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A mechanistic energy balance model for predicting water temperature in surface flow wetlands

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ABSTRACT

Several models have been developed to evaluate the dynamics of water temperature in open water bodies. However, few models have been successful in predicting the water temperatures of wetlands that have significant vegetation coverage. A mechanistic model is presented that estimates the water temperature within surface flow wetlands given basic information on influent flows and water temperature, wetland bathymetry, floating and emergent vegetation plant coverage, and meteorological data. The Heat Source Wetlands (HSW) model presented here was calibrated using data collected from two pilot constructed wetland cells in Salem, OR, USA and a wastewater oxidation pond in Stockton, CA, USA. Overall, the model performed well in predicting the effluent temperatures at these locations with annual root mean squared error values of 0.87–1.69 °C tested over a range in temperature gradients (influent minus effluent temperature) of 12.0 to −6.0 °C, a range of hydraulic retention times for wetlands (3.2–53 days) and ponds (7.4–27 days), and a wide range of emergent vegetation zone coverage (0–71 percent) under two different climate regimes. Additionally, the model was able to simulate the timing and amplitude of diurnal temperature variations in the CW over two annual cycles by accounting for the advection and dispersion and thermal heat storage within the wetland system, evaluating water and plant canopy energy balances separately, and by simulating the individual energy exchange processes on an hourly or shorter time period. Calibration of the models required local adjustments to the evaporation wind function coefficients to capture latent heat losses and adjustments to simulated water depth within the wetland models to capture the diurnal variations in water temperature. Water temperature dynamics in surface flow wetland systems are of increasing interest in settings where discharges are returned to regulated surface water bodies and the model presented here provides a comprehensive framework within which to evaluate these processes. The model also provides a powerful tool for design of engineered wetland systems when water temperatures are a key aspect of the required wetland system performance.

1. Introduction

Energy exchange processes and water temperature within wetlands are important for several reasons including their effect on: (1) rates of key biological processes; (2) water evaporation rates and water losses; and (3) temperature of water discharged from wetlands to other receiving waters. The regulation of water temperature in surface water bodies is an increasingly important issue in the United States and particularly in the Pacific Northwest where strict temperature regulations have been enacted to protect cold water fish such as salmon, trout, and steelhead. In response to new surface water quality criteria and temperature limits on point-source discharges, the use of surface flow wetlands systems has been studied and applied as a tool to passively cool treated wastewater and stormwater flows prior to surface water discharge (Emond et al., 2002; CH2M HILL, 2007; Herb et al., 2007; Gregory, 2009; Jones and Hunt, 2010).

Within a regulatory setting such as compliance with watershed specific temperature Total Maximum Daily Loads (TMDL) or National Pollution Discharge Elimination System (NPDES) permit conditions, the design and/or evaluation of surface flow wetland systems requires predictive models that can be used to accurately

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assess water temperature dynamics. Since surface water temperature standards are commonly measured on the basis of a 7-day moving average of the daily maximum water temperature (EPA, 2003; DEQ, 2008; Ecology, 2010) and peak diurnal water temperature fluctuations have been measured up to 6–6.5 °C in constructed wetlands (Kadlec, 2006, 2009), tools used for regulatory compliance evaluations must be capable of estimating both the seasonal and diurnal water temperature effects over the range of anticipated climatic conditions. Furthermore, design tools are needed that can evaluate water temperature variations under a range of incoming water temperatures, flow rates, wetland physical configurations, and under spatially and temporally varied emergent wetland vegetation coverage. Since the amount of water cooling required to meet discharge limitations is often only a couple of degrees Celsius for municipal wastewater effluent discharges, predictive tools are also needed that can provide a relatively high degree of precision. For the purposes described above, the authors suggest that a temperature model should be capable of predicting seasonal and diurnal water temperature under a range of operational and climate conditions with errors less than 1.0 °C and have set this as an error tolerance target.

Predictive approaches have been applied in the past to estimate wetland water temperatures in response to physical and climatic conditions. Kadlec and Knight (1996) and Kadlec and Wallace (2009) described the overall energy balance of wetland systems and presented empirical methods for estimating annual water temperature cycles. They also laid out an analytical approach to determine the "balance point" water temperature that represents a steady-state equilibrium condition for a given set of meteorological and wetland heat loading conditions. These approaches have been applied and tested with measured operational data over several different climates (Kadlec, 2006, 2009) and have been shown to describe average seasonal cycles and equilibrium energy balance conditions very well. However, these analytical methods do not provide predictive capability of wetland water temperatures under rapidly varied heat or hydraulic loading and meteorological conditions and they do not consider diurnal water temperature fluctuations.

Several mechanistic models with possible application to surface flow wetlands have been developed to estimate water temperature under dynamically varied conditions (Boyd and Kasper, 2003; Cole and Wells, 2011; Confalonieri et al., 2005; Herb et al., 2006a,b, 2007; Maruyama and Kuwagata, 2010; Swain and Decker, 2009, 2010). A summary comparison of these models is presented in Table 1. Although the reported root mean square error (RMSE) in temperature estimates from three of the models (Herb et al., 2006a,b, 2007;

Table 1
Comparison of water temperature models with potential application to surface flow wetlands.

Reference	Model application	Minimum time step	Spatial discretization	Emergent vegetation model	Temperature error (RMSE °C)	Comments
Maruyama and Kuwagata (2010)	Water temperature in flooded rice fields	Daily	Field average – no flow through	Yes	0.70–0.93	Reported error was for daily average water temperature over a four month growing season at 3 locations in Japan
Confalonieri et al. (2005)	Water temperature in flooded rice fields	Hourly or less	Field average – no flow through	Yes	2.8–4.3[a]	Reported error was for hourly water temperature over a four month growing season at 3 locations in Italy
Herb et al. (2006a,b, 2007)	Water temperature in stormwater runoff	Hourly or less	1-D (vertical)	Yes	1.3	Reported error was for hourly estimates over a two month summertime period in a Minnesota wetland with stable water levels
Swain and Decker (2009, 2010): FTLOADDS	Water temperature in the Florida Everglades	Hourly or less	2-D (lateral and longitudinal)	Yes	0.71–1.93	Reported error was for daily average water temperature over a seven-year period at 3 locations in the Florida Everglades
Boyd and Kasper (2003); Heat Source version 7.0	Water temperature in rivers and streams	Hourly or less	1-D (longitudinal)	Yes[b]	NA[b]	Used widely for stream systems that do not thermally stratify
Cole and Wells (2011); CE-QUAL-W2 version 3.7	Water temperature in lakes, rivers, and streams	Hourly or less	2-D (vertical and longitudinal)	No	NA[b]	Used widely for surface water quality modeling including systems that thermally stratify

[a] Reported error was 11–17 percent as relative RMSE. Actual RMSE estimated based on an average water temperature of 25 °C.
[b] Model has not been calibrated or evaluated for water temperature from surface flow wetlands with emergent vegetation.