

Monitoring sediment oxygen demand for assessment of dissolved oxygen distribution in river

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Abstract Sediment oxygen demand (SOD) has become an integral part of modeling dissolved oxygen (DO) within surface water bodies. Because very few data on SOD are available, it is common for modeler to take SOD values from literature for use within DO models. SOD is such an important parameter in modeling DO that this approach may lead to erroneous results. This paper reported on developing an approach for monitoring sediment oxygen demand conducted with undisturbed sediment core samples, where the measured results were incorporated into a water quality model for simulating and assessing dissolved oxygen distribution in the Xindian River of northern Taiwan. The measured results indicate that a higher freshwater discharge results in a lower SOD. Throughout a 1-year observation in 2004, the measured SOD ranged from 0.367 to 1.246 g/m²/day at the temperature of 20°C. The mean values of the measured SOD at each station were adopted in a vertical two-dimensional water quality model to simulate the DO distribution along the Xindian River.

The simulating results accurately depict the field-measured DO distribution during the low and high flow conditions. Model sensitivity analyses were also conducted with increasing and decreasing SOD values for the low and high flow conditions and revealed that SOD had a significant impact on the DO distribution along the Xindian River. The present work combined with field measurements and numerical simulation should assist in river water quality management.

Keywords Sediment oxygen demand · Dissolved oxygen · Monitoring · Model · Xindian river

Introduction

Sediments are an important feature of natural water environment. The physical, chemical, and biological processes that occur in the sediment have a profound effect on the quality of water body. A major interaction is the exchange of substances between the sediment and overlying water. Sediment oxygen demand (SOD) is the rate at which dissolved oxygen (DO) is removed from the overlying water column by biological processes in the river bed sediments. The sediments that make up the benthic zone of the river originate from natural river conditions, nonpoint source runoff, and wastewater effluents (Hu et al. 2001; Matlock et al. 2003; MacPherson et al. 2007). Significant rates of sediment oxygen uptake have

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been studies in rivers and estuaries that receive large amounts of solids from point and nonpoint sources. SOD rates observed under these natural environments are also due to soluble organic substances in the water column, which are derived from naturally occurring sediments containing aquatic plants, animals, and detritus discharged into water body from natural runoff (Truax et al. 1995; Chen et al. 2000; Higashino et al. 2004; Haag et al. 2006).

There are several factors that affect SOD rate. Primary focus is given to the biological components such as organic content of the benthic sediment and microbial concentrations. Mackenthun and Stefan (1998) measured the SOD in laboratory experiments in which sediment was exposed to water flowing at different velocities. The experiments were performed in a recirculating channel with well-defined flow characteristics. They found that the SOD is approximated by linear and Michaelis-Menten-type equations with the velocity being the independent variable. Ziadat and Berdanier (2004) adopted an in situ SOD chamber to measure SOD in a shallow stream. They found that the velocity of the stream is the less critical parameter for SOD in shallow stream. MacPherson et al. (2007) analyzed the rate of oxygen loss as the water column biochemical oxygen demand and the sediment oxygen flux at a tidal creek in North Carolina, USA. They found that the SOD ranged from 0.0 to 9.3 g/m²/day and was positively correlated with temperature, chlorophyll *a*, and total suspended solids, but negatively with DO. The SOD was elevated in the summer and fall. The average oxygen loss to sediments was greater and more variable than the oxygen loss in the water column. Utley et al. (2008) developed an in situ chamber to measure SOD in seven blackwater streams of the Suwannee River Basin within the Georgia coastal plain. The measured results revealed that the SOD was varied on average between 0.1 and 2.3 g/m²/day. Miskewitz et al. (2010) used a novel profile method to measure the gradient of dissolved oxygen concentration above the sediment surface and vertical eddy diffusivity in Millstone River, Georgia. Then the SOD flux was calculated through the measured data. The measured SOD ranged from 0.5 to 2.2 g/m²/day.

The effect of SOD on the oxygen budget of an entire river system should not to be underestimated, as it can be a critical sink of DO. In some rivers, SOD can account for over half of the total oxygen demand

and can play a primary role in the water quality of a river system (Matlock et al. 2003). Although SOD value may be a potentially major effect on the total oxygen demand within a river system, this parameter is often assumed (or estimated) in the water quality models (Hatcher 1986). Errors in this measurement could lead to inaccurate models for the river environment, at great biological and financial cost.

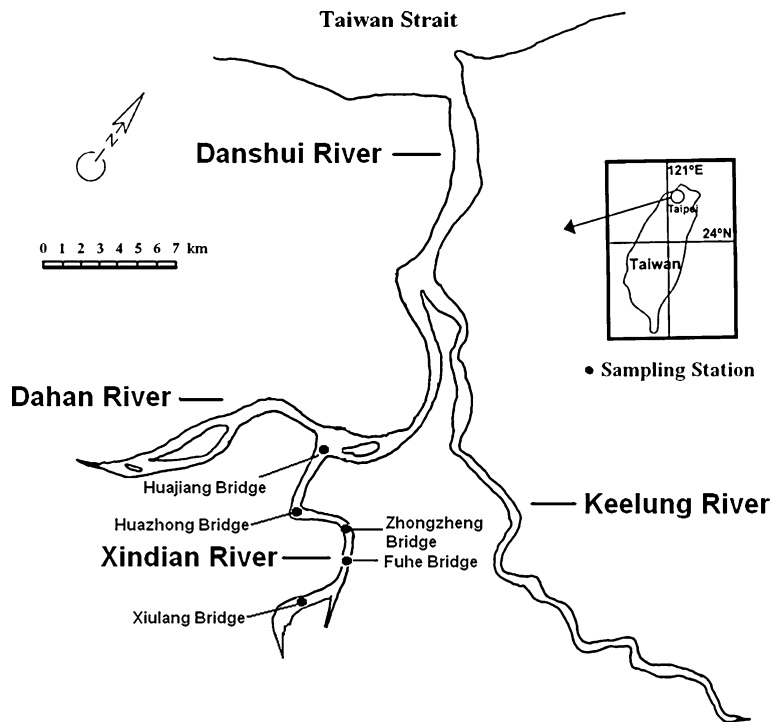
The objective of this study is to measure the SOD with undisturbed sediment sample in the Xindian River of northern Taiwan. Throughout a 1-year observation in 2004, the measurements of SOD were determined and incorporated into a vertical (laterally averaged) two-dimensional water quality model, which accurately simulates and assesses the distribution of DO in the Xindian River. Model sensitivity analyses of SOD were also implemented to investigate the influence on the DO concentration in the river.

Description of study site

The Xindian River (Fig. 1) is one of the major branches of the Danshui River estuarine system, which runs through the metropolitan capital city of Taipei, Taiwan and receives large amount of wastewater. The Xindian River has a drainage area of 916 km² and a total length of 83.9 km. The annual mean rainfall is 3,251 mm, 45% of which is concentrated in the months from June to September. The average limit of salt intrusion is located at the Zhongzheng Bridge, 6.28 km from its confluence with the Danshui River (Liu et al. 2004). Two Weirs, Ching-Tan Weir and Zhi-Tan Weir, were built primarily to provide domestic water supply to Taipei metropolitan area population over 5 million.

The study area occupies the low level part of the basin, where the main residential and industrial areas are located, and spans over two municipalities: Taipei City and Taipei County. Water quality data were collected from long-term field sampling programs of Taiwan Environmental Protection Administration. The observed data reveal very high nutrient concentrations in the river, with total nitrogen of order of several milligrams per liter. Many events of fish death occur at the reach of Xindian River due to the low dissolved oxygen (less than 1 mg/L). Chang et al. (1989) had stated that the dissolved oxygen concen-

Fig. 1 Map of the Xindian River in northern Taiwan and sampling stations



tration of 1 mg/L is the critical oxygen level for fish survival.

Materials and methods

Measurement

There are generally two categories of techniques for measuring the SOD: laboratory measurement of sediment core samples or in situ field measurement. Both methods have their own pros and cons. Murphy and Hicks (1986) concluded that the current techniques of in situ SOD measurement are still far from satisfactory and that a universally accepted or standard method has not yet been developed. Due to the limits of techniques and experimental equipment, the present study adopts a laboratory SOD measurement based upon sediment core samples.

Twelve slackwater surveys were conducted along the Xindian River from the period of January to December in 2004. A slackwater survey indicates that the velocity in the river is low. It is convenient to take the undisturbed sediment core in the central channel from a boat. The undisturbed sediment samples were collected using a Phlege Core Sediment Sampler

(Kahl Scientific Instrument Corporation, USA). Different volumes of sediment samples were collected, depending on the thickness of the sediment bed. In order to ensure a minimum disturbance, the core samples were secured in a car and transported to the laboratory. In the laboratory, continuous measurement of the amount of DO in the overlying water was carried out at every hour with a dissolved oxygen meter (Yellow Springs Instruments Company USA, Model 550A). Figure 2 presents the tidal ranges and

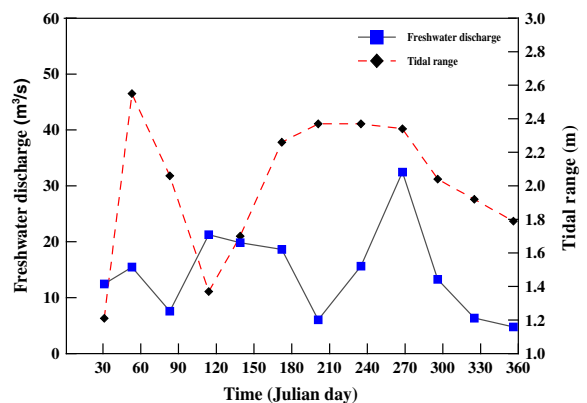


Fig. 2 Tidal range and freshwater discharge for the measured dates in 2004

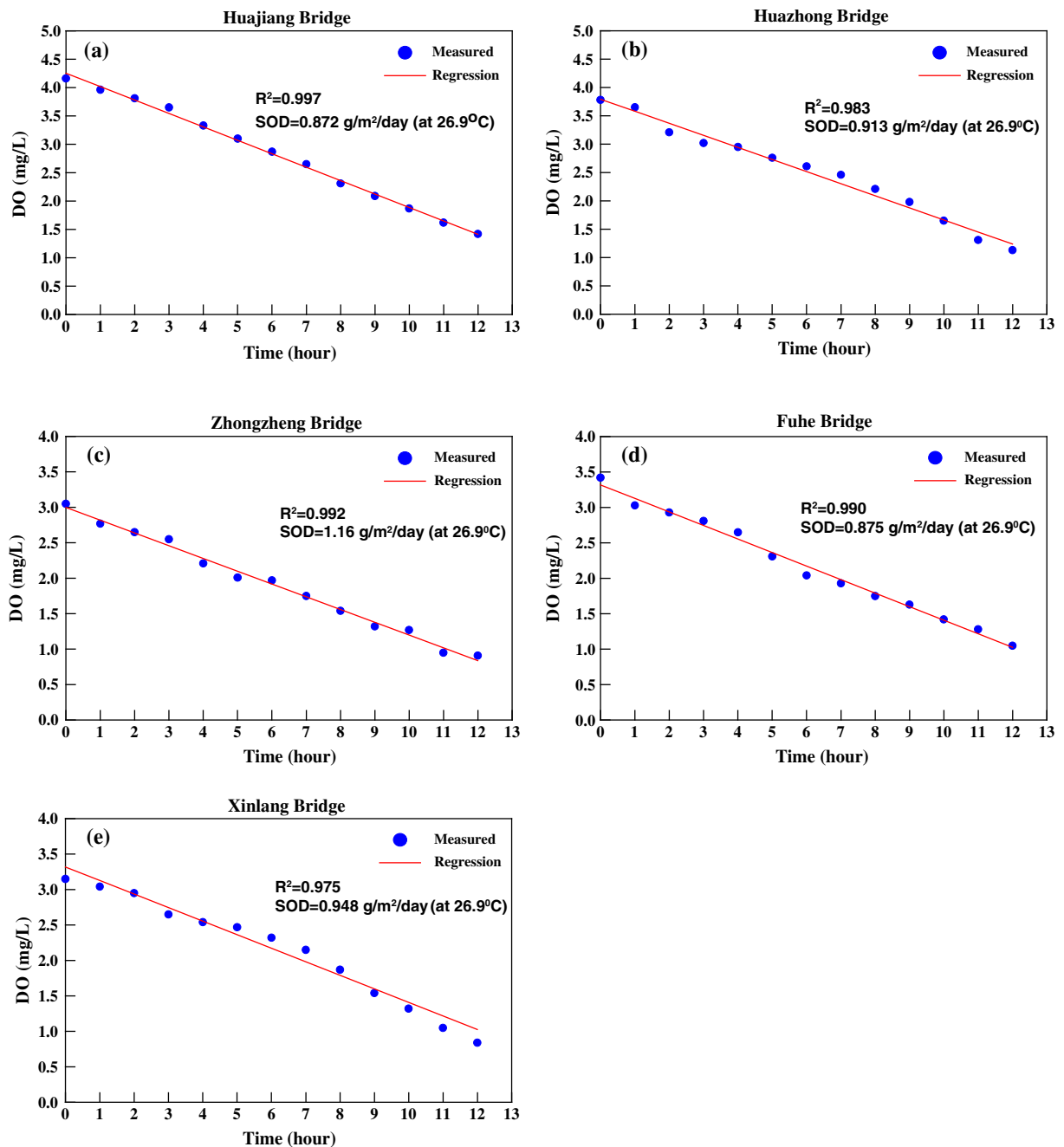


Fig. 3 Consumption rate of oxygen dissolved by sediment in SOD measurement on August 23, 2004 at **a** Huajiang Bridge, **b** Huazhong Bridge, **c** Zhongzheng Bridge, **d** Fuhe Bridge, and **e** Xinlang Bridge

freshwater discharges for each sampling date collected from the Taiwan Water Resources Agency. Tidal ranges ranged from 1.21 to 2.55 m and freshwater discharges ranged from 4.78 to 32.46 m³/s during the data measurement period, and the highest freshwater discharge was observed on September 25, 2004.

Water quality model

In a narrow channel with steep bathymetric variation, a vertical (laterally averaged) two-dimensional model is very suitable for rivers and estuaries. Therefore, a vertical two-dimensional, real-time model, HEM-2D

(2-dimensional Hydrodynamic Eutrophication Model; Park and Kuo 1993) was applied to the Xindian River of northern Taiwan. The model, consisting of a hydrodynamic model and a water quality model, is based on the principles of volume, momentum, and mass conservation.

The water quality model is based on the principle of conservation of eight interlinked water quality state variables: DO, chlorophyll *a*, carbonaceous biochemical oxygen demand (CBOD), organic nitrogen, ammonium nitrogen, nitrite–nitrate nitrogen, organic phosphorus, and inorganic phosphorus. For each state variable, the equation solved by the finite difference method has the general form (Liu et al. 2005):

$$\frac{\partial(cB)}{\partial t} + \frac{\partial(cBu)}{\partial x} + \frac{\partial(cBw)}{\partial z} = \frac{\partial}{\partial x}(K_x B \frac{\partial c}{\partial x}) + \frac{\partial}{\partial z}(K_z B \frac{\partial c}{\partial z}) + B \cdot S_e + B \cdot S_i \tag{1}$$

where *c* is the laterally averaged concentration of the water quality state variable, *u* and *w* are the velocity in the *x* and *z* directions, respectively, *B* is the river width, *K_x* and *K_z* are the turbulent diffusivities in the *x* and *z* directions, respectively, *S_e* is the time rate of external addition (withdrawal) across the boundaries, and *S_i* is the time rate of internal increase (or decrease) by biogeochemical reaction processes.

Dissolved oxygen

The present DO model includes the following components: sources from photosynthesis, reaeration through surface and external loading, and sinks due to the decay of CBOD, nitrification, algae respiration, and SOD. The mathematical representation is:

$$S_i = -K_c CBOD - a_{no} \frac{K_{n23} N_2}{K_{h23} + N_2} \frac{DO}{K_{nit} + DO} + a_c a_{co} \left(PQ \cdot G - \frac{R}{RQ} \right) Chl \tag{3}$$

$$S_e = (1 - \lambda_1) K_r (DO_s - DO) - \frac{SOD}{\Delta z} \times \frac{DO}{K_{DO} + DO} \frac{B_k - \lambda_2 B_{k+1}}{B_k} + \frac{WDO}{V} \tag{4}$$

where *a_c* is the ratio of carbon to chlorophyll in phytoplankton (*mgC/μg Chl*), *a_{co}* = the stoichiometric ratio of oxygen demand to the recycled organic carbon, 2.67 (Park and Kuo 1993), *a_{no}* = the stoichiometric ratio of oxygen consumed per unit of nitrified ammonia nitrogen, 4.57 (Park and Kuo 1993), *B* = the river width (cm), CBOD is the concentration of carbonaceous biochemical oxygen demand (mg/L), Chl = the concentration of chlorophyll *a* (μg/L), DO is the concentration of dissolved oxygen (mg/L), DO_{*s*} = the saturation concentration of DO (mg/L), *G* = the growth rate of phytoplankton (1/day), *K_c* = the first-order decay rate of CBOD (1/day), *K_{DO}* = the half-saturation concentration for the benthic flux of CBOD (mg/L), *K_{h23}*=the half-saturation concentration for nitrification (mg/L), *K_{n23}*=the nitrification rate of ammonia nitrogen to nitrite–nitrate nitrogen (mg/L/day), *K_{nit}* = the half-saturation concentration for the oxygen limitation of nitrification (mg/L), *K_r* = the reaeration rate (1/day), *N₂*=the concentration of ammonia nitrogen, PQ = the photosynthesis quotient (moleO₂/moleC), *R* = the respiration rate of phytoplankton (1/day), RQ = the respiration quotient (moleCO₂/moleO₂), *V*=the layer volume (cm³), WDO = the external loading of DO (mg/day) including point and nonpoint sources, Δ*z* = the layer thickness (cm); λ₁=0 for *k*=1 (at top layer), λ₁=1 for 2≤*k*≤*N*, and *N* is the number of layers at each segment, where λ₂=1 for 1≤*k*≤*N*-1, λ₂=0 for *k*=*N* (at the bottom layer).

Model implementation

The numerical model is supported with data describing the geometry of the Xindian River. The geometry

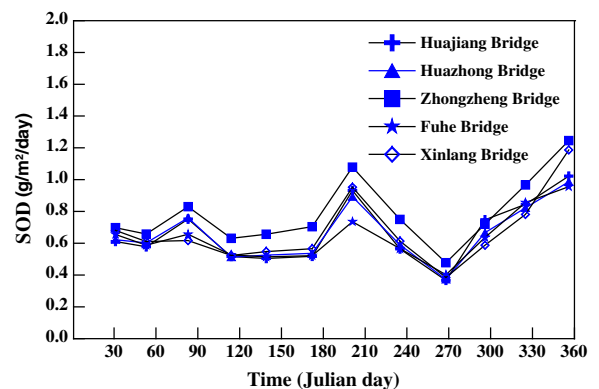


Fig. 4 Annual variation of measured SOD at different stations in 2004

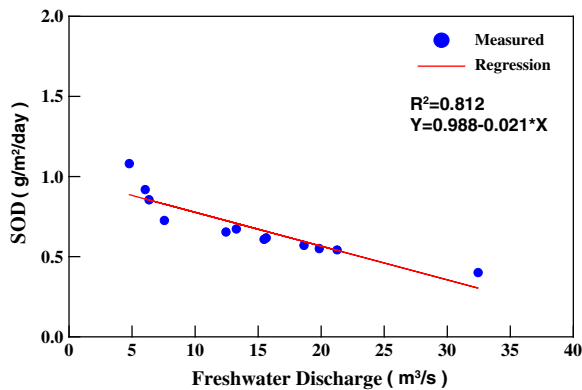
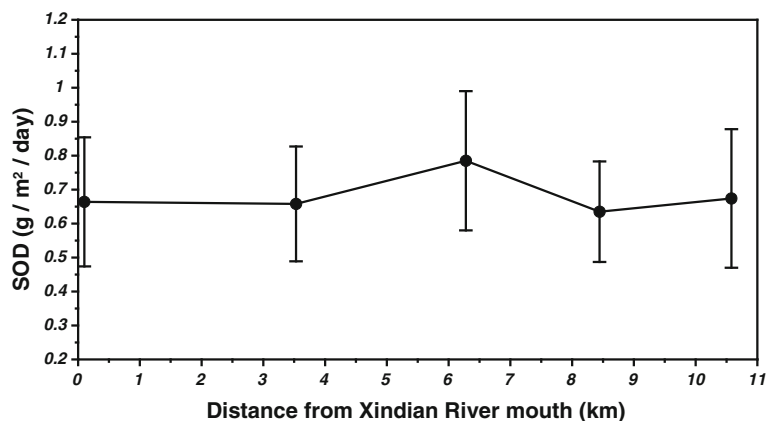


Fig. 5 Linear regression between SOD and freshwater discharge

in the vertical dimension is represented by the width of each layer at the center of each grid cell. A field survey in 2000 measured by the Taiwan Water Resources Agency collected the cross-sectional profiles at about 0.5 km along the tidal portion of the river. These profiles were used to schematize the river. The Xindian River was divided into 14 segments with a uniform segment length of 1.0 km ($\Delta x=1.0$ km). Because the surface elevation at low tide is about 1.5 m below the mean sea level at spring tide, the thickness of the top layer (Δz) is 2.0 m to maintain the water surface elevation (water level) above the top layer (i.e., 2.0 m) at all times. The thickness of the other layers is 1.0 m (Hsu et al. 1999). The time step Δt is limited by Courant–Fredrick–Levy stability condition $\Delta t \leq \Delta x/\sqrt{gh}$, where g = gravitational acceleration and h = total depth. A time step increment (Δt) of 108 s, which guaranteed stability, was adopted for the model simulations.

Fig. 6 The longitudinal distribution of measured SOD at 20°C. (the mean and standard deviation values are shown in the figure)



Results and discussions

Sediment oxygen demand

SOD was defined as the rate of oxygen consumption, biologically or chemically, on or in the sediment at the bottom of a water body. The DO depletion profiles in water overlying the sediment samples collected from sampling stations (Fig. 1) are graphically presented in Fig. 3; time zero represents the beginning of the experimental period. Figure 3 presents some examples of measured DO profiles for August 23, 2004, at the Huajiang Bridge, Huazhong Bridge, Zhongzheng Bridge, Fuhe Bridge, and Xinlang Bridge. The rates of oxygen consumption were calculated from the slopes along the DO versus time profiles and the area of the sediment–water interface, and the SOD was expressed as the oxygen consumption per unit interfacial area per unit time ($\text{g/m}^2/\text{day}$). The formula is given by:

$$\text{SOD}_T = S \times V_s / A_s \quad (5)$$

where SOD_T is the sediment oxygen demand at $T^\circ\text{C}$, S is the slope of the linear portion of the usage curve, V_s is the volume of the sample, and A_s is the area of the bottom sample.

To standardize the SOD values under 20°C, the following equation was applied:

$$\text{SOD}_T = \text{SOD}_{20} \theta^{(T-20)} \quad (6)$$

where SOD_{20} is the SOD rate at 20°C, and θ = the temperature coefficient. θ is an accepted. Empirically determined value ($\theta=1.065$) for relating SOD values at standard condition (20°C) to field temperature conditions (Zison et al. 1978).

Table 1 SOD values from literature reviews

Location/country	SOD (g/m ² /day)	Reference
Roskjide Fjord/Denmark	2.5	Sand-Jensen et al. (1990)
Tomales Bay, CA/USA	0.06–0.15	Dollar et al. (1991)
Ossterschelde/Netherlands	1.57	Hofman et al. (1991)
Chesapeake Bay/USA	0–1.64	Kemp et al. (1992)
Hiroshima Bay/Japan	0.1–0.61	Seiki et al. (1994)
Albufera, Majoeca/Spain	0.52–1.55	Lopez et al. (1995)
Chesapeake Bay/USA	0.33–0.85	Reay et al. (1995)
Shing-Mun River/Hong Kong	6.84 (maximum)	Chen et al. (2000)
Tidal Creeks, NC/USA	0–9.3	MacPherson et al. (2007)
Blackwater Streams, Georgia/USA	0.491–14.189	Todd et al. (2009)
Millstone River, NJ/USA	0.5–2.5	Miskewitz et al. (2010)
Xindian River/Taiwan	0.367–1.246	This study

All measurements were corrected to 20°C

Figure 4 illustrates the annual variation of SOD (at 20°C) at each measured station. The measured SOD values for different temperatures have been transformed to a SOD at 20°C via Eq. 6. The figure shows that the SOD drops sharply on September 25, 2004 because the high freshwater discharge inputs from upstream (see Fig. 2). Mitchell et al. (1999) found that a higher freshwater discharge results in a lower SOD and a higher DO in the upper Humber Estuary. Our measured SOD results are similar to the report of Mitchell et al. (1999).

The correlation between the SOD and freshwater discharge was calculated and is shown in Fig. 5. The equation is given by:

$$SOD_{20^{\circ}C} = 0.988 - 0.021 \times FD, \dots N = 12 \quad (7)$$

where, FD is freshwater discharge (m³/s) and *N* is the number of samples. The coefficient of determination (*R*²) is 0.812.

Figure 6 presents the longitudinal distribution of the measured SOD (at 20°C). The means and standard deviation values are also presented in the figure. It reveals that the highest SOD occurs at the Zhongz-

heng Bridge. Table 1 presents the measured SOD in the various systems and compares them with the present study. The measured SOD is in the range of 0.367–1.246 g/m²/day at a temperature of 20°C (see Table 2), which is within the usual range, as compared with other systems.

Simulation of dissolved oxygen distribution

SOD rate is often assumed or estimated in water quality modeling studies that are used to set discharge limits. Error in these assumptions can have a significant environmental and financial cost. In some rivers, SOD accounts for as much as 50% of the total oxygen depletion, making SOD a critical element in water quality modeling studies. SOD is therefore an integral part of assessing the quality of water in a system (Di Toro et al. 1990).

The mean values of the measured SOD listed in Table 2 for each sampling station are used in the water quality model to simulate the spatial DO distribution in the Xindian River of northern Taiwan.

Table 2 Statistics analysis of SOD measurement at five measured stations

Sampling station	Huajiang Bridge	Huazhong Bridge	Zhongzhen Bridge	Fuhe Bridge	Xinlang Bridge
No. of samples	12	12	12	12	12
Mean value of SOD	0.664	0.658	0.785	0.635	0.672
Standard deviation of SOD	0.190	0.169	0.205	0.148	0.204
SOD range	0.367–1.023	0.373–0.987	0.478–1.246	0.403–0.956	0.385–1.187

SOD Sediment oxygen demand at 20°C (g/m²/day)

Figure 7 presents the comparison between the model results and field measurements of the DO distribution from the slackwater survey of July 20, 2004 during the low flow condition. It shows the simulated results of the daily average DO concentration at the surface and bottom layers. The DO was measured along the central channel from a boat with a DO sensor. The freshwater discharge and tidal range were $6.05 \text{ m}^3/\text{s}$ and 2.37 m , respectively, on July 20, 2004. The DO concentration measurement stations are located at the Huajiang Bridge, Huazhong Bridge, Zhongzheng Bridge, Fuhe Bridge, and Xinlang Bridge (shown in Fig. 1) from downstream to upstream reaches in the Xindian River. The mean values of the field-measured DO concentration are plotted in the figure for comparison. The figure shows that the DO concentration increases from the Xindian River mouth to upriver reaches and the model accurately simulates the measured data.

Figure 8 shows a comparison between the model results and field measurements of the DO distribution from the slackwater survey of April 24, 2004 during high flow condition. The freshwater discharge and tidal range were $21.26 \text{ m}^3/\text{s}$ and 1.37 m , respectively, on April 24, 2004. The DO concentration is higher during the high flow condition than during the low flow condition, due to freshwater discharge dilution during the high flow condition. The model results are in reasonable agreement with the field measurement data in the DO distribution and with the mean values of the measured SOD at sampling stations. There are many coefficients in Eqs. 3 and 4 to influence the DO distribution and to be determined. Based on the

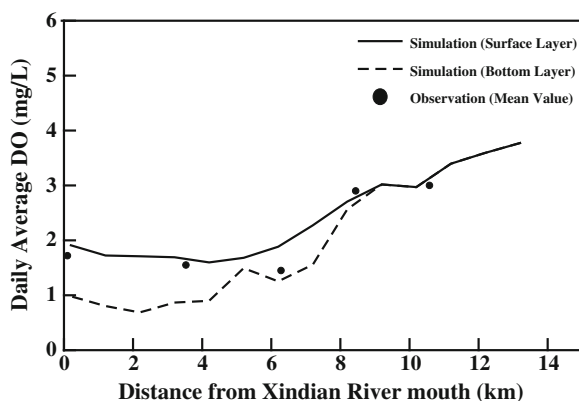


Fig. 7 Comparison of measured and computed dissolved oxygen distributions for July 20, 2004 (low flow condition)

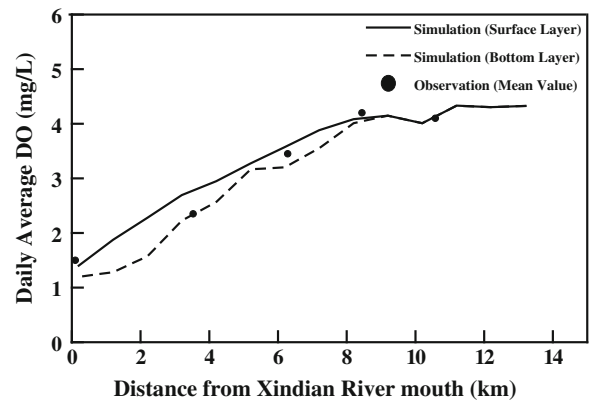


Fig. 8 Comparison of measured and computed dissolved oxygen distributions for April 24, 2004 (high flow condition)

literatures and testing by trial and errors, all coefficients were decided. Table 3 lists all coefficients (in Eqs. 3 and 4) adopted in the DO simulation. The sources for determining coefficients also present in Table 3.

Sensitivity analysis

A primary use of the validated model is sensitivity analysis, in order to examine the behavior of the prototype in response to any alterations made. Sensitivity analysis is a powerful tool that can be applied to improve the understanding of the present DO distribution in the Xindian River due to the SOD. The sensitivity analysis was implemented by running

Table 3 Coefficients adopted in the modeling of DO concentration

Coefficients	Value	Source
$K_c(20)$	0.1 day^{-1}	III
K_{DO}	0.5 mg/L	IV
K_{n23}	0.3 mg/L/day	IV
K_{h23}	1.0 mg/L	II, IV
K_{nit}	2.0 mg/L	I
a_c	$0.05 \text{ mg C}/\mu\text{g Chl}$	IV
PQ	$1.0 \text{ mole O}_2/\text{mole C}$	III, IV
RQ	$1.33 \text{ mole CO}_2/\text{mole O}_2$	III, IV
$R(20)$	0.17 day^{-1}	IV

I: Thomann and Fitzpatrick (1982)

II: Cerco and Kuo (1983)

III: Bowie et al. (1985)

IV: Kuo et al. (1991)

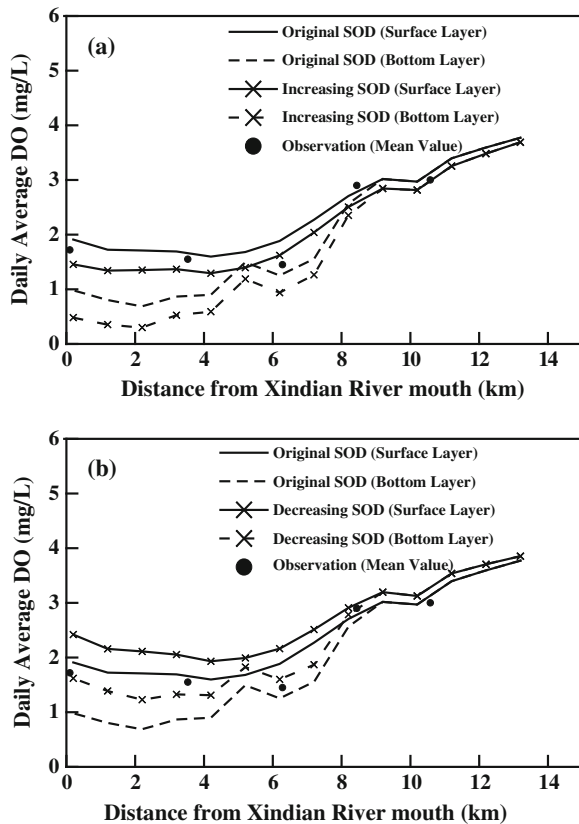


Fig. 9 Sensitivity analyses running with **a** increasing SOD and **b** decreasing SOD for the low flow condition

the model with all coefficients as in the previous section, except for the SOD values. The original bases depend on the simulation of the low flow and high flow conditions for July 20 and April 24, 2004. The effect of the SOD values on the DO distribution was investigated with two alternative cases; one involves measured mean values plus 50% SOD and the other involves measured mean values minus 50% SOD.

Figures 9 and 10 present the modeling results of the sensitivity run with low flow and high flow

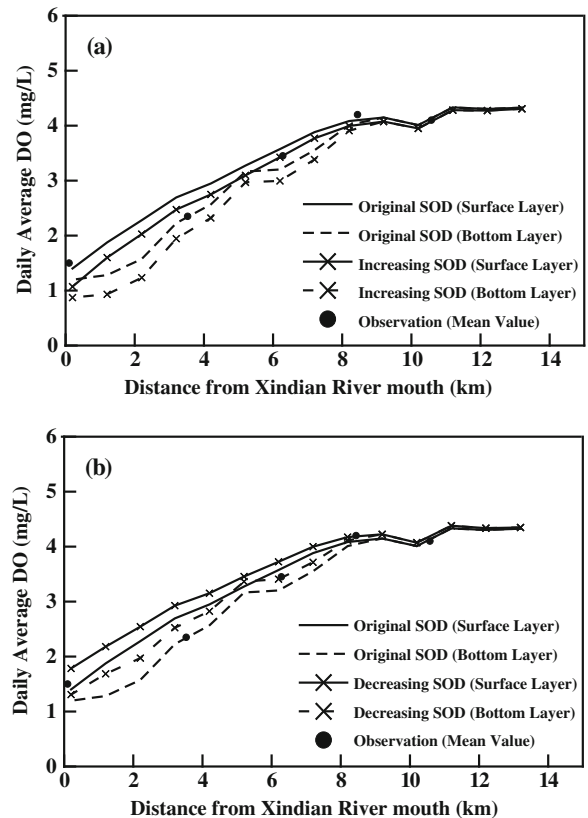


Fig. 10 Sensitivity analyses running with **a** increasing SOD and **b** decreasing SOD for the high flow condition

conditions, respectively. Table 4 summarizes the sensitivity results. It shows that an increase in the SOD results in a decrease in the DO at the surface and bottom layers (Figs. 9a and 10a). The maximum rates for decreasing DO are 23.8% and 56.3% at the surface and bottom layers, respectively, for the low flow condition and 23.5% and 27.2% at the surface and bottom layers, respectively, for the high flow condition (shown in Table 4). The maximum rate means that the maximum values were determined by

Table 4 Results of sensitivity run for low and high flow conditions

Condition		Maximum rate of dissolved oxygen concentration for surface layer (%)	Maximum rate of dissolved oxygen concentration for bottom layer (%)
Low flow	Increasing 50% SOD	-23.8	-56.3
	Decreasing 50% SOD	26.7	79.1
High flow	Increasing 50% SOD	-23.5	-27.2
	Decreasing 50% SOD	26.1	31.7

Minus and plus represent decreasing and increasing dissolved oxygen concentrations, respectively

the formula represented by $\frac{|C_{\text{base}} - C_{\text{sens}}|}{C_{\text{base}}} \times 100\%$, where C_{base} is the dissolved oxygen for the base runs, shown in Figs. 7 and 8, and C_{sens} is the dissolved oxygen for the sensitivity run, shown in Figs. 9a and 10a.

The decrease in SOD increases the DO at the surface and bottom layers for the low and high flow conditions shown in Figs. 9b and 10b. The maximum rates of increasing DO are 26.7% and 79.1% at the surface and bottom layers, respectively, for the low flow condition and 27.2% and 31.7%, respectively, for the high flow condition (see Table 4). The modeling results indicate that the SOD values have a significant impact on the DO distribution along the Xindian River.

Conclusions

The SOD is considered a critical and dominant sink for DO in many river systems and is often poorly investigated or roughly estimated in oxygen budgets. In this study, the SOD along the Xindian River was measured in a laboratory setting. Regression results between SOD and freshwater discharge indicate that a higher freshwater discharge results in a lower SOD. Throughout a 1-year observation period, the measured SOD ranged from 0.367 to 1.246 g/m²/day at the temperature of 20°C, which is within the usual range, as compared with other systems.

The mean values of the measured SOD at each station were adopted in a laterally averaged two-dimensional water quality model to simulate the DO distribution in the Xindian River. The modeling results accurately depict the field-measured DO distribution during the low and high flow conditions. Model sensitivity analyses for SOD were conducted for the low and high flow conditions. The results reveal that maximum rates of DO concentration with increasing and decreasing SODs for the low flow condition are actually higher than those for the high flow condition. It shows that the SOD is more important for the low flow condition than for the high flow condition and that it exerts an important impact on the DO distribution in the tidal estuary. Measured SODs are useful in understanding and quantifying the fluctuations of DO. The findings of this study with field measurements and numerical modeling should assist in river water quality management in the Xindian River.

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