Modeling the Effects of Macrophytes on Hydrodynamics

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Abstract: A computer model was created as a scientific and management tool for understanding the effects of macrophytes on hydrodynamics and water quality. A model was required that could simulate macrophytes in a complex water body and could be coupled to a multicompartment water quality model of phytoplankton, dissolved oxygen, nutrients, pH, and organic matter. This would permit the investigation of water resource issues where macrophyte growth, phytoplankton growth, nutrient loadings, and flood control were all contributing factors. The model was added as a compartment to the U.S. Army Corps of Engineers two-dimensional, laterally averaged, dynamic water quality model, CE-QUAL-W2 (Corps of Engineers, water quality, width averaged, two dimensional) and applied to the Columbia Slough, Ore. Features of the macrophyte model include the capability to simulate multiple submerged macrophyte species; transport of nutrient fluxes between plant biomass and the water column and/or sediments; growth limitation due to nutrient, light and temperature; simulation of the spatial distribution of macrophytes vertically and horizontally; the modeling of light attenuation in the water column caused by macrophyte concentration; and the modeling of open channel flow with channel friction due to macrophytes. The macrophyte model was tested through mass balances and sensitivity analyses. The modeling of channel friction was evaluated by comparing predicted water levels with data from tests conducted in a laboratory flume. Use of the model in the Columbia Slough showed reasonable predictive capability regarding estimated biomass and water level dynamics.

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Introduction

Macrophytes, rooted aquatic plants, can be a nuisance for surface water systems affecting both the channel hydraulics (by restricting the conveyance volume) and water quality (by nutrient and inorganic carbon cycling of the plants and the impacts of the biomass after sloughing—see Fig. 1). These plants can also support attached algae, or epiphyton. Being able to predict the growth and water quality and hydrodynamic impact of rooted aquatic plants is an additional tool that environmental managers can use to improve and manage water quality in surface water systems.

The objective of this research was the creation of a model that could be applied as a tool for understanding effects of macrophytes on the hydrodynamics and water quality of water bodies. A model was required that could simulate macrophytes in a complex water body and could be coupled to a hydrodynamic multicompartment water quality model of phytoplankton, dissolved oxygen, nutrients, pH, and organic matter. This would permit the investigation of water resource issues where macrophyte growth, phytoplankton growth, nutrient loadings, and flood control were all contributing factors.

Existing macrophyte models can be divided into three categories: (1) macrophyte models that simulate the complexity of the growth cycle and plant structures of a species and where environmental variables such as nutrient concentrations, meteorological conditions and light intensity are input variables and are not simulated separately; (2) simplified macrophyte models that do not distinguish between macrophyte parts or species and are included as a compartment in a whole-lake water quality model; and (3) hydrodynamic models that simulate the effect of macrophytes on channel friction. The model described herein simulates the coupled effect of macrophytes on open channel flow in a multidimensional model. Prior models have simulated the impact of macrophytes on hydraulics and water quality separately, but because macrophyte growth can increase channel resistance and detention time, there is a coupling between hydraulics and water quality that necessitates combined modeling. In order to model macrophytes two major objectives was required to be met:
• Modeling of the channel blockage and friction effects of macrophytes; and
• Development of an algorithm that simulates the growth of macrophytes.

This paper discusses modeling the channel blockage, growth, and friction effects of macrophytes. A future paper will more fully discuss the water quality effects of macrophytes. The model was incorporated as a subroutine in the Corps of Engineers water quality and hydrodynamic reservoir model CE-QUAL-W2 (Cole and Wells 2006), allowing it to be applied to other systems. The algorithm was tested and used to simulate macrophyte growth in the Columbia Slough, a eutrophic water body located in Portland, Ore.
Background

Macrophytes can be divided into four different groups. Emergent macrophytes grow in shallow water or where sediment is water saturated. Submersed macrophytes occur at all depths where there is enough light for them to exist. Nutrients needed for growth are obtained from the open water and the sediment. Nitrogen, phosphorus, iron, manganese, and micronutrients are primarily obtained from the sediments and calcium, magnesium, sodium, potassium, sulfate, chloride, and carbon are usually obtained from the open water (Barko et al. 1991). Macrophytes that are rooted to the sediments, but have leaves floating on the surface, are called floating-leafed macrophytes. Macrophytes not rooted to the sediments that float on the water surface are referred to as freely floating macrophytes. Their root systems are suspended below the water surface. Nutrients are obtained from the water column and examples include the water hyacinth and duckweed. Plants not in the active growth phase will not have significant nutrient uptake (O’ Brien 1981).

Macrophytes are generally modeled in terms of biomass, but some models only consider oxygen production and loss due to macrophytes (Rutherford 1977). The change in macrophyte biomass has been typically simulated by calculating the time rate of change in biomass as a function of photosynthesis, respiration, and plant washout and decay (Carr et al. 1997). The amount of carbon, nitrogen, and phosphorus contained in macrophyte biomass can vary depending on species, plant part, age, and the environment. Best (1977) found the dry weight carbon percentage of Ceratophyllum demersum to vary between 24.9 and 55.4% and Elodea canadensis to vary between 11.7 and 44.7%. Nitrogen content was found to vary between 1 and 4% of dry weight. For many models nutrients were assumed to be nonlimiting, so the accounting for the biomass fraction of the plants was neglected (Best and Boyd 1999; Scheffer et al. 1993; Titus et al. 1975). When the biomass fraction of macrophyte fraction was modeled, they were generally modeled as constants (Collins and Wlosinski 1989). For two species commonly found in the Columbia Slough, Ceratophyllum demersum and Elodea canadensis, the biomass fraction of nutrients can vary and this will limit growth when the nutrient uptake and release from macrophytes are modeled.

The chemical reactions controlling the rates of photosynthesis and respiration are a function of water temperature. The effect of temperature on macrophyte growth and respiration is typically modeled by multiplying a maximum growth rate by a limitation factor. Functions and algorithms used to simulate the effect of temperature on photosynthetic and respiration rates include the Hill function (Scheffer et al. 1993), the Thornton and Lessem (1978) temperature algorithm, the Arrhenius function, the Q_{10} or van’t Hoff equation, and the temperature function derived by Shugart et al. (1974).

Macrophyte growth rate is also a function of the amount of light reaching the macrophyte stems and leaves. As light intensity increases, photosynthesis increases until the light intensity reaches a saturation value. Depending upon the species, light intensity exceeding saturation may or may not result in photoinhibition (Titus and Adams 1979). Steele’s equation was used in the macrophyte compartment of the reservoir model CE-QUAL-R1 (Collins and Wlosinski 1989). Because the value of the function falls after light intensity exceeds saturation, photoinhibition can be modeled if necessary, although there is uncertainty about the prevalence of photoinhibition occurring in submerged macrophytes (Søndergaard 1988; Titus and Adams 1979).

The Michaelis–Menten equation is the mathematical function most commonly used to simulate nitrogen, carbon, or phosphorus growth limitation in macrophyte models (Collins and Wlosinski 1989; Wright and McDonnell 1986). Nitrogen and phosphorus are the nutrients with the greatest potential for limiting macrophyte productivity. Even when growing in infertile, coarse-textured sediments, submersed macrophytes obtained most of their phosphorus from sediments (Chambers et al. 1989). Barko et al. (1991) state that sediments are the source of much more than 50% of total P uptake in rooted macrophytes. Because many rooted submersed macrophytes obtain nitrogen and phosphorus from sediment interstitial water where nutrients are generally plentiful (Barko et al. 1991), macrophytes are most likely limited by light or carbon. Some studies have shown that nitrogen is more likely to limit production than phosphorus because it is depleted more rapidly (Barko et al. 1988; Carignan 1985; Chen and Barko 1988). In some species, ammonium is preferred over nitrate as the nitrogen source (Nichols and Keeney 1976; Short and McRoy 1984). Many macrophyte models assume that nutrients are not limiting and are limited only by light and temperature (Best and Boyd 1999; Scheffer et al. 1993; Titus and Adams 1979).

Most species of submersed macrophytes obtain carbon from the water column although a few acquire carbon from the interstitial water in the sediments and others through aerial leaves (Madsen and Sand-Jensen 1991). Carbon dioxide is the preferred source but bicarbonate can be used by certain species when the availability of free CO_{2} is limited. Elodea canadensis and Potamogeton pectinatus, for instance, can utilize bicarbonate and free CO_{2}.

Macrophyte biomass can be lost because of the high relative rate of respiration to photosynthesis, washout due to high current velocities, herbivores, microbial decay, and wave action. Losses are generally modeled using a constant loss rate because these mechanisms are more complicated and less understood (Wright and McDonnell 1986).

Macrophyte Model

The macrophyte compartment was added to the Corps of Engineers two-dimensional, laterally averaged, dynamic water quality model, CE-QUAL-W2 (Cole and Buchak 1995; Cole and Wells 2006). CE-QUAL-W2 consists of directly coupled hydrodynamic and water quality transport models. Developed for reservoirs and
narrow, stratified estuaries, CE-QUAL-W2 can handle a branched and/or looped system with flow and/or head boundary conditions. CE-QUAL-W2 simulates parameters such as temperature, algae concentration, dissolved oxygen concentration, pH, nutrient concentrations, organic matter and detention time.

**Macrophyte Growth**

The nutrient fluxes for the macrophyte compartment are shown in Fig. 2. The model is designed to simulate submerged macrophyte species. Light and temperature may limit growth and nitrogen and phosphorus are obtained from the sediments or the water column. Carbon may be obtained from the water column or the atmosphere. Plants grow upwards from the sediment through model layers (Fig. 3). When the biomass in a model layer reaches a specified density, growth is permitted in the above layer. Macrophyte shading was modeled by making light attenuation a function of macrophyte concentration. Because the macrophyte growth varies laterally across a model segment, they are represented as quasi-three dimensional.

The macrophyte growth rate is modeled as follows:

$$S_{mac} = \mu_{mmac} f(I, N, P, C) \gamma_1 \gamma_2 \Phi_{mac} - K_{mr} \gamma_1 \Phi_{mac} - K_{mm} \gamma_1 \Phi_{mac}$$

where

- $S_{mac}$ = macrophyte source/sink term (mg/L/d);
- $\Phi_{mac}$ = macrophyte concentration (mg/L);
- $I$ = solar radiation (W/m$^2$);
- $f(I, N, P, C)$ = growth limiting function as a function of light in-
tensity, nitrogen concentration, phosphorus concentration, and carbon concentration, respectively; \( \mu_{\text{max}} \) = maximum macrophyte growth rate (day\(^{-1}\)); \( K_{\text{m}} \) = maximum respiration rate (day\(^{-1}\)); \( K_{\text{mm}} \) = mortality/excretion rate (day\(^{-1}\)); \( \gamma_I \) = ascending temperature rate multiplier; and \( \gamma_s \) = descending temperature rate multiplier.

Growth rate, respiration rate, and mortality/excretion rate are temperature dependent. Temperature effects are modeled using the equations developed by Thornton and Lessem (1978) that are currently used in the phytoplankton compartment of CE-QUAL-W2. The growth limiting function \( f(I, N, P, C) \) is the minimum of the light \( f(I) \), nitrogen \( f(N) \), phosphorus \( f(P) \), and carbon \( f(C) \) limiting functions such that

\[
f(I, N, P, C) = \min(f(I), f(N), f(P), f(C))
\]

All the limiting functions are unit-less and have a value between 0 and 1. The limiting functions for the nutrients have the following Michaelis–Menten form:

\[
f(\Theta) = \frac{\Theta}{\Theta + H}
\]

(2)

where \( \Theta \) (mg/L) = nutrient concentration and \( H \) (mg/L) = half-saturation concentration. The Michaelis–Menten equation is the limiting function used in most models (Scheffer et al. 1993; Wright and McDonnell 1986). Light limitation was modeled with a hyperbolic equation that has the same form as the Michaelis–Menten function

\[
f(I) = \frac{I}{I + I_h}
\]

(3)

where \( I \) = solar radiation (W/m\(^2\)) and \( I_h \) = half-saturation coefficient for solar radiation (W/m\(^2\)). This function is frequently used in the absence of photoinhibition (Carr et al. 1997).

The attenuation of light due to macrophyte plant tissue has been modeled using a specific light coefficient dependent upon concentration (Ikusima 1970; Titus and Adams 1979; Van der Bijl et al. 1989) giving

\[
\gamma_{\text{mac}} = e_{\text{mac}} \Phi_{\text{mac}}
\]

(4)

where \( \gamma_{\text{mac}} \) (m\(^{-1}\)) = light extinction coefficient contribution due to macrophytes and \( e_{\text{mac}} \) (m\(^3\)m\(^{-1}\)g\(^{-1}\)) is the light extinction due to macrophyte concentration.

**Macrophyte Impact on Hydrodynamics**

The frictional resistance of flow through vegetation is dependent on the flow velocity, vegetation distribution, channel roughness, and the structural and hydrodynamic properties associated with stems and leaves of plants. A number of methods using and combining different techniques have been developed to model flow through vegetation. Included are methods considering porosity of the vegetation (Kadlec et al. 1981), drag force caused by single objects, bending of vegetation (Kouwen and Unny 1973), logarithmic velocity profiles above rough surfaces (Kouwen et al. 1969), linear regressions estimating the resistive force based on flow and vegetation characteristics (Roig 1994) and the Manning’s equation.

Open channel flow is frequently described by the uniform flow steady-state Manning’s equation (Streeter and Wylie 1985). Although developed to describe turbulent flow in open channels where the predominant frictional force is the result of bed shear, Manning’s equation has been applied to channels filled with extensive vegetation growth and debris (Gippel 1995). As noted by Kadlec (1990) and by Petryk and Bosmajian (1975), difficulties arise in applying the equation to channels where the drag forces due to debris and vegetation are controlling because \( n \) is nonconstant and varies with hydraulic radius and velocity. The channel hydraulic radius becomes less significant to flow where channels are filled with vegetation and debris. The density of vegetation also can vary with depth affecting the channel Manning’s \( n \). Despite these problems, Manning’s equation has been used to analyze flow in channels of debris and vegetation.

In this application modeling of flow through macrophytes incorporates the following concepts:

- Porosity of the macrophytes, which is the ratio of plant volume to total channel volume;
- The drag of individual stems and leaves is summed to determine the total drag force in a model cell; and
- The effective Manning’s \( n \) was calculated by combining the effect of bed shear and the drag force on the plants.

The total frictional force was partitioned into a bottom friction component and a vegetation drag component.

The Columbia Slough model had previously been calibrated without macrophytes (Wells 1992; Wells and Berger 1994). Manning’s friction factor for the model segments was typically around 0.03.

Petryk and Bosmajian (1975) developed a method for calculating Manning’s coefficient in vegetated channels given the hydraulic radius, the friction of the bed alone without vegetation, and vegetation characteristics. The analysis was applied to steady uniform flow conditions but the results can be applied to gradually varied flow conditions. An \( x \)-direction force balance was developed consisting of gravitational, individual plant drag, and bed shear force terms. Pressure forces in the \( x \) direction were assumed to cancel. The \( x \)-direction force balance for a channel section was

\[
\gamma ALS - \sum D_i - \tau_w P_w L = 0
\]

(5)

where \( \gamma \) = specific weight of water; \( A \) = cross-sectional area of channel; \( L \) = channel segment length; \( S \) = slope of the channel bed; \( D_i \) = drag on the \( i \)th plant; \( \tau_w \) = boundary shear stress; and \( P_w \) = wetted perimeter of the channel.

The drag force caused by the \( i \)th plant was described by

\[
D_i = \frac{C_d \gamma V_i^2 A_i}{2g}
\]

(6)

where \( C_d \) = drag coefficient; \( A_i \) = cross-sectional area of the \( i \)th plant perpendicular to the direction of flow; \( V_i \) = flow velocity on the \( i \)th plant; and \( g \) = gravitational constant. An expression for boundary shear stress was developed from the conventional derivation for shear stress

\[
\tau_w = \gamma \left( \frac{A}{P_w} \right) S_f
\]

(7)

and the Manning’s formula

\[
V = \frac{1}{n_b} \left( \frac{A}{P_w} \right)^{2/3} S_f^{1/2}
\]

(8)

where \( S_f \) = energy gradient and \( n_b \) = Manning’s coefficient for bed shear. Substituting for \( S_f \) gives
\[ \tau_w = \gamma V^2 n_b^2 \left( \frac{P_w}{A} \right)^{1/3} \]  

Assuming that the flow velocity on each plant \( V_i \) is identical to the mean flow velocity \( V \), the force balance for a channel segment is then

\[ \gamma ALS - \frac{\gamma C_d V^2 \sum A_i}{2g} - \gamma V^2 n_b^2 \left( \frac{P_w}{A} \right)^{1/3} P_w L = 0 \]  

Solving for \( V^2 \) gives

\[ V^2 = \frac{S}{C_d \sum A_i / 2gAL + n_b^2 \left( \frac{P_w}{A} \right)^{4/3}} \]  

The Manning's equation can also be expressed in terms of \( V^2 \) giving

\[ V^2 = \frac{1}{n^2} \left( \frac{A}{P_w} \right)^{4/3} S \]

where \( n \) = Manning's coefficient of the channel due to the effects of both the bottom shear and the vegetation. Equating the two expressions for \( V^2 \) and then solving for \( n \) results in

\[ n = n_b \sqrt{\frac{C_d \sum A_i}{2gAL} \frac{1}{1 + \frac{\gamma C_d}{2gAL} n_b^2 R^{4/3}}} \]

with an hydraulic radius \( R = A/P_w \).

The effect of vegetation on Manning's \( n \) was investigated in areas where flow occurs through vegetation (Petryk and Bosmajian 1975). Eq. (13) can also be expressed as

\[ \frac{C_d \sum A_i}{AL} = 2g(n^2 - n_b^2)R^{4/3} \]

where \( \sum A_i/AL \) was defined as the vegetation density (\( L^{-1} \)). The vegetation density calculated by the previous equation was then compared to values measured in the field. The effective Manning's \( n \) can be calculated for a given vegetation density.

Vegetative drag caused by macrophytes was modeled in a manner similar to that used by Petryk and Bosmajian (1975) where the effective Manning's \( n \) was calculated for each model cell using Eq. (13). It was assumed that the same drag coefficient applied to all plants being simulated in a specific macrophyte compartment. The horizontal velocity in a model cell \( U \) was assumed to be the same as the mean velocity \( V \). Thus, all macrophytes within a model cell at a given model iteration experience the same velocity. The total plant area normal to the direction of flow \( \Sigma A_i \) was estimated using surface area/dry weight ratios determined by Sher-Kaul et al. (1995) for several macrophyte species including *Elodea canadensis*, a species prolific in the Columbia Slough. The effective Manning's \( n \) for each model cell was then used to estimate friction in the CE-QUAL-W2 model (Cole and Wells 2006). The CE-QUAL-W2 model is a 2D vertical-longitudinal model, where the friction factors are determined for each vertical layer as layer resistance coefficients in contrast to cross-sectional averaged resistance factors as in Manning’s equation. The vertical layered average Manning’s friction factor calculation technique is illustrated in Yen (2002) for a channel that has different frictional characteristics as a function of depth. Model segments are divided vertically into cells and the bed shear of each cell is calculated using \( n_b \) and accounting for the wetted perimeter of the cell in contact with the sediments (the sides of the cell added to the width of the cell minus the width of the cell below). If the width of a model cell is not much greater than the width of the cell below, the wetted perimeter will be relatively small and the frictional contribution of the bed shear will be reduced relative to the frictional effect of any macrophytes. Vertical shear stress at cell interfaces are calculated internally using a vertical eddy viscosity formulation.

The governing equations in CE-QUAL-W2 were altered to account for porosity \( \phi \) and the frictional effects of macrophytes. Equations affected include the x-momentum equation, the continuity equation, the free water surface equation, and the constituent transport equation. The six governing equations were derived from three-dimensional, turbulent and time averaged equations. A discussion of their derivation is supplied in Edinger and Buchak (1978) and Wells (1997). The six unknowns are: pressure, \( p \); horizontal velocity, \( U \); vertical velocity, \( W \); constituent concentration, \( \Phi \); density, \( \rho_w \); and free water surface elevation, \( \eta \). Conservation of mass is governed by the continuity equation

\[ \frac{\partial}{\partial x} (U \phi B) + \frac{\partial}{\partial z} (W \phi B) = q \phi B \]

where \( B = \text{channel width and } q = \text{the lateral inflow/outflow per unit volume.} \) Assumptions implicit in the equation’s derivation include a width-averaged channel and constant fluid density.

Conservation of fluid momentum in the horizontal direction is governed by the x-momentum equation

\[ \frac{\partial}{\partial t} (U \phi B) + \frac{\partial}{\partial x} (UU \phi B) + \frac{\partial}{\partial z} (WU \phi B) = - \frac{\phi B \partial p}{\rho_w} \frac{\partial \phi \eta}{\partial x} + \frac{1}{\rho_w} \frac{\partial}{\partial x} (\rho_w \tau_{x\phi}) + \frac{1}{\rho_w} \frac{\partial}{\partial z} (\rho_w \tau_{z\phi}) \]

where \( \tau_{x\phi} = \text{turbulent shear stress acting in the } x \text{ direction on the } x \text{ face of the control volume and } \tau_{z\phi} = \text{turbulent shear stress acting in the } x \text{ direction on the } z \text{ face of the control volume.} \]

The vertical momentum equation simplifies to the hydrostatic equation by assuming that vertical velocities are very low compared to horizontal velocities (\( U \gg W \))

\[ \frac{1}{\rho_w} \frac{\partial \phi \eta}{\partial z} = g \]

The free water surface equation is obtained by integrating the continuity equation over depth

\[ \frac{\partial}{\partial t} (\phi B \eta) = \frac{\partial}{\partial x} \int_{\eta}^{h} U \phi B dz - \int_{\eta}^{h} q \phi B dz \]

where \( B = \text{surface width; } \eta = \text{free water surface elevation; and } h = \text{bottom elevation.} \) In CE-QUAL-W2 the free water surface elevation is integrated over all the layers in a segment.

Water density is governed by the equation of state and is a function of temperature \( T_s \), total dissolved solids concentration \( \Phi_{TDS} \), and suspended solids concentration \( \Phi_{ss} \)

\[ \rho_w = f(T_s, \Phi_{TDS}, \Phi_{ss}) \]

**Application to Laboratory Data**

The width of each model cell was multiplied by the macrophyte porosity to calculate the effective width of the model cell. The effective Manning’s \( n \) was used to calculate frictional resistance.
Because macrophyte density in each model cell varied depending on the layer, every model cell had an effective Manning’s \( n \).

A simple model test was performed by simulating a rectangular laboratory channel and comparing model predictions and data. Roig (1994) experimented using large numbers of cylindrical wooden dowels in a laboratory flume in order to model emergent vegetation in a tidal marsh. Data were obtained from Roig (1994) and compared with CE-QUAL-W2 predictions for different flow rates. Although the flume was artificial, a failed test for such a simple system would help rule out the appropriateness of Eq. (13) for real systems. The laboratory flume was 3.048 m (10 ft) long and 0.457 m (1.5 ft) wide, with 828 dowels distributed uniformly in the channel. Each dowel was 0.286 m (0.938 ft) long and a diameter of 0.00953 m (0.0313 ft). A detailed description of the flume is available in Roig (1994). Table 1 summarizes the flume tests that were simulated by CE-QUAL-W2.

The predicted water levels were compared with data in Fig. 4. Because the drag coefficient for vegetation has been shown to be on the order of 1.0 (Hoerner 1965; Hsi and Nath 1968; Petryk 1969), \( C_d \) was set to 1.0. Model predictions closely matched data with a root mean square error being less than 0.005 m and the mean absolute error less than 0.004 m. The error statistics for the four tests are shown in Table 2. The matching of data with model predictions showed that predicting channel friction using the method developed by Petryk and Bosmajian (1975) where Manning’s coefficient is calculated with Eq. (13) worked well for simulating wooden dowels in a laboratory flume. Roig (1994) felt that the roughness of the wooden dowels approximated the natural roughness of emergent marsh vegetation.

### Application to the Columbia Slough

The Columbia Slough is an extensive system of interconnected wetlands, channels, and lakes located within the Portland, Ore. metropolitan area. It was originally part of a much larger system located in the flood plain at the confluence of the Willamette and Columbia Rivers. Development has affected the slough through construction of levees, roads and culverts, filling of lakes and wetlands, realignment of channels, and urbanization of the watershed. Historically, the Columbia Slough has been managed and maintained primarily for irrigation and flood control. Eutrophic conditions are caused by increased water temperatures due to lack of shading, flow blockages and constrictions, increased detention times, and high nutrient loading from the urbanized watershed and groundwater.

### Table 1. Laboratory Flume Tests That Were Simulated by CE-QUAL-W2

<table>
<thead>
<tr>
<th>Run</th>
<th>Trial</th>
<th>Flow rate (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.0103</td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td>0.0131</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>0.0189</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>0.0188</td>
</tr>
</tbody>
</table>

Note: The run and trial numbers reference tests from Roig (1994).

### Table 2. Error Statistics Comparing Data from Flume Tests with Model Predictions

<table>
<thead>
<tr>
<th>Run</th>
<th>Trial</th>
<th>Mean absolute error (m)</th>
<th>Root-mean-square error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>0.0025</td>
<td>0.0028</td>
</tr>
<tr>
<td>1</td>
<td>14</td>
<td>0.0022</td>
<td>0.0025</td>
</tr>
<tr>
<td>1</td>
<td>25</td>
<td>0.0032</td>
<td>0.0045</td>
</tr>
<tr>
<td>1</td>
<td>30</td>
<td>0.0019</td>
<td>0.0021</td>
</tr>
</tbody>
</table>

Fig. 4. Comparison of laboratory flume tests with model predictions
The hydraulics of the Columbia Slough system are complex. The Lower Columbia Slough is connected to the Columbia and Willamette Rivers and affected by river stages and tidal fluctuations. The Upper Columbia Slough has been disconnected from the rivers by levees, and water levels can be managed through weirs and pumping. Numerous culverts have been constructed that create flow constrictions and control water levels. During the summer ground water is the largest source of inflows and provides a fairly steady source of 1.7–2.8 m$^3$/s (60–100 cfs). In recent years aquatic plants, or macrophytes, have become prolific and have contributed to a substantial increase in channel friction.

The CE-QUAL-W2 model originally developed and calibrated for the Columbia Slough did not simulate macrophytes because macrophytes were not as prevalent and their presence had not yet become a management concern. In order for the model to be an effective tool, the impact of macrophytes on hydraulics and water quality had to be simulated to adequately predict the impact of possible management strategies.

Model evaluation and testing was aided by hydraulic and water quality data collected over a multiyear period from the Slough. Data available included water level and flow data, instream nutrient data, continuous temperature, dissolved oxygen, and pH data, and macrophyte biomass.

Currently, the Columbia Slough model is composed of 397 longitudinal segments (segment lengths varying from 25 to 231 m) and 17 vertical layers (layer height of 0.30–0.61 m) and 41 branches, many of which are segregated by culverts. There are 51 point source tributaries (storm water, combined sewer overflows and surface runoff), 12 distributed groundwater inflows, 12 irrigation withdrawals, 39 culverts, 4 weirs, and 2 pump stations.

**Water Quality Issues**

The Columbia Slough water quality model was developed to forecast management strategies for improving water quality. Summer pH, algae concentration and ortho-phosphorus concentration frequently have exceeded the Oregon Department of Environmental Quality goals of 8.5, 15 µg/L chlorophyll a, and 0.1 mg/L, respectively. Typical average dissolved orthophosphorus and nitrate concentrations entering the Columbia Slough from groundwater are 0.1 mg/L P and 6 mg/L as N, respectively. Long detention times, caused by flow constrictions and the high water levels pooled in the Upper Slough historically for irrigation demand, provide algae ample time to grow. Periodic high pH and supersaturated dissolved oxygen concentrations are caused by high algae productivity.

Beginning in 1993, a management strategy of flow augmentation using groundwater coupled with shorter in-pool detention times has reduced algae growth. Water levels were lowered resulting in decreased residence times that limited algae growth and allowed light to reach the sediments. Before 1993 water levels were maintained at higher elevations to facilitate irrigation and the phytoplankton-rich water prevented sufficient light from reaching the sediments and allowing macrophyte growth. The resulting increase in water clarity has created an environment favorable to the growth of aquatic plants. Macrophytes have increased water levels and detention time by increasing channel blockage and friction. Macrophytes and epiphyton also affect nutrient cycling by removing nutrients from the water column and sediment.

Fig. 5 shows the change in water level slope caused by increased macrophyte populations in the main arm of the Upper Slough. Usually water is pumped or released by gravity at Multnomah County Drainage District Pumping Station #1 (MCDD#1) into the Lower Slough so that flow is from east to west toward MCDD#1. The channel bottom slope is fairly flat along the main arm and variation in water surface slope can be attributed to increased channel friction or areal blockage. Average water level at MCDD#1 varied from year to year due to slightly different management strategies, but the slope in the water level profile became steeper after 1993 as macrophyte populations increased. Macrophytes were particularly prevalent between the area known as Little Four Corners near the outlet of Prison Pond and the culvert at NE 82nd. In 1993 the water level difference between NE 105th and MCDD#1 was only 0.26 m but by 1996 difference had increased to 0.63 m.

Macrophytes identified in the Columbia Slough include coontail (Ceratophyllum demersum), Elodea canadensis, sago pondweed, duckweed (Lemma minora), curly pondweed (Potamogeton crispus), Illinois pondweed, and the water-starwort (Callitriche stagnalis).

**Calibration**

The model has been calibrated for the summers of 1992, 1993, and 1994. Water levels were lowered in 1993 to reduce algae growth but macrophytes were still not present in significant quantities. During 1994 macrophytes became much more prevalent and the impact on water levels became noticeable. The predominant macrophyte species in the Upper Slough during 1994, the first year of reduced water levels for a complete summer season, was Ceratophyllum demersum (coontails) and Elodea canadensis (S. Geiger, observational notes prepared for Multnomah County Drainage District #2, 1994). For the Columbia Slough project, the macrophytes were simulated using a single compartment. Macrophyte biomass was calibrated to total biomass data removed from the Slough at pumping stations, ground surveys of macrophyte growth extent, and to water level data. Water level data could be used to infer the location of greatest macrophyte density because of the resulting increase in channel friction and water levels. Observational ground surveys of macrophyte coverage also provided valuable data to where macrophytes were growing. Growth was concentrated along the main arm (north arm) of the Upper Slough.
Slough. According to the Multnomah County Drainage District #1, the amount of macrophyte mass removed annually after 1993 ranged from 250 to 500 cubic yards wet mass, which is equivalent to 750–1500 kg dry weight. Fig. 6 shows the 1994 water level predictions and data for six different locations along the main channel of the Columbia Slough. Error statistics for these locations were shown in Table 3. The water surface profiles for two dates in 1994 were shown in Fig. 7. The slope of the water surface profile is caused by increased drag due to the presence of macrophytes. Although plants are likely to have differing drag coefficients, assuming a single value was adequate for calibrating water levels in this system. If it had been necessary, two macrophyte groups with different drag coefficients could have been simulated.

Fig. 8 shows the model predicted macrophyte biomass for 1992, 1993, and 1994. Sloughing of macrophytes was not simulated, and for calibration the total biomass of the modeled macrophytes was compared to biomass removed at the pump stations after senescence in the Fall. The model predicted biomass was within the range of 750–1,000 kg dry weight biomass that was typically removed at the pump stations, during which macrophytes can lose more than 75% of their biomass (Davis and McDonnell 1997; Wright and McDonnell 1986). A comparison between predicted macrophyte biomass with observed macrophyte coverage density along the main arm of the Upper Columbia Slough for September, 1994 is shown in Fig. 9. Fig. 9 indicates that the model predicts macrophyte growth in areas where growth was observed. The observational data shown were qualitative (the percent of macrophyte coverage), whereas the model predictions were in the units of grams per model segment. The model predicts little growth in 1992 and 1993, but predicts significant growth in 1994. This was consistent with observational and water level data. Depth and the lack of water clarity due to algae growth hindered macrophyte growth in 1992. This was also the case in 1993, when water levels were only lowered

Table 3. Error Statistics between Water Level Predictions and Data for 1994

<table>
<thead>
<tr>
<th>River mile</th>
<th>Mean absolute error (m)</th>
<th>Root-mean-square error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.70</td>
<td>0.032</td>
<td>0.037</td>
</tr>
<tr>
<td>9.91</td>
<td>0.051</td>
<td>0.089</td>
</tr>
<tr>
<td>12.29</td>
<td>0.048</td>
<td>0.073</td>
</tr>
<tr>
<td>13.45</td>
<td>0.115</td>
<td>0.139</td>
</tr>
<tr>
<td>14.44</td>
<td>0.098</td>
<td>0.126</td>
</tr>
<tr>
<td>15.20</td>
<td>0.097</td>
<td>0.110</td>
</tr>
<tr>
<td>Average</td>
<td>0.074</td>
<td>0.096</td>
</tr>
</tbody>
</table>

Fig. 6. Comparison of model water level predictions and data along the main channel in the Upper Columbia Slough.

Fig. 7. Comparison of model predicted water level profile and data for two dates in 1994. The water level slope is largely the result of the frictional effects of macrophytes.
in the middle of August. In 1994, however, the lower water levels and improved water clarity permitted an increase in macrophyte populations.

**Conclusion**

This research created a macrophyte computer model that can be used as a tool to help inform resource managers and allowing them to make better decisions toward improving the ecology of water bodies. Because prolific macrophyte growth can create water quality and flood control concerns, this tool to evaluate management strategies will be valuable. The developed macrophyte model was able to simulate the hydrodynamic impacts on the system. The increased channel friction due to macrophyte beds required the model coupling and simultaneous calibration of water quality and hydrodynamics. The macrophyte model was added to the Corps of Engineers reservoir model CE-QUAL-W2, allowing simulation of the interactions of macrophytes with other parameters of concern such as algae, dissolved oxygen, temperature, pH, nutrients, and organic matter. The model was applied to the Columbia Slough, a eutrophic water body located in the Portland, Ore. metropolitan area.

The macrophyte model was able to predict the increase in macrophyte growth that resulted when water levels were lowered in order to control phytoplankton growth. The model predicted a total macrophyte dry weight biomass of approximately 1,000 kg for 1994, which was consistent with the 750–1,500 kg of biomass that has been removed annually from the Columbia Slough. Water levels were predicted with an average absolute mean error of 0.074 m for sites along the main arm of the Upper Slough, the reach of most prolific macrophyte growth.

**Notation**

The following symbols are used in this paper:

- \( A \) = cross-sectional area of channel (m\(^2\));
- \( A_i \) = cross-sectional area of the \( i \)th plant perpendicular to the direction of flow (m\(^2\));
- \( B \) = channel width (m);
- \( B_{0} \) = time and spatially varying surface width (m);
- \( C \) = carbon concentration (mg/L);
- \( C_d \) = drag coefficient;
- \( D_i \) = drag on the \( i \)th plant (N);
- \( D_{lt} \) = longitudinal temperature and constituent dispersion coefficient (m\(^2\)/s);
- \( D_{v} \) = vertical temperature and constituent dispersion coefficient (m\(^2\)/s);
- \( g \) = gravitational constant (m/s\(^2\));
- \( H \) = half-saturation concentration;
- \( h \) = bottom elevation (m);
- \( I \) = solar radiation (W/m\(^2\));
- \( I_{sh} \) = half-saturation coefficient for solar radiation (W/m\(^2\));
- \( K_{me} \) = mortality/excretion rate (day\(^{-1}\));
- \( K_{mr} \) = maximum respiration rate (day\(^{-1}\));
- \( L \) = channel segment length (m);
- \( N \) = nitrogen concentration (mg/L);
- \( n \) = effective Manning’s friction coefficient;
- \( n_b \) = Manning’s friction coefficient for bed shear;
- \( P \) = phosphorus concentration (mg/L);
- \( P_{w} \) = wetted perimeter of the channel (m);
- \( p \) = water pressure (N/m\(^2\));
- \( q \) = lateral inflow/outflow per unit volume (T\(^{-1}\));
- \( q_{k} \) = lateral inflow of constituent per unit volume (mg/L/s);
- \( R \) = hydraulic radius (m);
- \( S \) = channel bed slope;
- \( S_{e} \) = energy gradient;
- \( S_{k} \) = kinetics source/sink term for constituent concentration (mg/L/s);
- \( S_{mac} \) = macrophyte source/sink term (mg/L/day);
References


