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Modeling Macrophytes of the Columbia Slough, Oregon

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Abstract

The Columbia Slough is a tidally influenced freshwater system of wetlands, channels, and lakes located within the Portland, Oregon metropolitan area at the confluence of the Willamette and Columbia Rivers. It is a eutrophic water body susceptible to algae blooms and crashes and periods of high pH which violate water quality standards. High nutrient loads from groundwater principally controls algae productivity. Past structural changes to the Columbia Slough have included filling of wetlands and lakes and the construction of levees, dikes, culverts and irrigation channels. These changes have altered the natural flow dynamics creating an environment more conducive to eutrophication. A hydrodynamic and water quality model was used to evaluate management alternatives to improve water quality in the system. The model was developed using the Corps of Engineers two-dimensional, laterally averaged, dynamic water quality model, CE-QUAL-W2. CE-QUAL-W2 consists of directly coupled hydrodynamic and water quality transport.

Recently, a management strategy of flow augmentation using groundwater coupled with shorter in-pool detention times has reduced algae growth. However, the resulting increase in water clarity has created an environment favorable to the growth of aquatic plants. The aquatic plants, or macrophytes, have increased water levels and detention time by increasing channel friction and blockage. Accurate predictions of hydrodynamics were essential for evaluating the water quality impact of flow management strategies. Macrophytes and epiphyton affect nutrient cycling by removing nutrients from the water column and sediment. To help evaluate the study of new management alternatives, the Columbia Slough model was expanded to simulate the water quality and hydrodynamic effects of macrophytes and epiphyton.

Introduction

The Columbia Slough is an extensive system of interconnected wetlands, channels, and lakes located within the Portland, Oregon metropolitan area (Figure 1). 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

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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.

The hydraulics of the Columbia Slough system are very 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 which create flow constrictions and control water levels. During the summer groundwater 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 a contributed to a substantial increase in channel friction while reducing pH extremes and lowering algae concentrations.

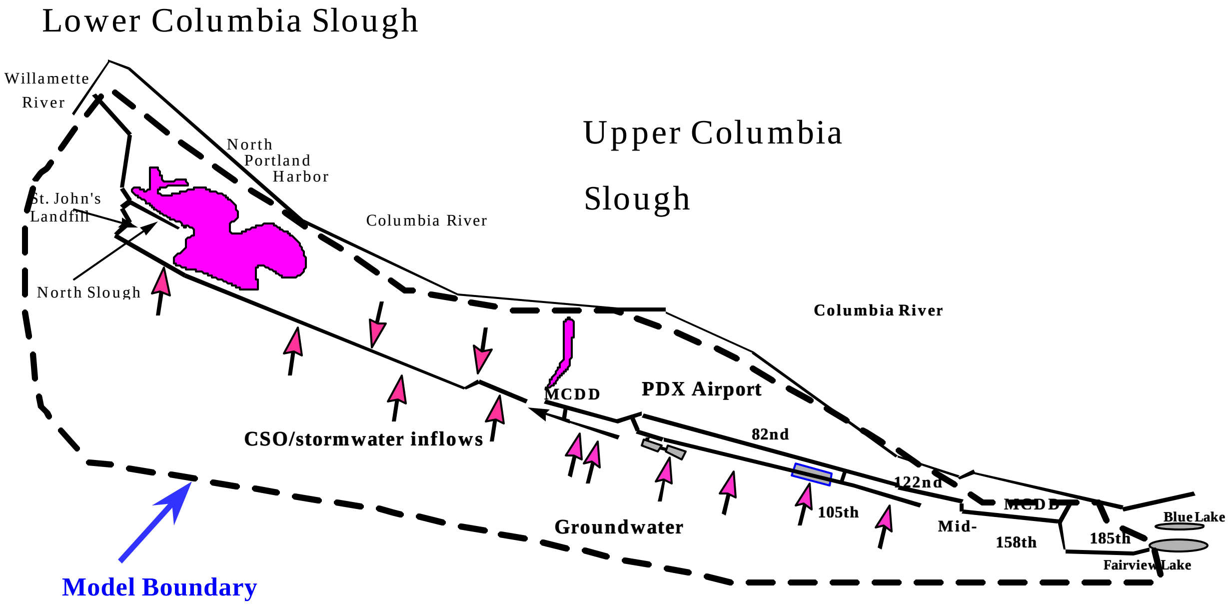

Figure 1. The Columbia Slough.

Water Quality Model

To investigate and evaluate solutions to eutrophication problems in the Columbia Slough, a model was developed using the Corps of Engineers two-dimensional, laterally averaged, dynamic water quality model, CE-QUAL-W2 (Cole and Buchak, 1995; Wells and Berger, 1995). This is a Corps of Engineers modification of the Laterally Averaged Reservoir Model (Edinger and Buchak, 1978). 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.

Currently, the Columbia Slough model is composed of 397 longitudinal segments (segment lengths varying from 25-231 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. Some of these water quality problems were:

- High summer pH
- High algae concentrations
- High summer water temperatures
- Low dissolved oxygen concentrations
- High nutrient concentrations (nitrate and ortho-phosphorus)

Summer pH, algae concentration and ortho-phosphorus concentration frequently have exceeded the Oregon Department of Environmental Quality (DEQ) goals of 8.5, 15 μg/l chlorophyll a, and 0.1 mg/l, respectively. Typical average dissolved ortho-phosphorus 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. The high pH and super-saturated 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.

Figure 2 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 0.84 feet but by 1996 difference had increased to 2.06 feet.

There are a number of trends in water quality parameters since 1992, which was the last year that water levels were maintained at higher levels during the summer for irrigation purposes. The changes in water quality can be explained by shorter detention times, decreased algae growth, and the hydrodynamic and water quality impact of macrophytes. The residence time of the groundwater fed into the Upper Slough was shorter which allowed less heating. Lower residence time resulted in less algae growth and this was reflected in a decrease in summer pH averages.

Nutrient concentrations were also affected by the change in water level management strategy. Ortho-phosphorus averages increased in 1993, the first year of low water levels, but then returned to lower concentrations in succeeding years. The macrophytes did not have a chance to become established in 1993, and in the following years it is possible that the ortho-phosphorus was being utilized by the macrophytes and/or attached epiphyton, instead of phytoplankton like in 1992. There did not seem to be variability in nitrogen concentrations species since the change in water level management.

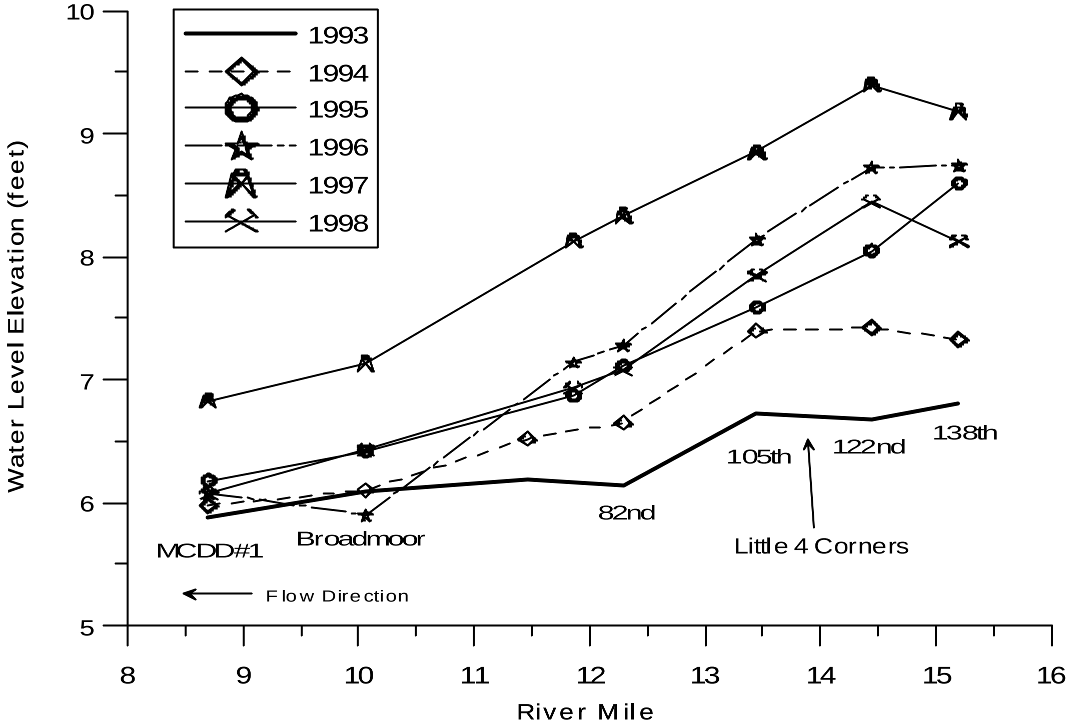

Figure 2. Comparison of 1993 to 1998 average water levels along the main arm of the Upper Columbia Slough for Julian Day 239-274.

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

Water Quality Compartment of Macrophyte Model

The nutrient fluxes for the water quality component of the macrophyte compartment are shown in Figure 3. 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 (Figure 4). 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. Since the macrophyte growth varies laterally across a model segment, they are represented as quasi 3-dimensional.

The stationary macrophyte term is modeled as follows:

$$\frac{\partial C_{23}}{\partial t} = S_{23} = \underbrace{m_{m\max} \frac{I}{I_s} \exp\left(-\frac{I}{I_s} + 1 \right) g_1 g_2 C_{23}}_{\text{growth}} - \underbrace{K_{mr} g_1 C_{23}}_{\text{respiratio n}} - \underbrace{K_{mm} C_{23}}_{\text{mortality}}$$

where C_{23} is macrophyte density (mg/l), I is solar radiation, I_s is saturating solar radiation, $m_{m\max}$ is the maximum macrophyte growth rate (day^{-1}), K_{mr} the maximum respiration rate (day^{-1}), K_{mm} mortality rate (day^{-1}), and g_1, g_2 are the ascending and descending temperature rate multipliers, respectively.

Growth rate and respiration rate temperature are dependent. Temperature effects are modeled using the equations developed by Thornton and Lessem (1978), which are currently used in the phytoplankton compartment of CE-QUAL-W2.

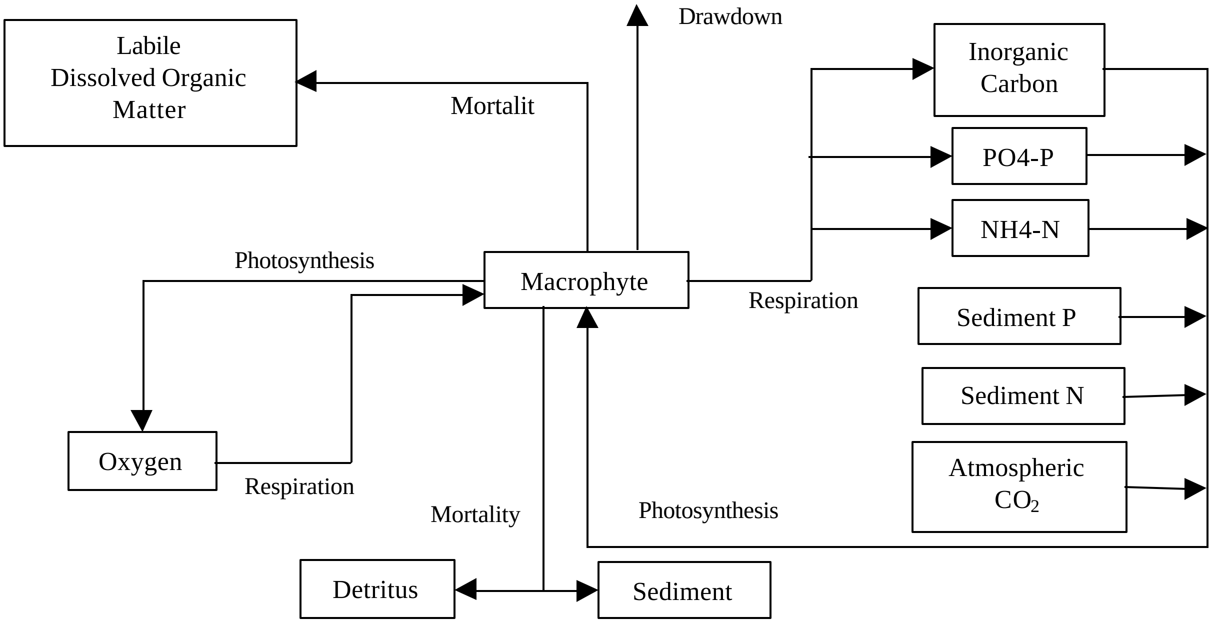

Figure 3. Nutrient fluxes for the macrophyte compartment in CE-QUAL-W2.

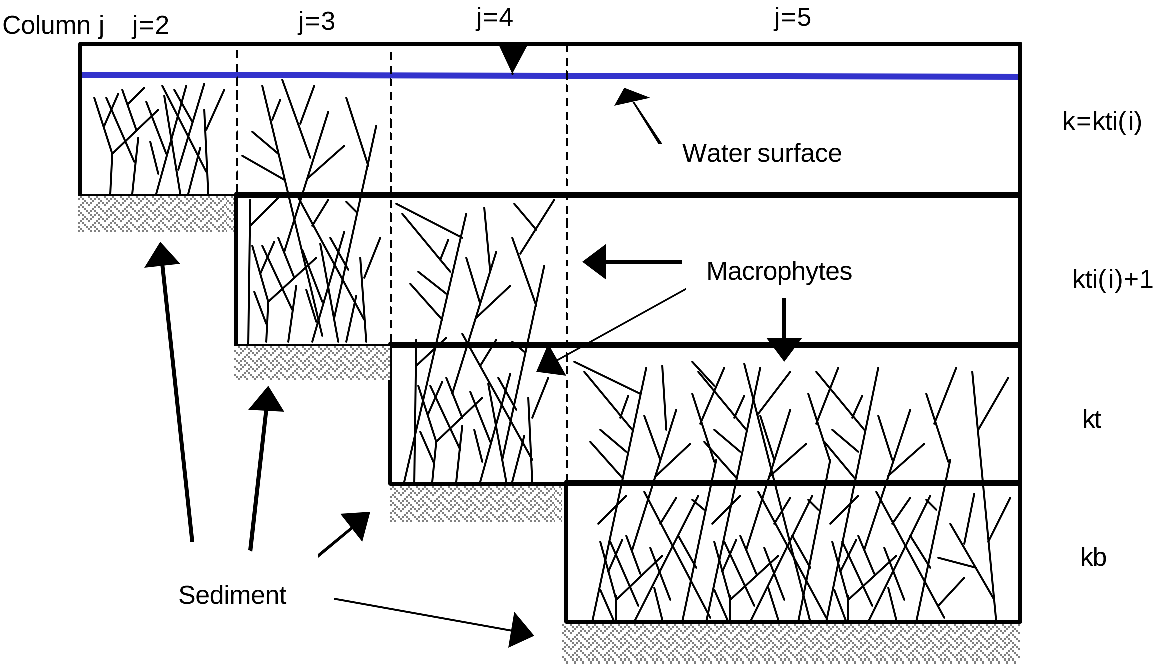

Figure 4. Macrophytes grow in vertical columns from the sediment upward through the model layers.

Hydrodynamic Modeling of Macrophytes

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
- The effective Mannings n was calculated by combining the effect of bed shear and the drag force on the plants

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

Bottom shear t_b was simulated using Manning's friction factor

$$t_b = \frac{r_w g n^2}{R^{1/3}} U\left|U\right|$$

where r_w is the density of water, g is the gravitational constant, U is water velocity, R is the hydraulic radius, and n is Manning's friction factor.

The Columbia Slough model had previously been calibrated without macrophytes. Manning's friction factor for the model segments was typically around 0.03.

Vegetative drag caused by macrophytes was modeled in a manner similar to that used by Petryk and Bosmajian (1975) where the drag force D_i on the i^{th} plant is

$$D_i = C_d A_i \left(\frac{r_w U^2}{2} \right)$$

with A_i being area of plant projected normal to the direction of flow and C_d is a drag coefficient.

The total drag force in a model cell due to vegetation is then

$$\sum D_i = C_d \left(\frac{r_w U^2}{2} \right) \sum A_i$$

If a simple force balance is applied in the manner used by Petryk and Bosmajian (1975), the effective Mannings n of each model cell was then

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

where n_b is the Mannings friction factor due to bed shear only.

The total plant area normal to the direction of flow $\sum A_i$ 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.

Governing Equations

The governing equations in CE-QUAL-W2 were altered to account for porosity f and the frictional effects of macrophytes. Equations affected are listed in Table 1 include the x-momentum equation, the continuity equation, the free water surface equation, and the constituent transport equation.

Table 1. CE-QUAL-W2 governing equations.

Name	Equation
Continuity	$\frac{\partial U f B}{\partial x}+\frac{\partial W f B}{\partial z}=q f B$
X-Momentum	$\frac{\partial U f B}{\partial t}+\frac{\partial UU\ f B}{\partial x}+\frac{\partial WU\ f B}{\partial z}=$ $-\frac{fB}{r}\frac{\partial P}{\partial x}+\frac{1}{r}\frac{\partial f B t_{xx}}{\partial x}+\frac{1}{r}\frac{\partial f B t_{xz}}{\partial z}$
Free Water Surface	$\frac{\partial f B_h h}{\partial t}=\frac{\partial}{\partial x}\int_h^h U f B dz-\int_h^h q f B dz$
Constituent Transport	$\frac{\partial f B\Phi}{\partial t}+\frac{\partial U f B\Phi}{\partial x}+\frac{\partial W f B\Phi}{\partial z}-\frac{\partial}{\partial x} f B D_x \frac{\partial\Phi}{\partial x}-\frac{\partial}{\partial z} f B D_z \frac{\partial\Phi}{\partial z}=$ $q_f f B+S_K f B$
Variable descriptions: U – x-direction velocity, m/s W - z –direction velocity, m/s B – channel width, m B_h – time and spatially varying surface width, m r - density, mg/l q - lateral inflow/outflow per unit volume (s^{-1}) P - Pressure, Newtons/m^2 Φ - constituent concentration, mg/l D_x - longitudinal temperature and constituent dispersion coefficient, m^2/s D_z - vertical temperature and constituent dispersion coefficient, m^2/s q_f - lateral inflow or outflow mass flow rate of constituent per unit volume, mg/l/s S_K - kinetics source/sink term for constituent concentration, mg/l/s h - free water surface elevation, m t_{xz} - vertical shear stress, N/m^2 t_{xx} - longitudinal shear stress, N/m^2	

Vertical shear stress t_{xz} is a function of interfacial shear stress, shear stress due to wind, and bottom and plant shear stress and is defined as

$$\frac{t_{xz}}{r} = A_z \frac{\partial U}{\partial z} + \frac{t_{wx}}{r} e^{-dkz} + \frac{t_{bm}}{r}$$

where is t_{bm} the bottom and plant shear stress, A_z the turbulent eddy viscosity, t_{wx} the wind shear stress, and k the wave number. Bottom and plant shear stress was calculated using the effective Mannings n determined above.

Calibration

The model has been calibrated for the summers of 1992, 1993 and 1994. The summer of 1992 algae growth was high due to high water levels and long residence times. Water levels were lowered in 1993 to reduce algae growth but macrophytes were still not present in significant quantities. During the 1994 macrophytes became much more prevalent and the impact on water levels became noticeable. Data used for macrophyte calibration include dead biomass removed from the trash racks in front of pumping stations at the end of the growing season and water level measurements. Figure 5 shows the 1994 water level predictions and data for 1993 and 1994. The slope of the water surface profile is caused by increased drag due to the presence of macrophytes. The water surface slope in 1993 was flatter because of the absence in macrophytes.

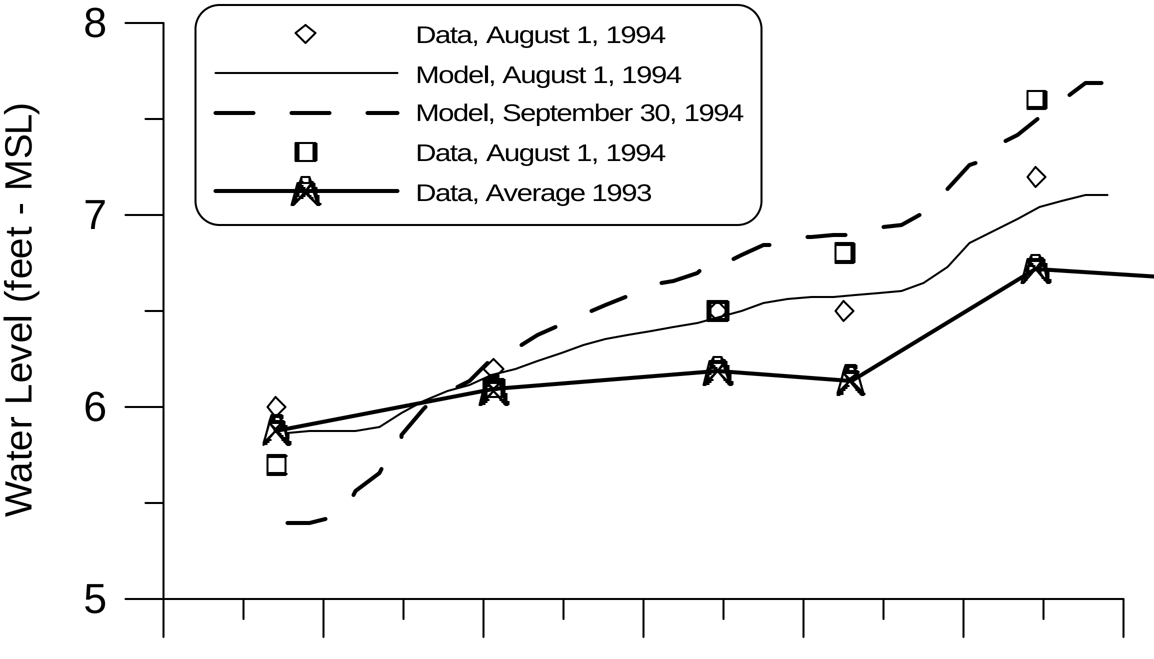

Figure 5. Comparison of model water level predictions and data. The water level slope is largely the result of the frictional effects of macrophytes.

Conclusion

The hydrodynamic and water quality model CE-QUAL-W2 has been expanded to model macrophytes. It has been applied to the Columbia Slough where macrophyte growth became prolific after a management strategy designed to control phytoplankton growth was implemented. The expanded model has been calibrated for several summer seasons and will be used to investigate new management strategies designed to improve water quality and control macrophyte growth.

Acknowledgement

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