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Monitoring and modeling dissolved oxygen dynamics through continuous longitudinal sampling: a case study in Wen-Rui Tang River, Wenzhou, China

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Abstract:

Synoptic water sampling at a fixed site monitoring station provides only limited 'snap-shots' of the complex water quality dynamics within a surface water system. However, water quality often changes rapidly in both spatial and temporal dimensions, especially in highly polluted urban rivers. In this study, we designed and applied a continuous longitudinal sampling technique to monitor the fine-scale spatial changes of water quality conditions, assess water pollutant sources, and determine the assimilative capacity for biochemical oxygen demand (BOD) in an urban segment of the hypoxic Wen-Rui Tang River in eastern China. The continuous longitudinal sampling was capable of collecting dissolved oxygen (DO) data every 5 s yielding a ~11 m sampling interval with a precision of ± 0.1 mg L^{-1}. The Streeter and Phelps BOD-DO model was used to calculate: (1) the oxygen consumption coefficient (K_1) required for calibration of water quality models, (2) BOD assimilative capacity, and (3) BOD source and load identification. In the 2014 m river segment sampled, the oxygen consumption coefficient (K_1) was 0.428 d^{-1} (20°C), the total BOD discharge was 916 kg d^{-1}, and the BOD assimilative capacity was 382 kg d^{-1} when the minimum DO level was set to 2 mg L^{-1}. In addition, the longitudinal analysis identified eight major drainage outlets (BOD point sources), which were verified by field observations. This new approach provides a simple, cost-effective method of evaluating BOD-DO dynamics over large spatial areas with rapidly changing water quality conditions, such as urban environments. It represents a major breakthrough in the development and application of water quality sampling techniques to obtain spatially distributed DO and BOD in real time.

KEY WORDS water quality monitoring; oxygen consumption coefficient; dissolved oxygen; hypoxia; Streeter and Phelps model; assimilative capacity

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INTRODUCTION

China currently faces severe urban water quality problems. The fact that 90% of urban waterways are classified as heavily polluted (SEPA-China, 2005) has raised great concerns about human and aquatic ecosystem health (Zhang *et al*., 2010; Voss, 2011). Monitoring water quality is the first step toward understanding the characteristics of water pollution and for devising effective mitigation strategies. Traditional synoptic sampling at a fixed monitoring station provides only a 'snap-shot' understanding of the complex spatial-temporal water quality dynamics occurring within a surface water system. This complexity is especially pronounced in river systems spanning urban and agricultural land uses where numerous point and non-point inputs occur over relatively short distances. Thus, the single constant assimilative capacity coefficient (self-purification coefficient) obtained from such sampling does not accurately portray the biochemical oxygen demand-dissolved oxygen (BOD-DO) dynamics for large surface water systems crossing urban and agricultural boundaries. In fact, direct quantification of the assimilative capacity of rivers is very difficult to measure (Tase *et al*., 1993).

As early as 1925, scientists have modeled BOD-DO dynamics in polluted surface waters. Streeter and Phelps (1925) proposed the well-known Streeter–Phelps (SP model) Oxygen Sag Formula to describe the oxygen balance in streams. Throughout the years, researchers further improved and applied these equations to various scenarios (Theriault, 1927; Fair, 1939; Thomas, 1948; Li, 1962, 1972; Camp, 1963; Beck and Young, 1976; Gundelach and Castillo, 1976; Thomann and Müller, 1987; Yu *et al*., 1991; Adrian *et al*., 1994; Jolankai, 1997). Despite the emergence of many complex water quality models (e.g. QUAL2E, Brown and Barnwell, 1987; WASP6, Wool *et al*., 2001) describing DO dynamics resulting from changes of BOD, the SP model and its modifications, still remain among those most widely used (Gotovtsev, 2010). In the SP model, the oxygen consumption coefficient (K_1) represents the rate of O_2 consumption due to oxidation of organic matter and other reduced substances (e.g. NH_4^+, Fe^{2+}, S^{2-}). The reaeration coefficient (K_2) represents the rate of O_2 input to the river and is influence by flow rate, water depth, turbulence (mixing), water temperature, and degree of water column oxygen

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saturation. There are other methods for calculating these coefficients, such as the empirical formula used to calculate K_2 in the EPD-RIV1 water quality model (Martin and Wool, 2002). The oxygen consumption coefficient (K_1) is an important parameter for current riverine water quality models, such as EPD-RIV1 and QUAL2K (Chapra and Pelletier, 2003). The accuracy of water quality predictions is critically dependent on the selected K_1 value as it is the primary driver describing oxygen consumption rates. However, it is not possible to determine K_1 from synoptic water quality sampling alone. While BOD kinetics can be determined in the laboratory, such procedures require substantial resources, and laboratory measures cannot account for the complexities of oxygen consumption occurring in the real-world river setting (e.g. sediment oxygen demand and diel cycles).

The Wen-Rui Tang River located in Wenzhou, Zhejiang province, is one of the most polluted rivers in China with many portions of the 1178 km of urban waterways being dead zones due to persistent hypoxia. The pollution problem is compounded by the very low gradient and diversion of upstream waters, which result in little or no flow to flush the pollutants from the urban river system during dry periods. Because of their spatial complexity, synoptic sampling may not accurately depict the distribution of the pollutants sources in this system, confounding proper management decisions. This river remains highly polluted despite a substantial investment by the local government in recent years to clean it up.

To better inform future policy and management decisions, the objective of this study was to monitor the rapid spatial changes of water quality using continuous longitudinal water quality monitoring technology and to model BOD-DO dynamics. These data are then used to identify the 'hidden' drainage outlets from which pollutants flow into the river, and to estimate the oxygen consumption coefficient to spatially evaluate the pollutant loads along the course of the river. These can be determined by the difference analysis of the SP model and its related parameters. In contrast to BOD values determined in the lab, continuous longitudinal monitoring for DO is easily achieved and inexpensive using current water quality sensor technology. Thus, the specific focus of this study was to calculate the spatial variability in oxygen consumption (K_1) and reaeration (K_2) coefficients using temperature, DO, and GPS coordinates derived from the continuous longitudinal monitoring. The modeling results also allow for quantification of the BOD assimilative capacity and BOD source and load identification. The results of this study provide important information to guide water quality modeling, BOD source identification, and numerical targets for BOD load reductions to meet water quality standards.

MATERIALS AND METHODS

The study site

The Wen-Rui Tang River watershed is located in Wenzhou City, Zhejiang, China (Figure 1). The watershed has an area of 740 km^2 with a population of about 7.2 million and land-use distribution consisting of 14.5% urban, 39.5% agriculture, 1.5% wetlands, 38% hilly forest, and 6.5% others. The main stem of the Wen-Rui Tang River

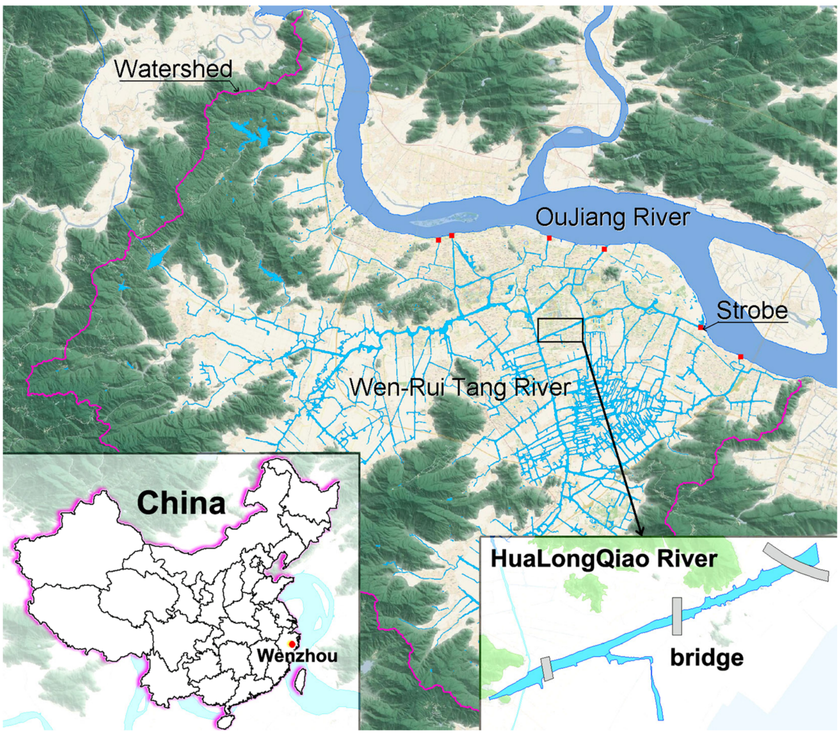

Figure 1. Map of Hualongqiao River, showing location of study site. Hualongqiao River is one branch of Wen-Rui Tang River in Wenzhou, China. The Coordinates of the river center is (27°59'28.06"N, 120°40'54.08"E)

spans 20.4 km in the urban area and flows through a network of interconnecting urban waterways with a total length of 1178 km. The width of the urban portion of the Wen-Rui Tang River is about 50 m on average, varying from about 13 to 150 m. Due to direct discharge of large amounts of domestic, industrial, and agricultural wastewater into the river, the water quality of the river is severely impaired, particularly since the rapid economic development of the 1980s. Many of the urban waterways are considered dead zones due to persistent hypoxia (AsianInfo Services, 2004). As a result, in 2008, the water quality was classified as inferior Type V, the lowest water quality classification in China (Wenzhou State of the Environment, 2008).

In this study, a tributary of the Wen-Rui Tang River, the Hualongqiao River, was selected as a case study for continuous water quality monitoring and BOD-DO analysis. This river segment is located at the urban–agricultural interface. It had a length of 2014 m, an average width of 53.7 m, and average depth of 20 m (Figure 1), and a very slow flow velocity of 4.5 m h^{-1} at the time of the study in October 2009. The river banks were occupied by an old one-story urban district on one side and a new residential district on the other. Domestic sewage was discharged directly into the river through rainwater runoff and a broken sewage collection network. In addition, several drainage outlets entered the river below the water line and were not easily visible from the surface.

Sampling design

A YSI 6920 multi-parameter water quality monitoring sonde (YSI, Yellow Springs, Ohio, USA) was used to measure temperature, probe depth, conductivity, pH, DO, total ammonia nitrogen (NH_4^+ + NH_3), and turbidity in real time. DO was measured with a YSI 6150 Optical DO sensor with a precision of ± 0.1 mg L^{-1} or 1% of the reading (whichever was greater) in the range of 0 to 20 mg L^{-1}. A handheld GPS (Trimble GEO-XT2008; Sunnyvale, California, USA) was used to log the longitude and latitude coordinates (0.5 m precision) for each of the YSI 6920 sampling points. The continuous longitudinal monitoring of surface water quality comprised five steps:

1. Calibration of the YSI 6920 water quality sensors immediately prior to data collection with verification of the calibration at the end of data collection.
2. Synchronization of the YSI 6920 and GEO-XT2008 GPS clocks and setting of the YSI sampling interval to 5 s; equivalent to ~11.2 m between sampling points.
3. Attachment of the YSI 6920 on a motor boat with the probe submerged 0.1 m into the water column followed by collection of data as the boat moves at a uniform speed (~8.06 km h^{-1}) along the center line of the river.
4. Export of data from the YSI and GPS into a GIS program after sampling.
5. Integration of YSI water quality data with the longitude and latitude for each data point.

This process produces a continuous water quality monitoring database containing nine parameters (time, temperature, depth, specific conductance, pH, DO, total ammonia-N, turbidity, and GPS coordinates). A total of 180 sample points were collected along the 2014 m river segment within a 1 h time interval.

GIS data source and Geodatabase design

Background GIS data were obtained from Wenzhou Department of Planning and Wenzhou River Assessment Office. The data included satellite images taken in 2004 with a 0.5 m resolution, the polygon water system of Wen-Rui Tang River, the census data of the underground storm water collection system (2004), and the sewage network system (2004) of the city. The GIS SuperMap Deskpro 2008 software developed by SuperMap Software Co., Ltd (Beijing, China) was used in this study. All the basic geographical data were imported to the GIS platform, which manages the data efficiently. The coordinate system was then set as the Wenzhou City coordinate system, based on the Xi'an reference system 1980 (Xian-80). When dealing with the field data, one should first import the database into GIS software to form a data attribute table; then, take the fields (longitude, latitude) as the horizontal and vertical (x, y) axes using a coordinate system to form point datasets based on the attribute table; and, finally, convert the coordinate system to Xian-80.

The analysis method of BOD-DO relationship

BOD-DO relationship model selection. Streeter and Phelps (1925) were the first to systematically study oxygen consumption and reaeration in streams. Although their model was modified for publicly available water quality models at various times, the basic functions of the SP model stayed the same in these later modified models. The original BOD-DO relationship equations were used for deriving the BOD dynamics based on our monitored DO values. Therefore, the capacity of a stream to oxidize sewage (i.e. organic matter and ammonia) depends upon its oxygen dynamics and can be described by the SP Oxygen Sag Formula (Streeter and Phelps, 1925) in the following equations:

$$D = C_s - C \tag{1}$$

$$\frac{dD}{dt} = K_1 L - K_2 D \tag{2}$$

$$D = \frac{K_1 L_0}{K_2\text{-}K_1} \times \left(e^{-K_1 t}\text{-}e^{-K_2 t}\right) + D_0 \times e^{-K_2 t} \tag{3}$$

$$\mathbf{D_c} = \mathbf{L_0} \times \frac{\mathbf{K_1}}{\mathbf{K_2}} \times \mathbf{e^{-K_1 t_c}} \tag{4}$$

$$\mathbf{t}_c = \frac{\mathbf{1}}{\mathbf{K_2\text{-}K_1}} \times LN\left(\frac{\mathbf{K_2}}{\mathbf{K_1}}\right)\left(1 - \frac{\mathbf{K_2\text{-}K_1}}{\mathbf{K_1}} \times \frac{\mathbf{D_0}}{\mathbf{L_0}}\right) \tag{5}$$

Where D is the oxygen deficit (mg L^{-1}), which is a function of C_s, DO concentration at 100% saturation as a function of temperature, salinity, and atmospheric pressure (mg L^{-1}) and C, the DO concentration (mg L^{-1}); L is the ultimate BOD (mg L^{-1}), while L_0 is the initial BOD (mg L^{-1}); K_1 is the oxygen consumption coefficient to the base e (per day); K_2 is the reaeration coefficient to the base e (per day); t is the time of travel as $t = x/v$, in which x is the distance from the upstream L_0 point (day); v is the velocity (m/day); and (t_c, D_c) is the critical point in which the rate of change of DO equals zero during downstream transport.

In the classical model of Streeter and Phelps, K_1, K_2, and L_0 can be computed using three data points – any point 1 (t_1, D_1), any point 2 (t_2, D_2) and the oxygen critical point (t_c, D_c) from the oxygen sag curve. However, the oxygen sag curve involves binary exponential equations, which are very difficult to solve. Therefore, in order to compute K_1 without the BOD data, some pragmatic approaches were developed.

Black and Phelps (1911) were the first to develop a pragmatic approach for determining the waste-assimilative capacity of a stream, and their methodology was later refined and used by Velz (Lin, 2001). This pragmatic approach was called the Velz Reaeration Curve (Velz, 1939) and calculates the biochemically consumed dissolved oxygen (DO_{used}) and dissolved oxygen absorbed from the atmosphere (DO_{rea}) by the following two equations.

$$DO_{used} = (DO_a - DO_{net}) + DO_{rea} \tag{6}$$

$$DO_{rea} = \left(1 - \frac{B_0}{100}\right)\left(\frac{R_0}{100}\right)\left(\frac{t}{M}\right)(5.39Q \times DO_s) \tag{7}$$

Where DO_{net} is the DO at the end of a reach; DO_a is the initial DO at the beginning of a reach; R_0 is the percent of the saturated DO absorbed into the water column when the initial DO is at 100 percent deficit (DO = 0); B_0 is the initial DO in percent of saturation; M is the mixing time in minutes; DO_s is the DO saturation load; and t is the time of travel.

After setting/manipulating the factors $Y = (\sum t / \sum DO_{used})^{1/3}$ and $X = \sum t$, a linear fit formula may be derived: $Y = S{*}X + b$. The results are $K_1 = 6S/b$ and $L_0 = b^3/K_1$, where K_1 is the oxygen consumption coefficient per day and L_0 is the initial BOD. This pragmatic approach involves estimating the waste assimilative capacity ($f = K_2/K_1$) of a water body using five of the parameters which were directly measured by our continuous longitudinal monitoring (flow volume, velocity, probe depth, temperature, and DO and the 13-step approach summarized by Lin (2001). The parameter R_0 is affected by many factors and requires manual lookup from several data sources. Therefore, this method was not suitable for the computerized estimation of the relevant parameters (K_1, L_0) listed above.

Method of data analysis. The DO saturation values, C_s, for various water temperatures can be calculated using the method of Elmore and Hayes (1960):

$$C_s = 14.652 - 0.41022\mathrm{T} + 0.0079910\mathrm{T}^2 - 0.000077774\mathrm{T}^3 \tag{8}$$

Because the Wen-Rui Tang River was a low-velocity river (4.5 m h^{-1}) at the time of the study, the reaeration coefficient (K_2) was estimated using the equations developed by O'Connor and Dobbins (1958) where the reaeration coefficient (K_2) is a function of the diffusivity of oxygen in addition to the river's average depth, flow velocity, and temperature:

$$K_2(20^\circ C) = \frac{(D_m u)^{0.5}}{d^{1.5}} \tag{9}$$

$$K_{2T} = 1.016^{T-20} \times K_2(20^\circ C) \tag{10}$$

$$K_{1T} = 1.047^{T-20} \times K_1(20^\circ C) \tag{11}$$

Where D_m is diffusivity of oxygen in water; d is average depth; u is flow velocity; and T is temperature.

Differential analysis of the SP model. According to the SP Oxygen Sag Formula, the following three equations can be derived from each other and used interchangeably.

$$-\frac{dC}{dt} = K_1 L - K_2(C_s - C) \tag{12}$$

The difference approximation is:

$$-\frac{\Delta C}{\Delta t} = K_1 L - K_2(\bar{C_s} - \bar{C}) \tag{13}$$

or

$$K_1 L_n = K_2\left(\frac{C_{s\,n+1} + C_{s\,n}}{2} - \frac{C_{n+1} + C_n}{2}\right) - \frac{C_{n+1} - C_n}{t_{n+1} - t_n} \tag{14}$$

Where n is the first monitoring point. Because K_2 is assumed to be a known constant, we can derive a series of $K_1 L_n$ values. According to the definition of K_1 ($dL/dt = K_1 L$), $K_1 L_n$ is the BOD oxygen consumption rate for the first sampling point (n).

Calculation of K_1. If we collect data at uniformly spaced points in the river, we can use $t = t_0 + n\Delta t$ and the following equation:

$$L_n = L_0 e^{-K_1 t} = L_0 e^{-K_1 t_0} \times \left(e^{-K_1 \Delta t}\right)^n \tag{15}$$

In general, K_1 (to the base e) is less than 1. When the distance of the continuous longitudinal sampling in the river is short enough to make $K_1 \Delta t < 0.1$, there will be a strong linear relationship between L_n and n or $K_1 L_n$ and n. As $K_1 \Delta t$ decreases in value, the linear correlation increases. Through this linear relationship, we can re-calculate $L_1^{'}$ and $L_n^{'}$, and use them to calculate K_1, as shown in the following equation:

$$K_1 = \frac{1}{(n\text{-}1)\Delta t} \times LN\left(\frac{L'_1}{L'_n}\right) = \frac{1}{(n\text{-}1)\Delta t} \times LN\left(\frac{K_1 L'_1}{K_1 L'_n}\right) \quad (16)$$

Selection of DO data meeting the SP model assumptions and for point source assessment. The SP model is a one-dimensional, steady-state model for DO-BOD relationships. In theory, it requires an instantaneous mixing of the sewage with the river water throughout the river cross section. In reality, near the sewage outlet, this is impossible. Therefore, we must identify the DO data from the continuous monitoring data which are suitable for use in the SP model. Ideally, these data should be from the section where the sewage has already been uniformly mixed with the water column and indicated by a good linear relationship between K_1L_n and n. At both ends of the longitudinal DO data set, the DO data deviate appreciably from this linear relationship, so these data were discarded.

We were also able to assess locations of point source BOD inputs within the river reach. In the longitudinal DO data set, the critical point is a key data parameter in which the rate of change for DO is zero, and the key data (C_c, t_c) point was used to compute the initial BOD (L_0) using the following formula:

$$L_0 = (C_s\text{-}C_c) \times \frac{K_2}{K_1} \times e^{K_1 t_c} \quad (17)$$

The initial BOD (L_0) is composed of two parts: one part of the discharge stems from the sewage outlet, L_{outlet}, while the other part originates from BOD imported from upstream sewage, L_0' ($L_{\text{outlet}} = L_0$ - L_0').

RESULTS

Table I provides an example of the continuous longitudinal data and its structure. Among the total of 180 data points collected along the 2014 m river segment (~11.2 m between sampling points), there were 36 data points which lacked GPS coordinates because the GPS receiver could not receive satellite signals when the boat navigated under bridges. These missing GPS coordinates were interpolated between measured GPS points assuming a uniform boat speed of 8.06 km h^{-1}.

Trend of dissolved oxygen and identification of the hidden drainage outlets

The average DO concentration was 21.8% of saturation (which is equivalent to 1.75 mg L^{-1}) and ranged from 9.4% (0.76 mg L^{-1}) to 36.4% (2.9 mg L^{-1}) (Figure 2). Average total ammonia nitrogen concentration was 7.25 mg L^{-1}, ranging from 5.93 to 8.16 mg L^{-1} (Figure 3) with many peaks within the river segment. Water temperature displayed about a 1°C variation along the river segment with an average temperature of 25.6°C (Figure 4). The peaks of temperature, ammonia, and DO occurred at a distance of 700 m where a tributary joins the Hualongqiao River (Figures 2–4).

Changes in DO concentrations along the river segment are shown in Figure 5. According to the SP Oxygen Sag Curve, Figure 5 displays eight positive peaks in the DO curve. The rate of change, i.e. ΔDO/ΔL, was verified to correspond to the maximum BOD concentrations as shown by the red solid line in Figure 5, which are related to the locations of eight sewage drainage outlets (point sources). The minimum values in the DO curve (when

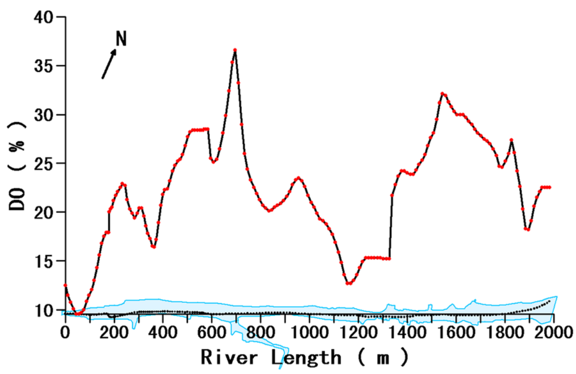

Figure 2. Dissolved Oxygen (DO) variations in Hualongqiao River from upstream to downstream. DO is percent of saturation. The light blue shows the river width in the sampled segment, similarly as shown in Figure 3 and 4

Table I. Longitudinal continuous water quality monitoring data

Time	lat	Long	Temp °C	Cond S cm^{-1}	Probe Depth m	pH	Ammonium-N mg L^{-1}	Turb NTU	DO %
14:17:34	120.6705	27.9869	25.3	0.25	−0.1	6.71	7.3	23.6	12.3
14:17:39	120.6706	27.9870	25.3	0.25	−0.1	6.70	7.5	22.5	11.3
14:17:44	120.6707	27.9870	25.3	0.25	−0.1	6.70	7.7	21.4	10.6
14:17:49	120.6708	27.9871	25.2	0.25	−0.1	6.70	7.8	20.3	9.9
. . .									
14:32:49	120.6873	27.9933	25.7	0.25	−0.1	6.76	7.1	6.4	25.0
14:32:54	120.6875	27.9934	25.7	0.25	−0.1	6.76	6.9	6.3	25.8
14:33:34	120.6883	27.9939	25.4	0.26	−0.1	6.75	7.4	7.1	18.9
14:33:39	120.6884	27.9940	25.5	0.26	−0.1	6.75	7.4	7.0	20.4

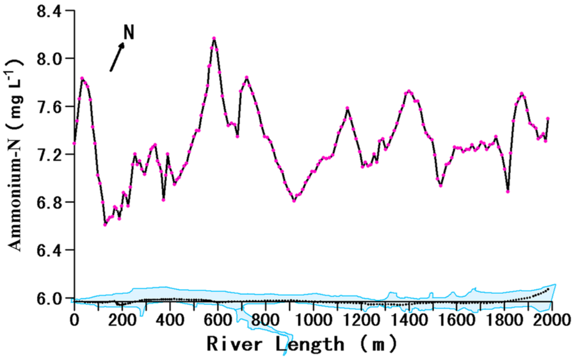

Figure 3. Ammonium-N variations in Hualongqiao River from upstream to downstream

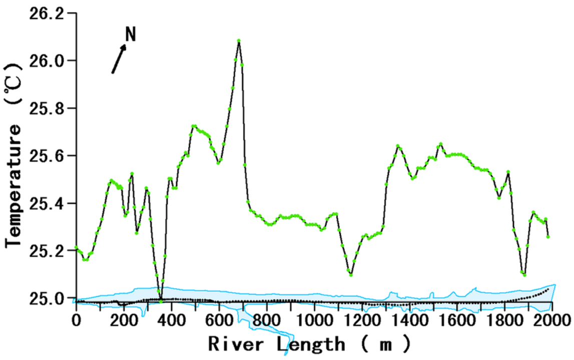

Figure 4. Temperature variations in Hualongqiao River from upstream to downstream

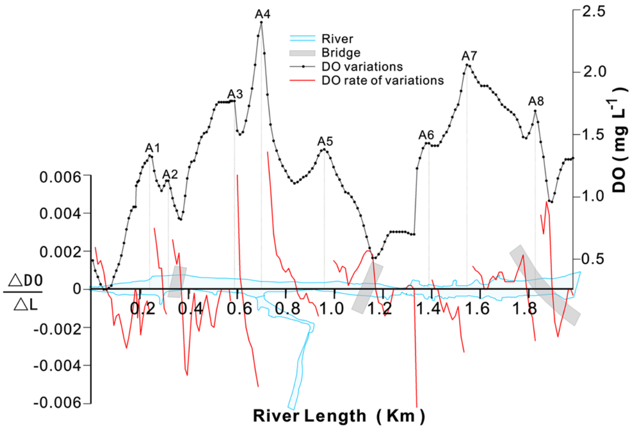

Figure 5. DO variations and DO rate of variations in Hualongqiao River from upstream to downstream. The symbols from A1 to A8 are the positions of the sewage outlets based on the analysis of DO peaks and verified in the field. The DO rates of variations are only shown between the two sewage outlets

$\Delta DO/\Delta L = 0$) are identified as the critical points at which DO rate of change is equal to zero. The SP Oxygen Sag Curve will show a single maximum and minimum peak in the trend of DO if there is only one wastewater outlet in a river. However, eight such twin peaks (maxima and minima) were observed in Figure 5, which correspond to eight major sewage outlets in the river segment. The locations of the outlets, designated A1 through A8 in Figure 5, were verified by the field investigation. This revelation shows that the continuous longitudinal sampling for DO can accurately identify the hidden sewage outlets under the water surface.

Calculation of K_1, the oxygen consumption coefficient

In general, K_1 to the base *e* is considered to be a constant. Therefore, K_1 was calculated using the DO data in the A4–A5 segment shown in Figure 5. This river segment contains more monitoring points, resulting in a smooth curve that indicates that there are no major wastewater sources in this segment. The DO data for the A4–A5 segment and related parameters used to calculate K_1 are listed in Table II.

In the case study, $\Delta t = 0.1147$ and $K_1 < 0.8$, so $K_1 \Delta t < 0.1$. Since the value of $K_1 \Delta t$ was much smaller than the threshold of 0.95 (as defined in section 2.4.4), a strong linear relationship between $K_1 L_n$ and n was expected. Figure 6 shows the linear relationship between $K_1 L_n$ and n using the DO data from the A4–A5 river segment. Based on Equation (17), oxygen consumption coefficients (K_1) of 0.552 d^{-1} (25°C) and 0.428 d^{-1} (20°C) were obtained.

When the Velz Reaeration Curve was used to independently calculate K_1, results were $b = 0.193$; $S = 0.017$; and $K_1 = 6s/b = 0.528$ d^{-1}. The results of the two K_1 estimation approaches using our derived approach and the Velz Reaeration Curve were similar (0.552 *vs* 0.528 d^{-1}, 25°C) supporting the validity of using our new approach in calculating K_1.

Calculation of L_0 and assessment of point source pollution

The calculated BOD discharge loads from wastewater outlets, A1 to A8, are listed in Table III. Outlets A5 and A7 released the largest amount of BOD at 226 and 234 kg d^{-1}, respectively, followed by the outlets A1 and A4 at 104 and 121 kg d^{-1}, respectively, while outlets A2, A3, A6, and A8 released BOD loads of less than 100 kg d^{-1} (Table III). The sum of BOD loads from the eight outlets indicates the total amount of BOD discharged into the river segment examined in this study was 916 kg d^{-1}.

Computation of self-purification capacity

The BOD assimilative capacity (K_2/K_1), i.e. self-purification capacity, was calculated based on designated minimum DO values, which correspond to the critical points of the oxygen sag curve. We assumed that the sewage outlets in the river were upstream, and that the amount of the initial DO was equal to the amount of DO at saturation or $D_0 = 0$. Following the analysis of inferences in Section 2.4.4, 2.86 days (t_c) were required for DO to change from the highest value to the lowest value.

The minimum dissolved oxygen (D_c) of the river was set to four water quality standard values ranging from 2–6 mg L^{-1}, which correspond to four water quality classification grades in China. The results of the computation for BOD load capacity ranged from 129 kg d^{-1} to maintain the 6 mg L^{-1} DO minimum standard to 382 kg d^{-1} to maintain the 2 mg L^{-1} DO minimum standard (Table IV).

Table II. Calculation of K_1 using the DO data in A4–A5 segment

No	Length meter	Temp. °C	C mg L^{-1}	Cs mg L^{-1}	Mean Cs mg L^{-1}	Mean C mg L^{-1}	Δt days	ΔC	K_2	K_1*L	n
74	0.0	26.3	2.90	7.97			0		0.207		
75	12.8	25.8	2.65	8.06	8.01	2.78	0.118	−0.25	0.205	3.19	
76	12.7	25.6	2.32	8.09	8.07	2.49	0.118	−0.33	0.204	3.94	
77	12.6	25.5	2.08	8.10	8.09	2.2	0.117	−0.24	0.204	3.26	
78	12.6	25.5	1.95	8.10	8.10	2.02	0.117	−0.13	0.204	2.36	1
79	12.5	25.5	1.87	8.10	8.10	1.91	0.116	−0.08	0.204	1.95	2
80	12.4	25.5	1.80	8.10	8.10	1.84	0.115	−0.07	0.204	1.89	3
81	12.4	25.5	1.75	8.11	8.10	1.78	0.115	−0.05	0.204	1.74	4
82	12.4	25.4	1.71	8.11	8.11	1.73	0.115	−0.04	0.204	1.65	5
83	12.3	25.4	1.66	8.11	8.11	1.69	0.113	−0.05	0.204	1.75	6
84	12.3	25.4	1.63	8.11	8.11	1.65	0.114	−0.03	0.204	1.58	7
85	12.2	25.4	1.61	8.11	8.11	1.62	0.113	−0.02	0.204	1.50	8
86	12.2	25.5	1.62	8.11	8.11	1.62	0.113	0.01	0.204	1.24	9
87	12.3	25.5	1.64	8.10	8.10	1.63	0.114	0.02	0.204	1.15	10
88	11.9	25.5	1.66	8.10	8.10	1.65	0.110	0.02	0.204	1.14	11
89	12.3	25.5	1.67	8.10	8.10	1.67	0.114	0.01	0.204	1.23	12
90	12.5	25.5	1.70	8.10	8.10	1.69	0.116	0.03	0.204	1.05	13
91	12.6	25.5	1.73	8.10	8.10	1.72	0.117	0.03	0.204	1.05	14
92	12.2	25.5	1.77	8.10	8.10	1.75	0.113	0.04	0.204	0.94	15
93	12.1	25.5	1.83	8.10	8.10	1.8	0.112	0.06	0.204	0.75	16
94	12.2	25.5	1.87	8.10	8.10	1.85	0.113	0.04	0.204	0.92	

Notes: Velocity = 0.00125m/s; Depth = 1.85m

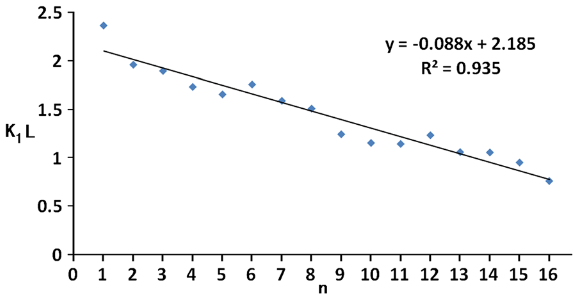

Figure 6. The analysis of the linear relationship between K_1L_n and n

Table IV. Computation of self-purification capacity

Water quality types	DO standards mg/L	Self-purification capacity mg/L	kg/day
II	6	3.7	129
III	5	5.5	192
IV	3	9.0	318
V	2	11	381

Notes: Flow = 0.407 m^3 s^{-1}; Average temperature = 25.52 °C; K_2 = 0.204 d^{-1}; K_1 = 0.552 d^{-1}.

Table III. Assessment of point source pollution

Station	L_0 mg L^{-1}	L_0' mg L^{-1}	$L_{outfall}$ mg L^{-1}	Flow Q m^3 d^{-1}	$L_{outfall}$ kg d^{-1}
A1	3.0	0.0	3.0	35 191	104
A2	3.3	2.0	1.3	35 191	46
A3	2.5	0.82	1.7	35 191	59
A4	4.9	1.4	3.4	35 191	120
A5	7.8	1.4	6.4	35 191	226
A6	2.8	0.8	2.0	35 191	69
A7	7.9	1.2	6.6	35 191	234
A8	3.5	1.9	1.7	35 191	58

Notes: L_0 is the initial BOD. L'_0 is the BOD from upstream. $L_{outfall}$ is the discharge of the sewage outfall.

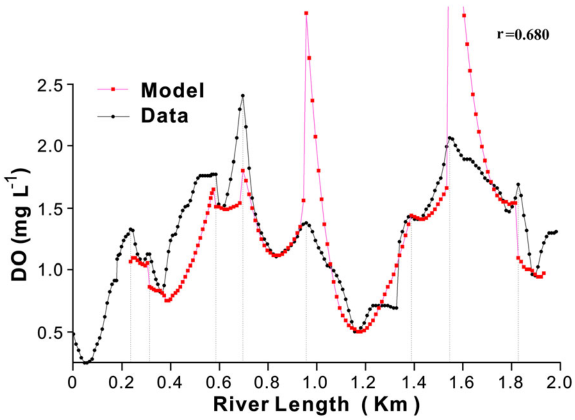

Figure 7. Observed DO data and model prediction curve in Hualongqiao River

Figure 7 shows that the observed DO (black line) was highly correlated (r = 0.68) with the model-generated DO (red line) concentrations along the river segment. This analysis indicated that the model reasonably predicted the DO values for the river segment in this study. Since the SP model requires an unrealistic instantaneous mixing of the wastewater with the river water, it is not surprising that the two large peaks for predicted DO do not match well with the observed DO.

DISCUSSION

The calculated oxygen consumption coefficient (K_1) varies with temperature as indicated by the value of 0.552 d^{-1} at 25.6°C (ambient) and 0.428 d^{-1} normalized for 20°C. The greater the K_1 value, the faster oxygen is being consumed. Thus, the relatively high K_1 value in the Hualongqiao River indicates that oxygen consumption is rapid and that inputs of oxygen demanding substances are very severe in this river segment. This is consistent with the water quality classification of inferior Type V (<2 mg L^{-1} O_2) that is common throughout Wenzhou City waterways (Wenzhou State of the Environment, 2008). The calculated BOD discharged into the river segment, 916 kg d^{-1}, was considerably higher than the BOD receiving load capacity for type V water quality of 381 kg d^{-1}, based on the 2 mg L^{-1} DO minimum. Thus, BOD discharge into the river segment would need to be reduced by 535 kg d^{-1} to meet the minimum water quality standard DO concentration of 2 mg L^{-1}. This specific reduction target provides a useful reference point for the municipal government to properly devise water management decisions.

This theoretical analysis has practical implications for water quality assessment. By showing that the K_1 and BOD assimilative capacity may be computed using only DO data collected in a rigorous longitudinal fashion, this method obtains real-time water quality information using far less resources than traditional laboratory methods. Although the Velz Reaeration Curve (Velz, 1939; Lin, 2001) also calculates an oxygen consumption coefficient (K_1) using only DO data (K_1 was 0.528 d^{-1} using the Velz Reaeration Curve), it is far more cumbersome if continuous longitudinal DO data are not available.

The new monitoring and calculation approach analyzed and demonstrated in this study is direct, simple, and suitable for automated computer processing for water quality assessment. The ability to rapidly collect densely packed DO concentration measurements with high precision using the continuous longitudinal monitoring technology makes this new approach possible in real times. The oxygen consumption coefficient (K_1) is a critical parameter driving oxygen dynamics in many water quality models, such as the EPD-RIV1 and QUAL2K developed by the US Environmental Protection Agency. However, with the application of these water quality models, parameter calibration has been a key problem that is difficult to resolve with confidence. The data collection and analysis methods proposed in this study can be used to spatially determine the critical oxygen consumption coefficient (K_1) for a given watershed. This approach is especially useful in highly polluted rivers, which are common in many rapidly developing countries.

The essence of this approach is the use of dense DO sampling to obtain the rate of change for DO concentrations, allowing the use of $\Delta C/\Delta t$ instead of dC/dt in the differential equations used to describe the BOD-DO relationships. This greatly reduces the difficulty of solving the differential equations. Dense sampling requires data collection methods that are convenient, fast, reliable, and low cost. The continuous longitudinal water quality monitoring using sondes with multiple sensors meets these requirements. However, to facilitate subsequent data analysis and optimize model results, some additional requirements for sampling frequency and uniform sampling distance by continuous longitudinal monitoring must be met.

Data quality and its influence

A sensitivity analysis examining experimental variability in water quality data acquired by the YSI sonde in this study indicates low (<2%) variability in predicted parameters based on the expected sonde variability. The YSI 6150 Optical DO sensor uses a fast interception system for measuring DO. This type of fast interception system uses a Clark sensor to measure the return of electrons diffused through a Teflon membrane. The accuracy of DO measurements is influenced by temperature and the flow of the water system around the sonde. Temperature was automatically corrected using the measured water temperatures. Based on the YSI user's manual, DO readings will be decreased by 2–3% at the speed of our boat compared to DO readings in still water. Considering this difference, we recalculate the K_1 as 0.554 ~ 0.556 d^{-1} (25°C) compared to $K_1 = 0.552$ d^{-1} (25°C) for non-velocity corrected values. These differences result in K_1 value differences 0.4–0.7% lower and L_0 values 0.7–1% higher. Since all DO measurements were taken at a constant boat travel velocity, all of our measurements are internally consistent.

Sampling frequency requirements

The continuous longitudinal monitoring of rivers is actually a kind of digitization of the continuous DO data. Therefore, in accordance with the requirements of the Sampling Theorem (Shannon, 1949), the sampling frequency must be greater than twice the highest frequency of the analog signals. Under this condition, the sampling results may be fully representative of the original analog signal. For best results with respect to real-world sampling, the sampling frequency should be set as three to five times the highest signal frequency. The SP model requires an instantaneous mixing of the wastewater with the river water to produce a valid sampling point, but these mixing conditions near the sewage outlets are not possible to fully achieve. Considering these factors, we set the sampling frequency at eight times higher than the signal frequency. In the river segment examined, the minimum distance between the identified sewage outlets was 85 m; therefore, the distance between monitoring points was set to approximately 11 m (85/8 m).

Limitation and applicability

The application of continuous longitudinal water quality sampling data provides a theoretical basis for obtaining the oxygen consumption coefficient which is otherwise difficult to acquire, however, there are some limitations. One of the conditions required to maintain the linear relationship between K_1L and n is a uniform Δt. If we assume that the water flow rate is constant, this is accomplished by uniformly spaced sampling times (5 s interval in this study). The water quality sonde is fixed on the boat, which must move at a uniform speed to meet the uniform sampling distance requirement. The continuous longitudinal monitoring method presented here is also one dimensional, so the monitoring boat must move along the center line of the river to achieve optimum data collection. In addition, due to the specific conditions of the river segment examined, two complicated terms in the equations were considered negligible. Future research may explore the non-linear relationships between the K_1L and n as well as expanding the analysis to two- or three-dimensional calculations of the essential water quality parameters for broader application to sustainable water resource management.

CONCLUSION

This study used a branch of the Wen-Rui Tang River as a case study to demonstrate the efficacy of using a longitudinal continuous water quality monitoring methodology to model BOD-DO dynamics in a hypoxic urban river. The results indicated that continuous longitudinal monitoring of temperature and DO is a powerful approach for quantifying several BOD-DO parameters. This method allows direct computation of the oxygen consumption coefficient (K_1), BOD assimilative capacity, BOD point source locations, and total BOD loads discharged into the river segment of interest. With these values, we are able to better evaluate changes in water quality and chart the continuous temporal and spatial distributions of BOD-DO dynamics in complex urban waterways. This approach can be applied to any other complex urban waterways with slow flow movement for water quality assessment.

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