

Sedimentary microbial oxygen demand for laminar flow over a sediment bed of finite length

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Abstract

Dead organic material accumulated on the bed of a lake, reservoir or wetland often provides the substrate for substantial microbial activity as well as chemical processes that withdraw dissolved oxygen (DO) from the water column. A model to estimate the actual DO profile and the “sedimentary oxygen demand (SOD)” must specify the rate of microbial or chemical activity in the sediment as well as the diffusive supply of DO from the water column through the diffusive boundary layer into the sediment. Most previous experimental and field studies have considered this problem with the assumptions that the diffusive boundary layer is (a) turbulent and (b) fully developed. These assumptions require that (a) the flow velocity above the sediment bed is fast enough to produce turbulent mixing in the boundary layer, and (b) the sediment bed is long. In this paper a model for laminar flow and SOD over a sediment bed of finite length is presented and the results are compared with those for turbulent flow. Laminar flow near a sediment bed is encountered in quiescent water bodies such as lakes, reservoirs, river backwaters, wetlands and ponds under calm wind conditions. The diffusive oxygen transfer through the laminar diffusive boundary layer above the sediment surface can restrict the microbial or chemical oxygen uptake inside the sediment significantly. The developing laminar diffusive boundary layer above the sediment/water interface is modeled based on the analogy with heat transfer, and DO uptake inside the sediment is modeled by Michaelis–Menten microbial growth kinetics. The model predicts that the rate of SOD at the beginning of the reactive sediment bed is solely dependent on microbial density in the sediment regardless of flow velocity and type. The rate of SOD, and the DO penetration depth into the sediment decrease in stream-wise direction over the length of the sediment bed, as the diffusive boundary layer above the sediment/water interface thickens. With increasing length of the sediment bed both SOD rate and DO penetration depth into the sediment tend towards zero if the flow is laminar, but tend towards a finite value if the flow is turbulent. That value can be determined as a function of both flow velocity and microbial density. The effect of the developing laminar boundary layer on SOD is strongest at the very lowest flow velocity and/or highest microbial density inside the sediment. Under quiescent conditions, the effective SOD exerted by a reactive sediment bed of a lake or wetland approaches zero, i.e. no or very little oxygen demand is exerted on the overlying water column, except at the leading edge.

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1. Introduction

Diffusional mass transfer across the sediment/water interface of a lake, e.g. oxygen uptake, sulfate uptake, or phosphorus release, can control the mass balance of a substance in the water column, and/or affect the ecosystem. Dissolved oxygen (DO) flux from the water column into the sediment (sedimentary oxygen demand, SOD), and phosphorus release from the sediment to the water are two important processes, and affect water quality in many lakes or reservoirs (Wetzel, 1983). SOD is related to the composition of the sediment itself; more organically rich sediments generally have higher SOD. Models of SOD have focused on oxidation reactions and microbial activities inside the sediments. More sophisticated models relate SOD fluxes to the flux of particulate organic carbon to the sediments and its decomposition into reduced chemical species (DiToro, 2001; Boudreau, 1997). In addition to the composition and the chemical and biological kinetics of the sediments, the supply of DO from the water to the sediments can severely reduce the ‘actually exerted SOD’. In this case the SOD is said to be ‘transport limited’.

The flow over the sediment surface can affect the vertical diffusive flux of solute, e.g. DO, sulfate, or phosphorus, at the sediment/water interface because the solute concentration profile near the sediment/water interface varies with the velocity of water flowing over the sediment surface (Sweerts and DeBeer, 1989;

Revsbech, 1983; Revsbech et al., 1979; Gludetal et al., 1994; Lorenzen et al., 1998; Revsbech et al., 1998).

Experimental studies also have clearly shown that SOD depends on the velocity of the water flowing over the sediment surface (Belanger, 1981; Joergensen and Revsbech, 1985; Whittemore, 1986; Joergensen and DesMarais, 1990; Mackenthun and Stefan, 1998; Josiam and Stefan, 1999; Steinberger and Hondzo, 1999). Several formulas have been proposed to quantify the value of SOD for turbulent flow above a smooth sediment surface (e.g. Rahm and Svensson, 1989; Dade, 1993; Nakamura and Stefan, 1994), based on boundary layer theory and experimental studies.

Flow above the sediment/water interface (Fig. 1) can be induced by wind, or inflows and outflows. The flow over the sediment bed is either turbulent or laminar. Previous models or formulas of SOD were developed for turbulent flow. DO concentration profiles and SOD were treated as uniform in flow direction, i.e. the diffusive boundary layer was assumed to be fully developed. The effect of a developing diffusive boundary layer on an organic sediment bed of finite length was only recently investigated (Higashino and Stefan, 2004, 2005), and a model giving steady-state SOD-values for *turbulent* flow was developed. Unsteady SOD in fully-developed turbulent flow was investigated by Higashino et al., 2004. However, *laminar* flow occurs in “standing” water bodies under “calm” conditions, and severely restricts SOD. We have not found any study of *laminar* flow over a sediment bed, and none is referenced in

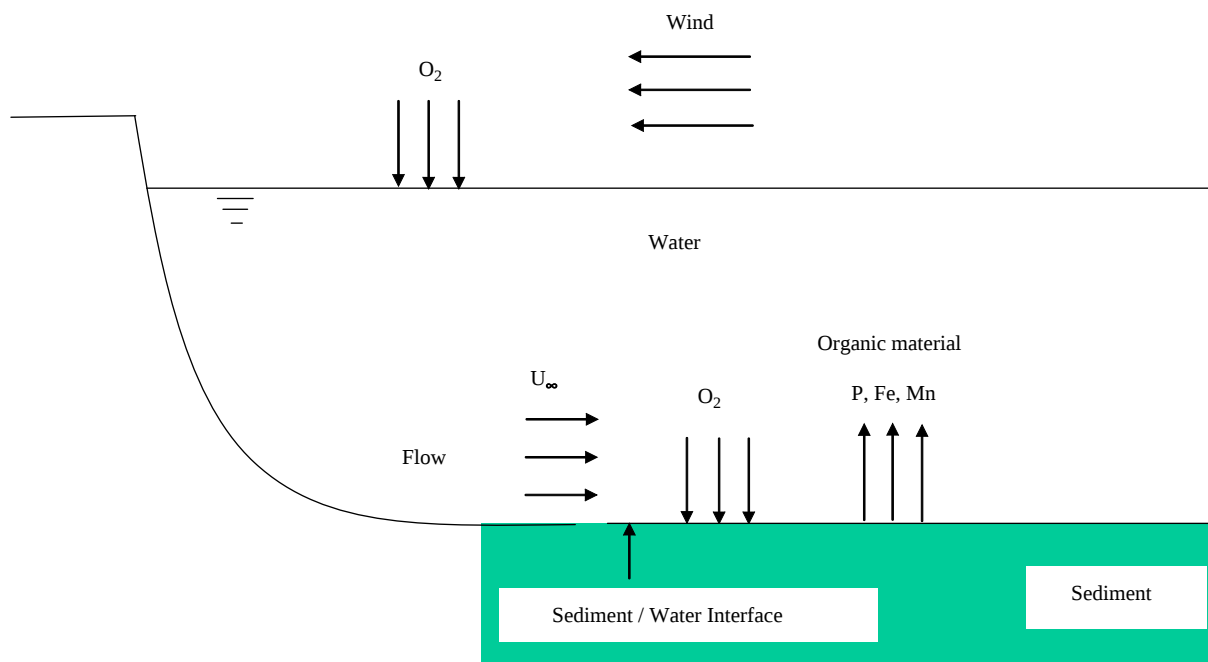


Fig. 1. Schematic of diffusional mass transfer at the sediment/water interface in a lake.

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