Ecological Modelling 393 (2019) 85–97

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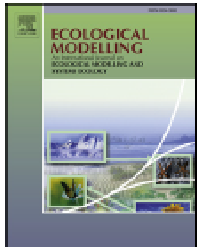
Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel



Dissolved oxygen modeling of effluent-dominated macrophyte-rich Silver Bow Creek

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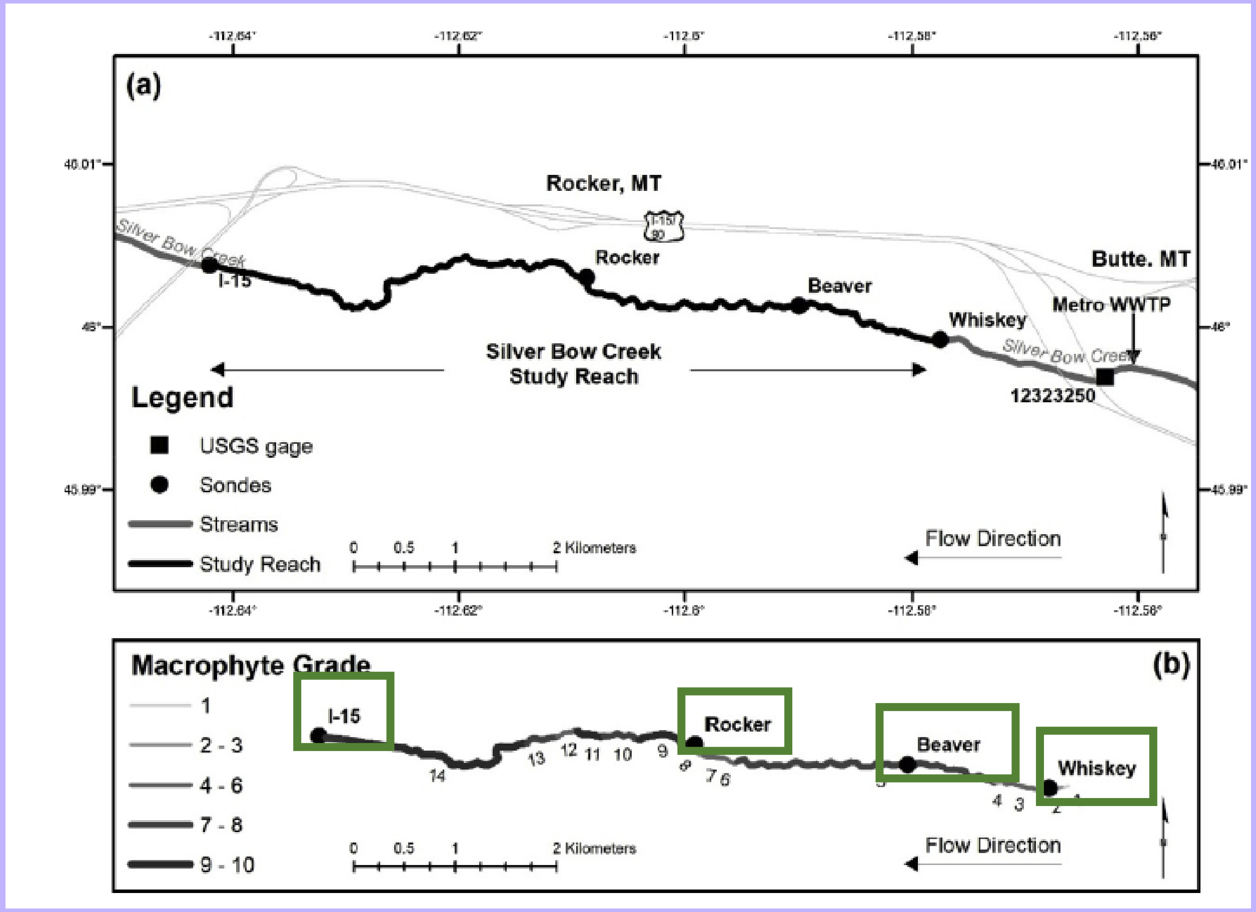
Impacts of wastewater treatment plants (WWTPs) on the DO balance of a receiving water are widely noted (Haggard et al., 2001, 2005; Marti et al., 2004; Gücker et al., 2006; Aristi et al., 2015). In both raw and treated wastewater, nitrogenous or carbonaceous forms of biochemical oxygen demand (BOD) cause deoxygenation. When the rate of DO consumption from ammonium (NH_4^-) oxidation or degradation of labile and refractory forms of carbon exceeds reaeration, an oxygen sag occurs. The most widely publicized of these is documented in the seminal work of Streeter and Phelps (1925) on the Ohio River. Based on an elegant analytical model relating the physics, chemistry, and biology to saturation deficit downstream of a point source, the DO sag minimum can be computed, which occurs at the location where the rate of BOD decomposition and reaeration are equivalent (Chapra, 2008).

Silver Bow Creek (MT)

- impaired by nitrate, nitrogen, and phosphorus
- does not support aquatic life
- documented observations of diurnal fluctuations
- *macrophytes:* sago pondweed, white buttercup, duckweed, water moss



The model QUAL2K (Chapra et al., 2012) was used for oxygen accounting in the reach. Key processes that were simulated in the model included: nitrification, sediment oxygen demand, macrophyte photosynthesis and respiration, and reaeration. QUAL2K is a widely used one-dimensional advection-dispersion river model and part of the U.S. Environmental Protection Agency's water-quality modeling toolbox (USEPA, 2015). State-variables are simulated on a longitudinal basis, with diel water-quality kinetics that enable the user to study the daily fluctuation of DO over a 24-hr cycle. Numerical computations are programmed in Fortran 90 and are implemented from the Microsoft Excel Visual Basic for Applications (VBA) environment. An explicit forward-time/backward-space scheme corrected for numerical dispersion is used to determine the concentration in each model element at each time step.

QUAL2K requires 24-hour headwater forcing functions to account for the temporal changes in the daily cycles of inputs. These are believed to be important in a stream with large diurnal cycling like SRC, where the upstream headwater is heavily influenced by the Metro WWTP. As mentioned previously, diurnal field water quality parameters were measured at this location using two YSI EXO 2 and two Hydrolab Sondes. However, grab samples were also collected concurrently at 10 a.m., 2 p.m., 6 p.m. and 10 p.m. on those dates. Samples were analyzed as outlined previously in Table 1.

The mass balance for DO (o_i) in a QUAL2K element having steady flow is (Chapra et al., 2012)

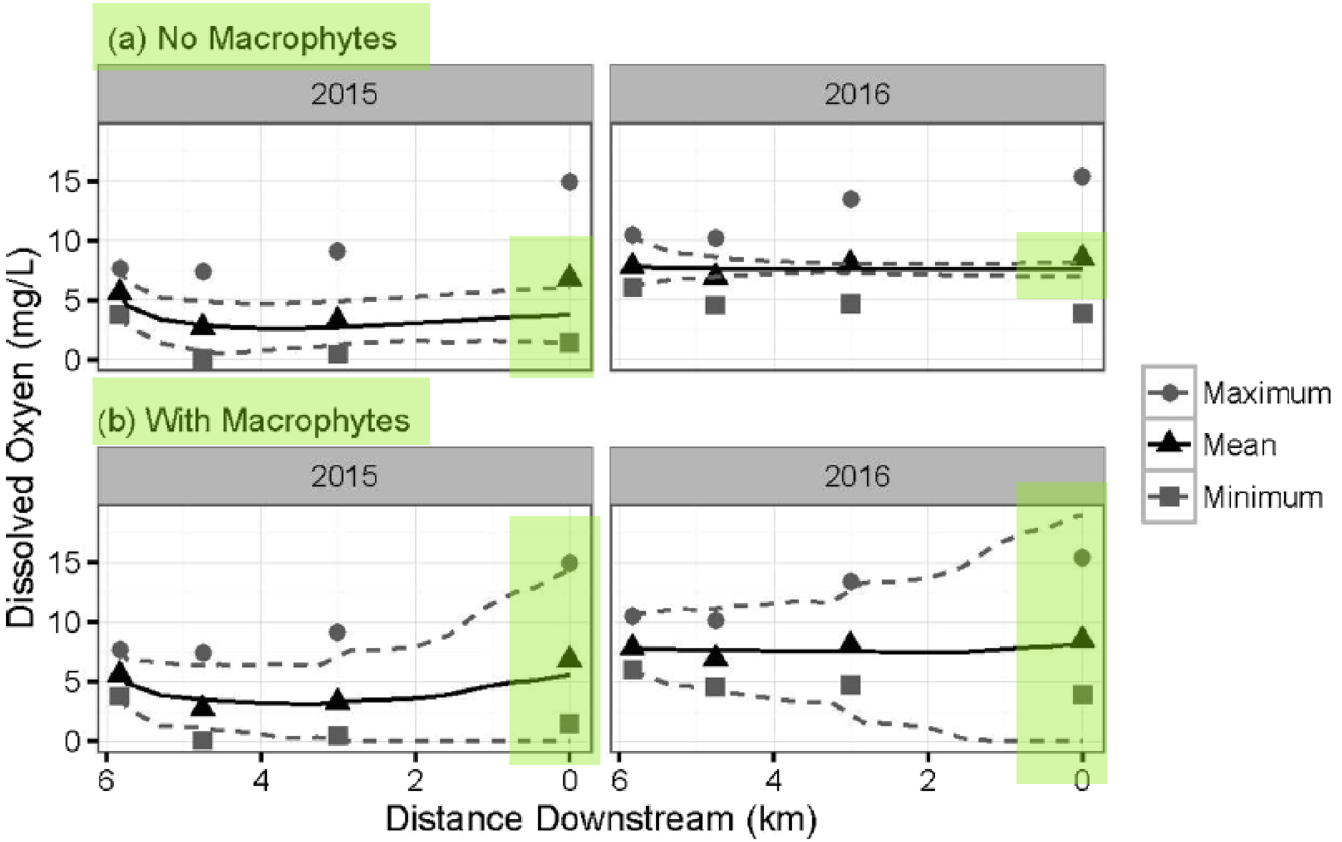
$$V_i \frac{do_i}{dt} = Q_{i-1} o_{i-1} - Q_i o_i - E'_{i-1}(o_{i-1} - o_i) + E'_i(o_{i+1} - o_i) + W_i \pm S_i$$

We used external forcing functions to simulate the influence of macrophytes on the oxygen mass balance. The macrophyte source/sink of oxygen is approximated using a sinusoid (Chapra, 2008)

$$\mathrm{S}(t) = Q_M [o_{Macrophytes} + o_a \sin(\omega t + \theta)] \quad (2)$$

Dissolved oxygen modeling in QUAL2K suggests macrophytes have a significant effect on DO diurnal variation in SBC. Preliminary model runs without macrophyte oxygen equivalents suggest that while the model predicts the daily average values reasonably well, diurnal variation of DO is substantially underestimated (Fig. 8a). However, once oxygen equivalents for macrophytes have been added to the simulation, the model shows reasonable agreement with longitudinal and diurnal variation in DO as evidenced by the calibration to field data (Fig. 8b).

The model confirmation shows comparable results, although in this instance a substantial increase in the concentration of DO in the study reach occurs; presumably as a result of the WWTP upgrade. While no



As evidenced in this study, rooted macrophytes or submerged aquatic vegetation can play a significant role in aquatic ecosystems. Beyond their direct effect on DO dynamics, they also provide food and cover for a wide range of species (Dennison et al., 1993), contribute to biogeochemical cycling of autochthonous resource pools, and improve water quality by filtering nutrients and polluted runoff (Carpenter and Lodge, 1986; Janauer and Dokulil, 2006). However, as observed in this study, excessive macrophyte growth can become problematic and cause hypoxic DO conditions, reductions in biodiversity, declines in ecosystem health, or replacement of desired species (Duarte, 1995; Torn and Martin, 2012).

In SBC, DO was the primary response indicator evaluated. Poorly oxygenated conditions prevailed throughout much of the reach prior to the upgrade of the WWTP, due in part to both macrophyte respiration and the oxygen sag from ammonia nitrification. The latter significantly impacted stream hypoxia and appears to be mitigated post-WWTP upgrade, while macrophytes still appear to be influencing the stream via large DO delta. Several items are worth highlighting in review of our Results.