, or provide long-term storage of a variety of pollutants. Pollutants include elements such as heavy metals, nutrients such as nitrogen and phosphorus, compounds such as PAHs, herbicides and pesticides, and particulates. These compounds may enter wetlands through aerial deposition, surface runoff, groundwater exchange, or through streams or manmade conveyances. A quantitative *measure* of water quality function would require a determination of the amount of pollutant removed or retained per unit area during a specified period of time (e.g. $g/m^2/year$). Such data-intensive studies are rarely undertaken in the context of functional assessment. Rather, functional assessment models are used by regulators and land use managers to inform decisions regarding proposed activities in wetlands. In this context, functional assessment models have been used to *estimate* the type and degree of functions that would be gained or lost in wetland conversions.

Most HGM models developed for depressional wetlands have used a single model for retention or removal of nutrients, organics, heavy metals and other contaminants. However, most contaminants have unique fate and transport pathways. For example, the wetland characteristics that promote nitrogen removal will not necessarily optimize the removal of other pollutants. To incorporate our understanding of the fate and transport of specific contaminants in wetlands, we have developed separate water quality models for nitrogen, phosphorus, selected heavy metals, and organics.

Nitrogen Retention/Removal Function

Nitrogen pollution is an important consideration in the Galveston Bay area and near-shore ecosystems, particularly as anthropogenic inputs associated with development continue to increase. Nitrogen retention/removal function is defined as the capacity of a wetland to reduce the water column concentrations of nitrogen compounds such as organic nitrogen, ammonium, and nitrate. This may occur through short-or long-term storage of nitrogen in biota and sediments; or through permanent removal of nitrogen primarily through the nitrification-denitrification process.

Nitrogen may enter CPFWs through precipitation, surface runoff, and from direct faunal deposition. Nitrogen transformations in wetlands may be substantial depending upon the nature of nitrogen loading as well as characteristics of the individual wetland. Nitrogen is removed from the water column primarily by four processes (Reddy and Patrick 1984): (1) uptake by plants, (2) immobilization by microorganisms during plant decomposition, (3) adsorption of ammonium onto organic matter and clay, and (4) most importantly, through the nitrification-denitrification process.

The nitrification–denitrification process leads to permanent removal of nitrogen from wetland systems. Nitrification is the microbially mediated oxidation of ammonium to nitrite and then nitrate. The process consumes approximately 4.3 grams of oxygen gas for each gram of nitrogen oxidized, and therefore occurs primarily in aerobic areas of the wetland (surface waters, unsaturated soils, rhizospheres of emergent plants, etc.). Once ammonium is oxidized, the resulting nitrate then diffuses to anaerobic areas of the wetland where it may be denitrified. This transport of the resulting nitrate from aerobic to anaerobic zones has been shown to be the rate limiting step in the removal of nitrogen from flooded systems (Patrick and Reddy 1976).

Denitrification is the reduction of nitrate into gaseous nitrous oxide (N_2O) and molecular nitrogen (N_2), which are then released to the atmosphere (Mitsch and Gosselink 1993). Denitrification occurs primarily in reduced soils and sediments where abundant organic matter is used as a carbon source for denitrifying bacteria. Denitrification has been shown to remove relatively large quantities of nitrogen from wetlands, particularly when the proportion of nitrate in incoming loads is high (Nelson et al. 2004).

The type of wetland that will favor permanent nitrogen removal will depend on the characteristics and quantity of nitrogen inputs. For example, wetlands receiving inputs primarily from precipitation, runoff from undisturbed catchments, or inputs with low nitrate loads, will require both aerobic and anaerobic conditions to nitrify and denitrify nitrogen inputs. In contrast, wetlands receiving runoff from fertilized agricultural fields or other sources associated with high nitrate levels, will reduce nitrogen loads most efficiently when they are anaerobic (Figure 1). In the first case, wetlands with a fluctuating hydrologic regime would optimize nitrogen removal because aerobic zones within the wetland promote nitrification. In fact, it has been demonstrated that nitrification is enhanced in wetlands where soil moisture contents fluctuate repeatedly

(Patrick and Mahapatra 1968, Ponnamperuma 1972, Reddy and Patrick 1975), such as in the wet meadow zone.

In the second case, denitrification rates would be enhanced by wetlands that are more or less permanently inundated because inundation promotes reducing conditions. Denitrification rates would be further increased with higher initial concentrations of nitrate. Thus the highest rates of nitrogen removal may occur in permanently inundated wetlands receiving high nitrate runoff.

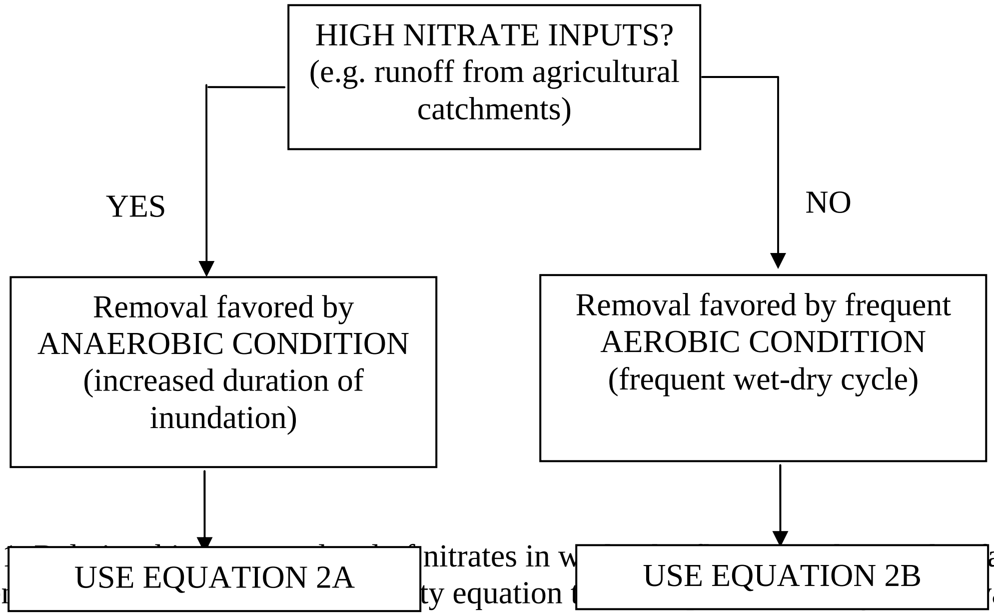

Figure nitrates in w avor nitroge ty equation t al potential.

Two conceptual models (Eqs. 2A and 2B) are proposed for predicting nitrogen removal in CPFWs with . Equation 2A is for wetlands receiving high nitrate inputs and Eq. 2B for all other wetlands. An important variable in Eq. 2A describes the wetland hydroperiod (V_{hydro}), which is scaled to reflect the duration of inundation (Table 3 Appendix A). The corresponding variable in Equation 2B describes the frequency of wet-dry cycles, since variable redox conditions would promote nitrification. Both models contain variables for percent of buffer that is vegetated (V_{buff}), percent of wetland area that is vegetated with macrophytes (V_{mac}), and wetland soil organic matter (V_{som}).

$$FCI_{NO3} = V_{hydro} \times \left(\frac{V_{buff} + V_{mac} + V_{som}}{3} \right) \qquad \text{(Eq. 2A)}$$

The wetland water regime, or hydroperiod, was defined by Cowardin et al. (1979) and designated on NWI maps. V_{hydro} is assigned a high value for systems that are permanently or semi-permanently inundated and a lower value for systems that are infrequently inundated. Details regarding V_{hydro} values are provided in Appendix A

In catchments where runoff does not have high nitrate concentrations, nitrogen removal would be best predicted by Equation 2B which replaces V_{hydro} with V_{wetdry}. V_{wetdry} values are high for systems with frequently fluctuating water levels which support both aerobic and anaerobic conditions. These types of wetlands correspond with Cowardin classifications such as seasonally flooded or saturated. Lower values would be assigned to wetlands with hydroperiod classified as permanently flooded or intermittently flooded. Details regarding V_{wetdry} values are provided in Appendix A

$$FCI_N = V_{wetdry} \times \left(\frac{V_{buff} + V_{mac} + V_{som}}{3} \right) \qquad \text{(Eq. 2B)}$$

Phosphorus Retention Model

Phosphorus retention is defined as the capacity of a wetland to remove phosphorus from overlying water and provide long-term storage of that phosphorus in sediments, soils, plant material, or other biota. Although phosphorus removal may occur when vegetation is harvested, sediment is removed, and other biota leaves the wetland, these processes are difficult to predict and therefore are not considered in this model.

Phosphorus enters CPFWs primarily via wet and dry deposition, surface runoff, and piped or channelized inflows. Because phosphate has a strong affinity for clay and other mineral particles, much of an annual phosphorus load may enter wetlands sorbed to particulate matter during one or two large flood events (McKee et al. 2000). These particulate phosphorus loads often settle out in wetlands and become a permanent part of the bottom sediments. Thus wetlands with low water velocities and high hydraulic roughness would be expected to have good suspended sediment and particulate phosphorus removal. Macrophytes also contribute to total phosphorus retention by providing hydraulic roughness which slows water velocities and thus enhances sedimentation of particulate-phosphorus.

The primary mechanisms of wetland phosphorus storage are: (1) microbial uptake by plankton and periphytic organisms, (2) plant uptake, (3) incorporation of organic phosphorus into soil peat, and (4) soil adsorption (Richardson 1985). Inside the wetland, phosphorus may be taken up by plankton and periphyton, but this storage pool is small with rapid turnover. Macrophytic production may account for measurable phosphorus uptake, however approximately 30-75% of the nutrient is seasonally released back to the water column during senescence, with some permanent storage as peat and litter (Richardson and Craft 1993). Adsorption of dissolved phosphorus to soil and sediments is the largest retention processes in wetlands with mineral soils.

Whereas the atmosphere is the ultimate sink for nitrogen, the sediment-litter compartment contains greater than 95% of the phosphorus in natural wetlands (Faulkner and Richardson 1989). Phosphorus associates with sediments through sorption, precipitation, and incorporation into the crystalline lattice of iron, aluminum and calcium compounds (Nichols 1983). Several researchers have found that phosphorus sorption to natural and artificial substrates is correlated to their iron and aluminum contents (Sakadevan and Bavor 1998, Reddy and D’Angelo 1997, Pierzynski 1991). Although anaerobic conditions can lead to the release of iron-bound phosphates from sediments, soils with high mineral or clay contents are generally predicted to have high phosphorus retention capacities (Zahina et al. 2001, Masscheleyn et al. 1992, Cedfeldt et al. 2000). However, even wetlands with high phosphate-sorbing mineral soils can become saturated with respect to phosphorus. At high phosphorus loading rates (e.g. wastewater effluent at concentrations of 2 ppm or higher), wetlands may eventually become a phosphorus source rather than a sink (Tilton and Kadlec 1979, Forbes et al. 2004).

Wetlands with shallow, slow moving water and dense vegetation would be predicted to have a high capacity for settling particulate phosphorus. In addition, wetlands with clay soils would be expected to retain phosphorus at low phosphorus loading rates. Wetlands with high vegetation production rates and prolonged inundation would also provide some long-term phosphorus storage through the accumulation of litter and peat (Mitsch and Gosselink 1993). A conceptual model for phosphorus retention in CPFWs (Eq. 3) includes variables for adjacent buffer (V_{buff}), the density of macrophytes (V_{mac}), and the soil clay content (V_{clay}). To account for a wetland’s potential for phosphorus saturation, land use (V_{LU}) and the ratio of the wetland surface area to catchment surface area ($V_{W:C}$) are also included.

$$FCI_P = \left(\frac{V_{LU} + V_{catch}}{2}\right) \times \left(\frac{V_{buff} + V_{mac} + V_{clay}}{3}\right) \qquad \text{(Eq. 3)}$$

Heavy Metal Retention Model

Heavy metal retention is defined as the capacity of a wetland to remove heavy metals from the overlying water and provide long-term storage in sediments, soils or plant material. Heavy metals enter wetlands from a variety of sources including fertilizer impurities, tire dust, cement production, wastewater, urban runoff, combustion products of fossil fuels, industrial sources, and natural sources. The dispersion of heavy metals into the atmosphere, both as particles and as vapors, often exceeds levels associated with natural releases (Stumm and Morgan 1996).

There are three primary mechanisms for heavy metal sequestration in wetlands (Kadlec and Knight 1996): (1) binding to particulates and soluble organics through cation exchange and chelation, (2) precipitation as insoluble salts, principally sulfides and oxyhydroxides, and (3) uptake by biota. Studies of heavy metal retention by treatment and natural wetlands indicate that sediments are the primary storage components for metals, with minor (~2%) retention in plant tissue (Lesage et al. 2007, Zuidervaart et al. 1999).

There is considerable variation in behavior and removal efficiencies among individual metals. For example, iron and manganese have been shown to increase in some treatment wetlands due to their solubilities under reducing conditions (Lesage et al. 2007, Nelson et al. 2004). Mercury is unique for several reasons: it is primarily transported atmospherically, it may volatilize from sediments to the atmosphere, it may be methylated under anaerobic conditions to a more toxic form (mono- and dimethyl mercury) which also bioconcentrates in animal tissue. Due to the unique properties of mercury, this metal is not included in the functional model.

In general, well buffered, alkaline soils and the presence of organic matter or clay increase the ability of wetlands to remove heavy metals from the water column via sorption and precipitation. In nonacidic soils with plentiful sulfates, carbonates, or phosphates, metals can form insoluble complexes (e.g. metal sulfides) and be retained more or less permanently in the sediments. Soil organic matter may also form stable complexes with metal ions. The presence of vegetation and appropriate soil types adjacent to the wetland (buffer) also enhances retention of heavy metals by slowing runoff, settling particulates, and facilitating contact with soils. The functional assessment model for heavy metal retention is shown below (Eq. 4). The index increases when wetlands contain nonacidic soils, soils with high organic matter or clay contents, dense macrophyte cover, and vegetated buffers. A low rating is assigned to wetlands with acidic soils or soils that are low in organic matter or clay, and with sparse vegetation.

$$FCI_{Me} = \frac{\frac{V_{buff} + V_{mac}}{2} + V_{clay} + V_{som} + V_{soilpH}}{4} \qquad \text{(Eq. 4)}$$

Model for Retention or Removal of Organic Compounds

Organic contaminant removal or retention is defined as the capacity of a wetland to remove or transform organic contaminants present in the water column. Organic contaminants include a wide variety of compounds, both natural and synthesized. Organics that are of particular concern for water quality include pesticides, petroleum hydrocarbons, and other industrial organics such as solvents. Of particular importance in the Galveston Bay area are polycyclic aromatic hydrocarbons (PAHs) due to the abundance of both pyrogenic (combustion) and petrogenic (petroleum-derived) sources. Additional pathways for the removal or retention of organics in wetlands are a function of their tendency to serve as food for microbes and to degrade over time particularly when exposed to the atmosphere and sunlight. The major pathways for removal of hydrocarbons from wetlands waters are: (1) volatilization, (2) photochemical oxidation, (3) sedimentation, (4) sorption, and (5) biological degradation (Kadlec and Knight 1996). While volatilization may remove some organics from the water column, it does not appear to be a measurable removal process for PAHs. In fact, studies in both the Chesapeake Bay (Gregory et al. 2005) and Galveston Bay areas (Park et al. 2000) indicate that gas transfer from the atmosphere to surface waters is the major transport mechanisms of PAHs, followed by wet and dry deposition.

Photochemical oxidation rates are chemical specific. In general, however, longer hydraulic retention times and shallow water depths should result in greater degradation of organics via this process. The capacity of an organic contaminant to settle out of the wetland would be dependent upon its ability to associate with particulate matter. Charged (polar) organics may associate ionically with clays while nonpolar molecules tend to associate with organic matter in the wetland. Partitioning of organics between aqueous and solids (particulates, sediments, etc.) can be predicted to some extent using physicochemical properties of organic compounds such as the relative partitioning between the liquid octanol and water coefficient (K_{ow}) and water solubilities (Sawyer et al. 1994). Some research has shown that sediment organic matter, particularly humins, increase sorption of PAHs. Plant density has been indirectly attributed to enhanced sequestration of PAHs through increased soil organic matter (Gregory et al. 2005), their role in stimulation of microbial activity, and the ability of root exudates to enhance the sequestration of organic contaminants (Baker et al. 1991).

A conceptual model for removal or retention of organics (Eq. 5) includes variables for a wetland surface area to catchment surface ratio (V_{catch}), density of vegetation (V_{mac}) and amount of organic matter in the wetland soil (V_{som}). V_{catch}, which is correlated to relative hydraulic retention time, is predicted to have a greater role in functional capacity than vegetation density or soil organic matter.

$$FCI_{org} = \frac{\frac{V_{mac} + V_{som}}{2} + V_{catch}}{2} \qquad \text{(Eq. 5)}$$

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APPENDIX A

Model Variables

Definitions, Rationales

and

Measurement Methods

List of Variables by Model

The following variables are defined and their measurements explained in the order that they appear in the previous section:

Water Storage Model

1. Wetland Volume (V_{vol})
2. Wetland Outlet (V_{out})
3. Wetland Area to Catchment Area Ratio (V_{catch})
4. Macrophyte Density (V_{mac})

Nitrogen Removal Model

1. Wetland Hydroperiod (V_{hydro})
2. Wet-dry Potential (V_{wetdry})
3. Wetland Buffer (V_{buff})
4. Macrophyte Density (V_{mac})
5. Soil Organic Matter (V_{som})

Phosphorus Retention Model

1. Wetland and Catchment Land Use (V_{LU})
2. Wetland Area to Catchment Area Ratio (V_{catch})
3. Wetland Buffer (V_{buff})
4. Macrophyte Density (V_{mac})
5. Soil Clay Content (V_{clay})

Heavy Metal Retention Model

1. Wetland Buffer (V_{buff})
2. Macrophyte Density (V_{mac})
3. Soil Clay Content (V_{clay})
4. Soil Organic Matter (V_{som})
5. Soil pH (V_{soilpH})

Organic Retention / Removal Model

1. Macrophyte Density (V_{mac})
2. Soil Organic Matter (V_{som})
3. Wetland Area to Catchment Area Ratio (V_{catch})

Model Variables

Wetland Volume (V_{vol})

Definition: The wetland volume refers to the storage volume capacity of the wetland that is typically available (i.e. empty) at the onset of precipitation events.

Rationale: The wetland volume is an important predictor of the wetland's capacity to attenuate flooding of downstream areas. Wetlands with a large volume that are permanently flooded may have limited available storage capacity for precipitation and runoff.

Measure/Units: Cubic meters, ac-ft, or other appropriate volume units.

Field Measurement: The water storage volume of the wetland is calculated by multiplying the wetland area by the average wetland flood storage depth. Average flood storage depth is defined as the elevation range within the wetland multiplied by 0.5. The elevation range is the difference in elevation between the open water boundary and the wetland-upland boundary, as determined by a hand held level and stadia rod to the nearest tenth of a foot. Field indicators such as high water marks, drift lines, and vegetation changes may be used to determine the location of the wetland-upland boundary. The wetland area shall be delineated using a hand-held GPS unit.

GIS Measurement: The elevation at the wetland boundary as indicated on the National Wetland Inventory map will define the surface water boundary of the wetland. Where possible, the wetland-upland boundary will be determined using aerial photography. The elevations of these locations will be determined using topographic or LIDAR databases.

Wetland Outlet (V_{outlet})

Definition: This variable refers to the presence or absence of hydrologic alterations such as dikes, water control structures, artificial water inputs, ditching, or water removal by pumping. The effect that such alterations have on a wetland's ability to store water is organized into categories and assigned a value (Table 2).

Rationale: Wetland outlet modifications tend to prevent the wetland from storing water during precipitation events by either lowering the elevation of the natural outlet and thereby reducing storage capacity, or by preventing the outflow of water between precipitation events and thereby reducing the available storage volume. This variable is relative to the natural condition of the wetland.

Measure/Units: The variable is indexed based on Table 2 below.

Field Measurement: Note the presence of dikes, artificial outlets, fill material, irrigation pipes, artificial pumps, ditches or other wetland modifications.

GIS Measurement: Using aerial photography, USGS maps, NWI maps or other resources, note the presence of dikes or other water control structures.

Table 2. Subindex values for V_{out} based on observations of various wetland outlet modifications (from Stutheit et al. 2004).

Alterations	Sub index Value
Natural conditions present, no dikes or fill within the wetland that restrict or redirect flow or change the wetland water regime class, no pumping or groundwater inputs -OR- wetland has been fully restored.	1.0
Dike(s) or fill bisects the wetland area and the amount of isolated wetland is proportional to the amount of the isolated catchment area –OR- dike has an unrestricted culvert(s) with the invert at or below natural grade.	0.9
Dike(s) with water control capability keep water on a wetland and does not change the wetland water regime class –OR- increased flows to the wetland supplement or correct altered hydrology.	0.6
Dike(s) or fill bisect and change the wetland water regime class –OR- groundwater presence has altered the natural wetland water regime class and soil characteristics –OR- sediment/soil ridge ponds shallow water outside of the wetland..	0.3
Dike(s) or artificial pumping keep the wetland drained –OR- land leveling or fill has raised the elevation of the bottom of the wetland above the temporary zone.	0.0

Wetland Area to Catchment Area Ratio (V_{catch})

Definition: The ratio of the wetland surface area to the surface area of that wetland’s catchment (watershed). The catchment area includes the wetland.

Rationale: The ratio of watershed size to wetland size provides an estimate for relative hydraulic retention time. The retention time of water in a wetland is an important consideration for pollutant removal/retention processes, particularly those that rely on biological activity. Longer retention times generally result in greater pollutant removal or retention.

Measure/Units: This variable is a unitless ratio.

Field Measurement: The watershed (catchment) and wetland sizes may be determined using GPS and survey techniques where possible. In larger catchments, topographical maps or LIDAR will be used, in conjunction with field verification, to estimate catchment size. A mean ratio will be determined for the study area based on 80 to 120 CPFWs. An index will then be developed based on the sample distribution.

GIS Measurement: Topographical maps or aerial photography will be used to delineate and measure catchment and wetland area.

Emergent Macrophytic Vegetation (V_{mac})

Definition: The relative coverage of the wetland area by erect vegetation. Submersed vegetation is not included.

Rationale: High densities of emergent wetland vegetation are associated with abundant dissolved and particulate organic matter and the buildup of litter and peat substrates. Abundant plant matter also indicates that microbial activity is high and reducing conditions would be likely. These qualities are predictive of long-term phosphorus storage, sequestration of metals, partitioning of organic contaminants, and denitrification.

Measure/Units: percent cover.

Field Measurement: A 0.25-m^2 quadrat will be used to determine percent cover in the wetland. Transects will be laid out approximately 10 m apart and one quadrat analyzed every 10 m along that transect.

GIS Measurement: Percent of open water within each wetland will be determined and the percent cover of emergent vegetation will be calculated as follows:
V_{mac} = (100 – percent open water).

Wetland Hydroperiod (V_{hydro})

Definition: The frequency and duration of inundation that a wetland experiences in a typical year according to the Cowardin classification as shown on National Wetland Inventory maps. This variable is for use with Equation 2A.

Rationale: The wetland hydroperiod indicates the frequency and duration of inundation and therefore is associated with the extent of oxidation and reducing conditions in wetland soils. Reducing conditions are necessary to transform nitrate to nitrogen gas via denitrification. Therefore wetlands with longer periods of inundation are expected to have a higher potential for removing high nitrate loads (Table 3).

Measure/Units: The categorical hydroperiods as described by Cowardin et al. (1979) are assigned arbitrary values according to the duration of inundation (Table 3).

Field Measurement: Water level recorders will operate continuously and indicate the frequency and duration of inundation in selected wetlands.

GIS Measurement: Cowardin classifications and values assigned in Table 3.

Table 3. V_{hydro} and V_{wetdry} values based on Cowardin classification of water regimes.

Water Regime	Weeks Flooded	Description of Surface Water	NWI symbol	V_{hydro} Eq. 2A	V_{wetdry} Eq. 2B
Permanently flooded	52	Present year round	H	1.0	0.1
Intermittently exposed	41 – 51	Present except during extreme drought	G	0.8	0.4
Semipermanently flooded	18 - 40	Present most of year, when absent, very shallow water table	F	0.6	0.8
Seasonally flooded	5 - 17	Wet during growing season, typically exposed during some period of each year	C	0.4	1.0
Saturated	seldom	Seldom present but soils saturated for extended periods	B	0.2	0.8
Temporarily flooded	1 – 4	Present for brief periods, lower water table, facultative vegetation	A	0.1	0.4
Intermittently flooded	seldom	If present, no seasonal pattern, hydric soils unlikely	J	0.05	0.1

Wet-dry Potential (V_{wetdry})

Definition: The potential frequency of water level fluctuations that a wetland experiences in a typical year based on the Cowardin classifications as listed on National Wetland Inventory maps. This variable is for use with Equation 2B.

Rationale: The wetland hydroperiod indicates the frequency and duration of inundation and therefore is associated with the extent of oxidation and reducing conditions in wetland soils. Oxidizing conditions are necessary to transform organic and ammonium nitrogen to nitrate before denitrification can proceed. Therefore wetlands with wet-dry hydrologic regimes have a higher potential for removing organic-nitrogen, ammonium and nitrate loads (Table 3).

Measure/Units: The categorical hydroperiods as described by Cowardin et al. (1979) are assigned arbitrary values according to the duration of inundation (Table 3).

Buffer Density (V_{buff})

Definition: The extent to which the area immediately adjacent to the wetland (30 m from wetland perimeter) is vegetated.

Rationale: High density of vegetation within the buffer area around the wetland contributes to filtration of particulate matter that carries pollutants. During runoff events, these moist soil areas may also contribute to transformation and sequestration of nitrogen, phosphorus, metals, and organics through microbial and sorption processes. The buffer area can be thought of as an extension of the wetland ecosystem, particularly during wet periods, during which the buffer areas may exhibit wetland characteristics such as hydric soils and vegetation.

Measure/Units: percent cover of vegetation within a 30 m zone perpendicular to the perimeter of the wetland.

Field Measurement: A 0.25-m^2 quadrat will be used to determine average percent cover in the wetland. Transects will be laid out perpendicular to the perimeter every 20 m. Along each transect, one quadrat will be analyzed every 10 m.

GIS Measurement: Percent of area that is vegetated within the 30-m wide buffer around the wetland determined using raster, digitized aerial photography.

Soil Organic Matter (V_{som})

Definition: The percent by weight of a soil sample that is comprised of organically derived matter.

Rationale: High soil organic matter has been described as the most important property for assessment of soil quality. Sufficient soil organic matter indicates that microbial activity and sequestration of metals, partitioning of organic contaminants, and denitrification are favored.

Measure/Units: Percent of soil organic matter in samples taken from the top 30 cm. An indexed value based on the range of values samples will be created to assign values between 0.0 and 1.0 to this variable.

Field Measurement: Soil samples will be taken from a subset of locations that are sampled for vegetation composition (quadrats). Samples will be collected with a soil boring tool and placed in centrifuge tubes which will be placed on ice. In the laboratory, wet weight, dry weight and volatile solids weight will be determined on samples. Volatile solids provide an estimate of organic matter in solids (APHA 1998).

GIS Measurement: Percent of soil organic matter will be derived from SSURGO database. If more than one toil type occurs within the wetland, a weighted average will be calculated.

Land Use (V_{LU})

Definition: The dominant land use in the catchment area (including the wetland) based on categories defined in the National Land Cover Database.

Rationale: Land uses in the catchment predict the quality and quantity of runoff that will enter the wetland. This variable is used only to determine whether high levels of nitrate will be likely to enter the wetland during runoff events.

Measure/Units: A weighted average of pollution associated with various land uses (Table 4), multiplied by the percentage of that land use present in the wetland catchment.

Field Measurement: Direct observation will confirm the predominant land uses in the area for comparison to aerial photography. The delineation of catchment boundaries will be determined using standard surveying equipment, LIDAR (where available), or topographic maps.

GIS Measurement: Land use will be obtained from the 2001 National Land Cover Database.

Table 4. Mean runoff concentrations from selected land use types (from Adamus and Bergman 1995). a. Value set to zero to indicate no additional pollution loading from natural lands.

Land Use Category	**Total Nitrogen (mg L^{-1})**
Low Density Residential	1.77
Medium Density Residential	2.29
High Density Residential	2.22
Low Intensity Commercial	1.18
High Intensity Commercial	2.83
Industrial	1.79
Agriculture - Pasture	2.48
Agriculture - Crops	2.68
Agriculture - Other	2.32
Mining	1.18
Recreation, Open Space, Range	1.25
Natural Areas	0.00

Soil Clay Content (V_{clay})

Definition: The percentage of a soil sample, by weight, that is comprised of material classified as <0.002 mm in size.

Rationale: Clay particles in soil have very high surface areas as well as a surface chemistry that enhance the sorption of polar molecules such as ammonium, heavy metals, some organics, and phosphates. Soils with high clay contents are also more likely to retain these contaminants over time.

Measure/Units: This measurement yield categorical values based on the surface texture of subsamples and is unitless.

Field Measurement: Soil samples are taken from a subset of locations and the "Texture-by-feel" method (Figure 2) is used to determine the soil textural class (clay, silt, sand, etc.). The class is then used to determine the average clay content as indicated by the soil pyramid (Figure 3.). The textural class of soil is indexed to provide values between 0.0 and 1.0 (Table 5).

GIS Measurement: Soil clay content will be estimated from surface texture (SURFTEX) attribute data from the Soil Survey Geographic (SSURGO) database. The conventional definitions for soil textural classes of clay (material below 0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2.0 mm) are used to define the different soil types. The database classifications are ranked and assigned values from 0.0 to 1.0 for GIS application. If more than one toil type occurs within the wetland, a weighted average will be calculated.

Table 5. V_{clay} subindex values based on soil surface texture and clay content.

Textural Classification	Range of Clay Content (%)	FCI Value
Clay	56-100	1.00
Silty clay	40-60	0.64
Sandy clay	38-56	0.60
Silty clay loam	28-40	0.44
Clay loam	28-40	0.44
Sandy clay loam	20-38	0.37
Loamy sand	10-15	0.23
Sandy loam	15-20	0.22
Loam	8-28	0.18
Silt loam	0-28	0.16
Silt	0-12	0.08
Sand	0-10	0.06

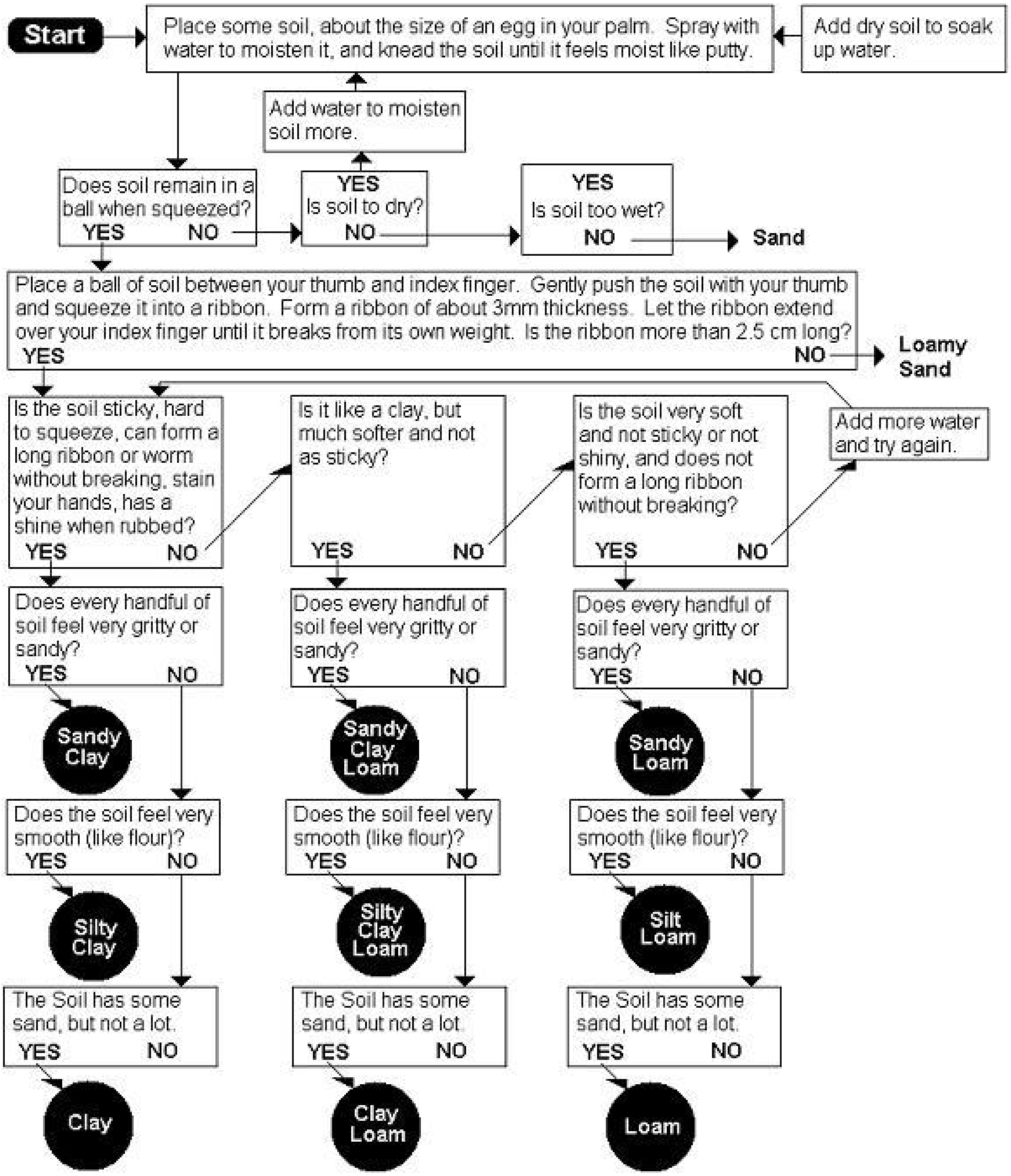

Figure 2. A method for determining soil class by surface texture. Modified from S.J. Thien. 1979. A flow diagram for teaching texture by feel analysis. *Jour. of Agron. Educ.* 8:54-55. http://soils.usda.gov/education/resources/k_12/lessons/texture/

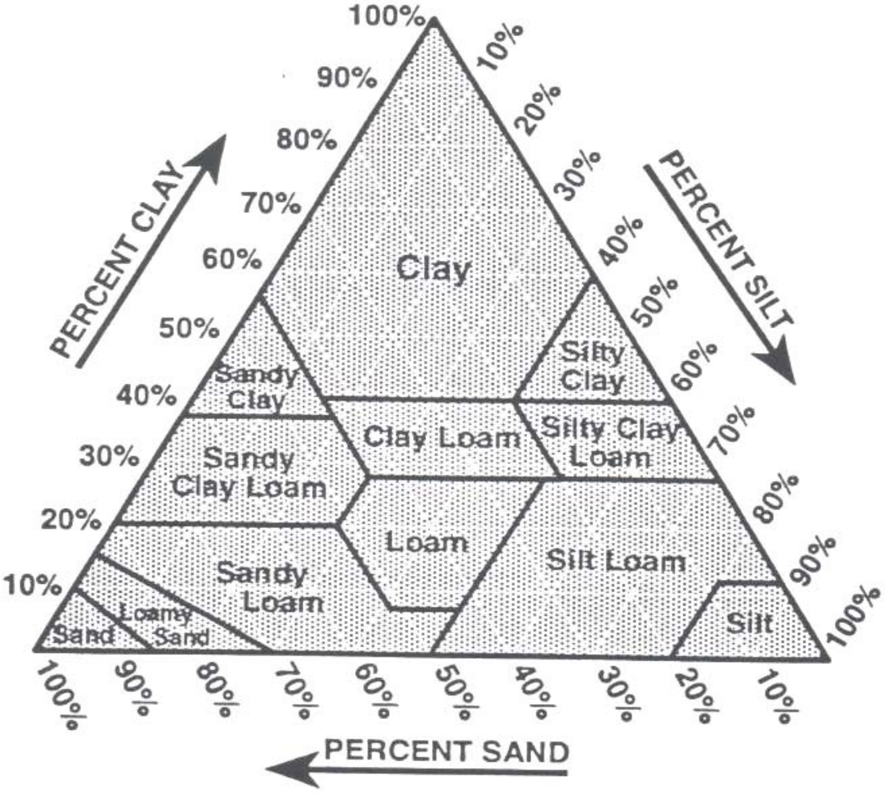

Figure 3. Soil pyramid for textural classifications.

Soil pH (V_{soilpH})

Definition: The pH (acidity) of a soil-water mixture on a scale of 0 to 14 with 7.0 being neutral.

Rationale: Soil pH influences water quality and sorption/precipitation mechanisms. Many pollutants are more soluble in acidic conditions. In alkaline soils, calcium and magnesium will form insoluble precipitates with many pollutants, especially phosphates and metals.

Measure/Units: Soil pH ranges and categories are included in USDA Soil Survey Manuals for each mapped soil type. The pH ranges are converted to index values as shown in Table 5.

Field Measurement: Soil collected for determination of soil organic matter, and textural analysis will be used for determination of soil pH. After determination of soil dry weight, 40 grams of dried soil will be added to an equal weight of distilled water and mixed. A pH probe will be used to determine the pH of the supernatant. Three replicates will be analyzed for pH. Soil pH classes and FCI values are shown in Table 6.

GIS Measurement: Soil pH descriptions will be obtained from the SSURGO database and converted to FCI values according to Table 6. If more than one toil type occurs within the wetland, a weighted average will be calculated.

Table 6. Soil pH classes, associated pH values, and indices values for $V_{soilpH.}$

Soil pH Class	**Soil pH range**[a]	**FCI Value**
Ultra acid	< 3.5	0.0
Extremely acid	3.5 – 4.4	0.1
Very strongly acid	4.5 – 5.0	0.2
Strongly acid	5.1 – 5.5	0.3
Moderately acid	5.6 – 6.0	0.4
Slightly acid	6.1 – 6.5	0.5
Neutral	6.6 – 7.3	0.6
Slightly alkaline	7.4 – 7.8	0.7
Moderately alkaline	7.9 – 8.4	0.8
Strongly alkaline	8.5 – 9.0	0.9
Very strongly alkaline	> 9.0	1.0

a. From the National Soil Survey Handbook (USDA 1993).