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Reaeration Caused by Intense Boat Traffic

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Abstract: In rivers, reaeration is an important process that occurs at the air-water interface to restore dissolved oxygen (DO) equilibrium and this process is characterised by its reaeration coefficient. Existing empirical equations to predict reaeration coefficient is merely based on natural reaeration (K_u), which refers to the oxygen transfer across the natural free surfaces while reaeration coefficient concerned with artificial reaeration caused by turbulence due to intense boat traffic (K_b) has not been explored previously. This study investigated the influence of boating activities on DO and its associated reaeration coefficient, K_b, along the Brunei River. Spatial analysis of DO distribution indicates that the water is better oxygenated when it travels through areas with boat traffic. Using the DO balance equation, it was discovered that K_b is between 0.19 (day^{-1}) and 1.99 (day^{-1}) while K_u is between 0.20 (day^{-1}) and 0.51 (day^{-1}) which implies the importance of boat activities as an additional source of oxygen for the river. A predictive equation was derived for K_b as a function of boat traffic intensity (N) and water depth (H). This equation is useful for the analysis of purification capacity of a navigated river and water quality modelling.

Key words: Boat traffic, dissolved oxygen, reaeration, reaeration coefficient.

Introduction

Dissolved oxygen (DO) is one of the most important indicators of water quality (Benedini and Tsakiris, 2013; Ji, 2008), since DO is required for a healthy aquatic ecosystem. Reaeration is an important natural process by which a river replenishes oxygen consumed in the biodegradation of organic wastes. The rate at which oxygen is replenished through reaeration with respect to time is recognised to be a function of oxygen deficit and the reaeration coefficient. The reaeration coefficient depends on turbulence at the air-water interface. Numerous studies have been made and many prediction equations have been presented for the reaeration coefficients. These studies ranged from theoretical investigations (O'Connor and Dobbins, 1958) to empirical field studies (Churchill et al., 1962; Owens et al., 1964) which relate reaeration coefficient due to the natural process, K_u, to stream characteristics such as velocity, depth and channel slope. The various empirical relationships of reaeration coefficient were reviewed broadly by Cox (2003) and Bennett and Rathbun (1972). However, any empirical equation cannot always be adequate for every channel and can vary within the same channel (Benson et al., 2014). Applying these empirical equations on rivers with conditions outside the range of variables considered in the original correlation can produce large errors (Bennett and Rathbun, 1972).

In a water system with human interventions such as boating activities, DO concentration will differ from rivers that have not been navigated through. Turbulence produced by the propellers of boats during navigation can affect reaeration at the air-water interface. Estimating reaeration coefficient due to other factors other than natural processes such as boating activities using existing empirical equations may not be appropriate. There has been a significant rise in boating activities around the globe particularly to cater

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to coastal recreations and tourism interests (Whitfield and Becker, 2014; Byrnes et al., 2016). To date, water quality studies related to boating activities have focused on heavy metals, suspended sediments, and nutrients in waters. For instance, Whitfield and Becker (2014) investigated heavy metals from antifouling paints and boat exhaust emissions, whereas Prygiel et al. (2015) investigated the biogeochemistry of phosphorus, heavy metals and other chemical parameters, such as oxygen content, in rivers that are subject to heavy navigation and have determined the possible role of boat traffic on water quality. They have found that the navigated rivers have better water quality with better oxygenation and less phosphorus and heavy metal contents than the non-navigated rivers. They suggested that besides primary production which promotes good oxygenation, boat traffic is another factor that sustains oxygen levels and causes resuspension of sediments. Nonetheless, the study focused more on nutrients and heavy metals due to sediment resuspension caused by boats rather than the actual oxygenation processes. Other studies such as the one conducted by Kleeberg et al. (2012) looked at heavy metals and phosphorus budget of aerated lakes, while Lenzi et al. (2005) investigated the sediment disturbance in the shallow water of lagoon created by boats, which affects nutrient distribution.

Studies that assess the influence of boating activities on DO in a river and its associated reaeration process at the air-water interface is generally lacking. The potential findings would provide important information to environmental managers such as in the modelling of DO for water quality management as an inaccurate estimation of reaeration coefficient would lead to an imprecise model, inadequate regulation systems and will potentially cause harmful effects to the aquatic ecosystems (Benson et al., 2014) or unnecessary environmental costs. Accordingly, this research investigated the influence of boat activities on the distribution of DO in a river that is subject to heavy navigation and the potential role of boat activity in the reaeration process. As suggested by Prygiel et al. (2015), this type of study could not be done in a laboratory as laboratory experiments could not systematically mimic the natural systems. Before, After, Control-Impact (BACI) design on a river would also not have been possible as the fluvial traffic could not be controlled by the researcher (Prygiel et al., 2015). Therefore, this study was conducted on a river with actual settings that have the spatial intensity of boating activities.

This study was conducted at the Brunei River, which is an important surface water system in Brunei that drains to the inner Brunei Bay. Firstly, this is due to its location within the most populous district, the Brunei-Muara District and where the capital city, Bandar Seri Begawan is located. Secondly, it is due to its importance to the country's tourism sector as the river is renowned to support the largest water village in Southeast Asia, *Kampong Ayer*. Kampong Ayer is located at the lower reach of the Brunei River. Around this area, boat traffic is high as motorboats are used as a means of transport for people who want to commute between the mainland and Kampong Ayer. The objective of this study is, by measuring the DO concentration in different layers at different locations of the Brunei River with different intensity of boat traffic, to estimate the reaeration coefficient due to boating activities, K_b. In the data analysis, the dissolved-oxygen balance equation was employed, which consists of various sources and sinks of dissolved oxygen (Bennett and Rathbun, 1972; Cox, 2003; Parmar and Keshari, 2012). Finally, a predictive equation of K_b was developed based on the intensity of boat traffic, N, and depth, H, by using non-linear regression analysis.

Methodology

Site Selection

In order to observe spatial distribution of DO, seven sites were selected based on the intensity of boat traffic and feasibility to carry out the field work (Figure 1). Site 1 and Site 2 are located upstream within the mangrove-fringed reaches, and these areas are less impacted by boat activities. Since Site 2 is located within the border of Kampong Ayer, DO is affected by nearby navigated boats. Thus, Site 1 was included in the study which is located further upstream from Site 2. Site 3 is bordered

Figure 1: Map showing the sites for in-situ investigations of DO and tidal station.

with houses of Kampong Ayer at the river banks and is impacted by boat navigation. Site 4 is located in the vicinity of big shopping complexes at the mainland and where most people linger to commute between the mainland and Kampong Ayer; hence Site 4 is considered as the most trafficked area. Site 5 is bordered with houses of Kampong Ayer and government offices at the river banks and Site 6 is within Kampong Ayer. Both Site 5 and Site 6 are located next to each other within the main routes of boat crossings. Site 7 is located downstream and surrounded with mangroves on the right bank as well as houses and government offices at the left bank.

Scheme of Survey

Water quality parameters consisting of DO, pH and temperature were recorded directly in-situ using YSI Multiparameter at all stations in three events (30 November 2016, 30 December 2016 and 27 February 2017). Due to tidal cycles, in each event investigations were carried out for three runs each during low tide, intermediate tide and high tide periods respectively. Furthermore, water samples were taken for the analysis of biochemical oxygen demand (BOD_5) and ammonia (NH_3).

The survey was purposely proceeded against flow direction to avoid the same water body being tracked. Based on tide predictions obtained from the Marine Department (2016) at *Sg Lampai* of the Brunei River near downstream of the studied area, low tide tests were conducted before the lowest peak of low tides and ended before the river flow changes direction. As the water flows from upstream to downstream, the test was done starting from Station 7 to Station 1. High tide tests were conducted before the second highest peak of high tide and were conducted before the flow direction reversed and this was done from Station 1 to Station 7, as the water flows from downstream to upstream. The intermediate tide tests were conducted in between the peak low tide and high tide and as the river was experiencing reversed flow, the survey was done from Station 1 to Station 7 which was against the flow. The concentration of DO was recorded at layers of 0.5 m and 2.0 m underwater surfaces at all sites. Additionally, DO was measured vertically at five layers (surface, between surface and middle, middle, between middle and bottom, and bottom) in one run of investigation at four sites in order to observe DO stratification. The intensity of boat activities, *N*, was visually accounted with one hour of time interval in one hectare of area at each river cross-section where DO was measured. This data is deemed to represent its daily routine throughout the year and does not consider unusual boat activities during any special events when the number of navigating boats at the Brunei River is expected to be more intense.

Data Analysis

The DO variability in rivers is influenced by its sources and sinks where it is often presented by the classical or modified form of Streeter-Phelps model. The basic Streeter-Phelps model incorporates two primary mechanisms governing the fate of DO in the river where BOD of the carbonaceous material is the main sink while reaeration is the main source of DO. Modified forms of the model include other sinks of DO such as nitrification, sediment oxygen demand and respiration by aquatic plants, whereas the sources of DO include photosynthesis by aquatic plants and DO from tributaries. However, all the processes that affect DO may not occur simultaneously in a river (Haider and Ali, 2010). In the Brunei River, photosynthesis and respiration will have less effect on DO due to high turbidity of the water (Marshall et al., 2016; Marshall et al., 2008; Bolhuis et al., 2014). As the river is tidally influenced, sediment oxygen demand will not have a significant effect on DO as sediments are frequently washed away with floods (Haider and Ali, 2010). Therefore, in the Brunei River which is subject to intense boat activities, a water body travelling a distance of Δx in the time duration of Δt would experience reaeration by boat activities, reaeration due to river flow and oxygen consumption by pollutants, causing a change in DO concentration, ΔDO. These are presented in a mathematical form as follows:

$$\frac{dDO}{dt} = -K_d L_{CBOD} - K_n L_{NBOD} + K_u D + K_b D \quad (1)$$

Or

$$\frac{1}{D}\frac{\Delta DO}{\Delta t} + K_d \frac{L_{CBOD}}{D} + K_n \frac{L_{NBOD}}{D} - Ku = K_b \quad (2)$$

where D is oxygen deficit, DO is DO concentration, and $D = DO_s - DO$. DOs are saturated dissolved oxygen and is a function of water temperature, T, which was measured on site during the survey, and can be calculated by Equation (3) (Elmore and Hayes, 1960):

$$DO_s = 14.652 + T\{-0.41022 + T(0.007991 - 0.000077774T)\} \quad (3)$$

K_d is deoxygenation coefficient and L_{CBOD} is the concentrations of BOD_5, K_n is nitrogenous deoxygenation coefficient and L_{NBOD} is the concentrations of NH_3-N.

Thomann and Mueller (1987) suggested that K_n is approximately equal to K_d and 0.30 was employed for the polluted river (Zainudin et al., 2010; Cox, 2003; Chapra, 1997). K_u is reaeration coefficient due to water flow (O'Connor and Dobbins, 1958) and can be measured using Equation (4). This equation is applied for ranges of depth, $H = 0.3 - 9.14$ m and velocity, $u = 0.15 - 0.49$ m/s.

$$K_u = \frac{3.9u^{\frac{1}{2}}}{H^{\frac{3}{2}}} \quad (4)$$

where u is the velocity of the water flow in the river and it is observed to be 0.2 m/s on average in the concerned river course. H is average water depth of respective river segments during different tidal periods and can be estimated from bathymetry data of the river and adjusted by adding or subtracting with the mean water level during high tide and low tide respectively.

Temperature correction was made for the coefficients using Equation (5):

$$(K)_T = (K)_{20}(\theta)^{T-20} \quad (5)$$

where $(K)_T$ and $(K)_{20}$ is the coefficient at temperature, T, and at 20°C respectively. The temperature correction factor, θ, is 1.047, 1.08 and 1.024 for K_d, K_n and K_u respectively.

The time taken for the DO change in a water body passing the river segment, Δt, can be calculated by:

$$\Delta t = \frac{\Delta x}{u} \quad (6)$$

The reaeration coefficient due to boating activities, K_b, can then be determined by Equation (2), and it is assumed to be proportional to intensity of boat traffic (N) and reversely proportional to depth of river (H), i.e.:

$$K_b = \alpha\left(\frac{N}{H}\right)^{\beta} \quad (7)$$

where α and β are constants to be determined by this research.

In data analysis using Equation (2), ΔDO is the difference of measured DO between two sites, whereas for other data such as DO concentration, boat intensity, N, temperature, T, BOD_5 and NH_3-N between sites, the distance-weighted averages of the measured data at the sites were used since the distances between two sites are normally different. Referring to Figure 2, for instance, boat intensity, N, between sites was calculated using Equation (8) and (9), etc. In Figure 2, H1,2 denotes average depth between Sites 1 and 2; and so on so forth.

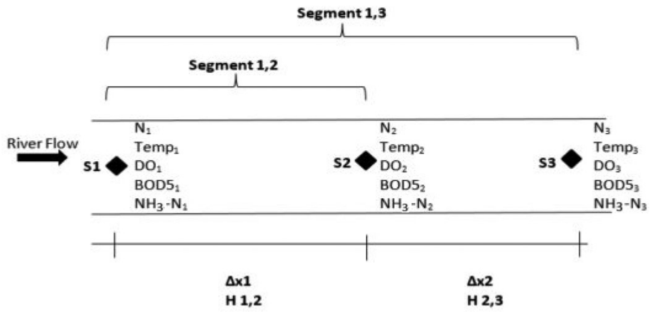

Figure 2: Examples of sites, segment between sites, and data at sites.

$$N_{1,2} = \frac{\left(\frac{\Delta x1}{2}.N_1\right) + \left(\frac{\Delta x1}{2}.N_2\right)}{\Delta x1} \quad (8)$$

$$N_{1,3} = \frac{\left(\frac{\Delta x1}{2}.N_1\right) + \left(\frac{\Delta x1}{2}.N_2\right) + \left(\frac{\Delta x2}{2}.N_2\right) + \left(\frac{\Delta x2}{2}.N_3\right)}{\Delta x1 + \Delta x2} \quad (9)$$

Investigation of DO concentration at five layers of river depth of several sites (Table 1) indicates that DO is slightly stratified. Due to this, measured DO needs to be adjusted to represent the DO concentration for the whole cross-section. From the measured data, it was found that:

$$\frac{\left(DO_{0.5} + DO_{2.0}\right)}{2} / DO_{avg} \approx 1.13 \quad (10)$$

Therefore, $$DO_{avg} = \left(\frac{\left(DO_{0.5} + DO_{2.0}\right)}{2}\right) / 1.13 \quad (11)$$

where DO_{avg} represents average DO concentration on the cross-section.

Results and Discussion

Spatial variations of DO concentrations along the investigated sites observed at 0.5 m ($DO_{0.5}$) and 2.0 m ($DO_{2.0}$) underwater surfaces are shown in Figure 3. In Figure 3, $DO_{2.0}$ was not recorded for Sites 6 and 7 as the water columns were quite shallow. During low tide periods (Figure 3a), it can be seen that there is a general trend that $DO_{0.5}$ increases downstream from upstream site (Site 1 or Site 2) to downstream site (Site 7). For instance, on 30 November 2016, DO at the upper layer increased significantly downstream from 3.62 mg/L to 3.82 mg/L, 3.93 mg/L, 4.28 mg/L, 4.34 mg/L to 4.68 mg/L at Sites 2, 3, 4, 5, 6 and 7 respectively. During the later event on 30 December 2016, DO slightly increased from upstream to downstream with 5.18 mg/L, 5.17

Table 1: DO concentration measured at five layers of river depth at four stations in one run of investigation to observe DO stratification

	Site	*DO (mg/L)*					
		Surface	*(Surface+ Middle)/2*	*Middle*	*(Middle+ Bottom)/2*	*Bottom*	*Average of DO between five layers*
High tide	2	6.43	6.32	5.94	5.26	5.17	5.82
	3	6.44	6.06	5.74	5.20	5.16	5.72
	4	6.60	6.44	5.40	5.20	5.70	5.87
	5	6.40	6.10	5.16	5.16	5.16	5.60
Low tide	2	5.63	5.77	4.71	4.13	4.06	4.86
	3	6.70	6.63	5.59	4.45	4.23	5.52
	4	6.85	6.84	6.06	5.05	5.06	5.97
	5	7.12	6.13	5.80	5.66	5.66	6.07
		6.52	6.29				5.68
	(Average of $DO_{0.5}$ between sites)		**(Average of $DO_{2.0}$ between sites)**				**(Average of DO of five layers between sites)**

mg/L, 5.37 mg/L, 5.36 mg/L, 5.4 mg/L and 5.36 mg/L at Sites 2, 3, 4, 5, 6 and 7 respectively. Similarly, $DO_{2.0}$ increases downstream in the order of Sites 2, 3, 4 and 5, although at some sites the DO decreases (Figure 3b). This trend indicates that as the lower oxygenated water of upstream site (Site 1) travels downstream passing through areas with a greater number of boat traffic such as Site 3 and Site 4, the oxygen content in the water is increased. Prygiel et al. (2015) also found that navigated rivers have a better water quality with better oxygenation.

Likewise, $DO_{0.5}$ and $DO_{2.0}$ are also spatially distributed during high tide periods where the concentration increases from downstream site to upstream site (Figures 3c and d). For instance, $DO_{0.5}$ on 30 November 2016 is from 4.74 mg/L to 5.48 mg/L, 5.42 mg/L, 6.65 mg/L, 7.22 mg/L and 7.45 mg/L respectively whereas on 27 February 2017, the $DO_{0.5}$ is 5.15 mg/l, 5.18 mg/L, 5.2 mg/l, 5.24 mg/l, 5.49 mg/l and 5.75 mg/l respectively (Figure 3c). In Figure 3d, $DO_{2.0}$ also increased upstream in the order of Sites 5, 4, 3, 2 and 1, although at some sites $DO_{2.0}$ is constant between Site 4 and Site 3 (6.31 mg/L) on 30 December 2016 and slightly lower at Site 2 (5.36 mg/L) on 27 February 2017. Similar to low tide trend, the oxygen content of the water tends to increase as the water travels through areas with boat traffic. On the other hand, fluctuation of DO was observed during intermediate tides between different sites (Figures 3e and f) which shows that the oxygenated water transported downstream during low tides was carried back upstream by reversed flow during flooding period.

Throughout the three events, the spatial variation of DO concentration indicates that the change in DO during low and high tide varies from site to site depending on the intensity of boat traffic at the navigated reaches. Analysis on the role of boat navigations on change of DO concentration was made only for one event (27 February 2017) at several sites since observation of the intensity of boat traffic and test of water samples were not done for every event due to the resource limit. Data collected during intermediate tests were not included in the analysis due to the reason as was mentioned previously. Table 2 listed $DO_{0.5}$, $DO_{2.0}$, average DO calculated using Equation (11), temperature, BOD_5 and NH_3-N for different sites measured in low tide and high tide event. Again, as the water column is quite shallow, $DO_{2.0}$ was not recorded for Sites 6 and 7. Hence only $DO_{0.5}$ was used for calculation of average DO concentration.

Based on the data in Table 2, all parameters needed in the DO balance equation (2) are calculated between the arbitrary two sites as tabulated in Table 3 and Table 4. As seen in Table 4, K_u is between the range of 0.20 (day^{-1}) and 0.51 (day^{-1}), whereas K_b is between 0.19 (day^{-1}) and 1.99 (day^{-1}). This suggests that reaeration efficiency due to boat traffic is higher than natural reaeration. This is understandable based on the mechanism of oxygen transfer from the air to water. According to the classical theories (O'Connor and Dobbins, 1958), K_u denotes the natural aeration caused by air entrainment of flowing river under the assumption that the surface remains continuous. The 'two-film'

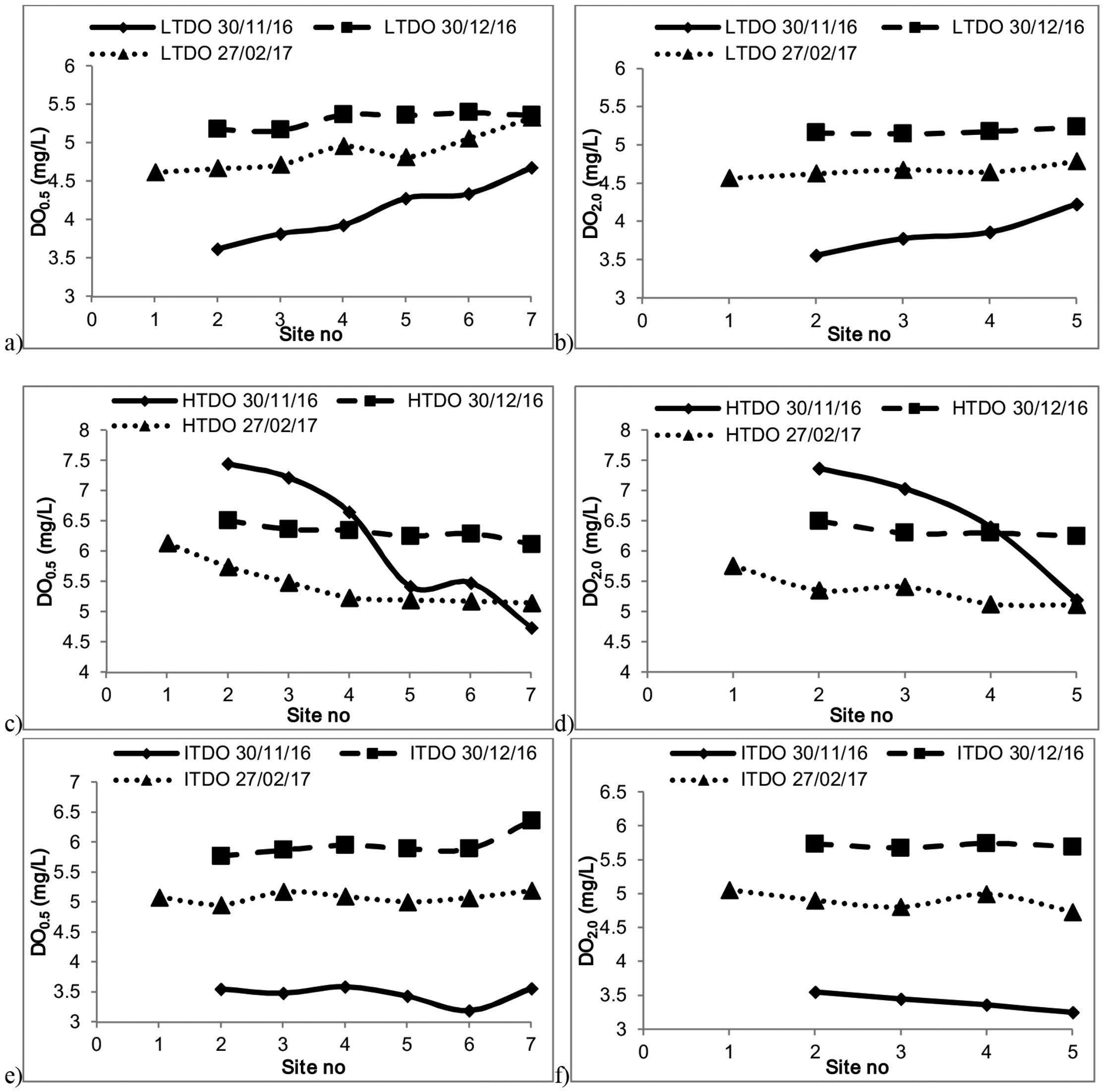

Figure 3: Spatially distribution of $DO_{0.5}$ and $DO_{2.0}$ across different sites during low tide tests (a and b respectively), high tide tests (c and d respectively) and intermediate tide tests (e and f respectively).

Table 2: Measured data in low tide and high tide event on 27 February 2017

	Site	*$DO_{0.5}$ (mg/L)*	*$DO_{2.0}$ (mg/L)*	*Average of $DO_{0.5}$ and $DO_{2.0}$(mg/L)*	*DO_{avg} (mg/L)*	*Temp. (°C)*	*BOD_5 (mg/L)*	*NH_3-N (mg/L)*	*N (Number/ hectare/hr)*
Low tide	**1**	4.62	4.57	4.60	4.07	28.81	2.39	0.3	0
	2	4.67	4.63	4.65	4.12	28.82	2.39	0.3	12
	3	4.72	4.68	4.70	4.16	28.83	2.16	0.8	42
	4	4.96	4.65	4.81	4.25	28.61	4.32	0.8	150
	6	5.06	-	-	4.48	28.38	4.58	0.4	144
High tide	**7**	5.15	-	-	4.56	29.37	2.16	0.5	42
	6	5.18	-	-	4.58	28.74	2.16	0.5	96
	4	5.24	5.13	5.19	4.59	28.90	1.92	0.6	312
	3	5.49	5.42	5.46	4.83	28.94	1.64	0.5	42
	2	5.75	5.36	5.56	4.92	28.76	1.49	0.9	30

Table 3: Measured data that are needed in equation (2)

Segments	Δx (m^2)	Δt (day^{-1})	*Temp* (°C)	*DO* (mg/L)	DO_S (mg/L)	*D* (mg/L)	ΔDO (mg/L)	BOD_5 (mg/L)	NH_3-N (mg/L)	k_d (day^{-1})	k_n (day^{-1})	*H* (m)	*N (Number/ hectare/hr)*
1,2	742	0.043	28.82	4.09	7.61	3.52	0.049	2.39	0.30	0.45	0.59	4.38	6
2,3	738	0.043	28.83	4.14	7.60	3.47	0.044	2.27	0.55	0.45	0.59	2.65	27
3,4	926	0.054	28.72	4.21	7.62	3.41	0.093	3.24	0.80	0.45	0.59	2.59	96
4,6	732	0.042	28.50	4.37	7.65	3.29	0.226	4.45	0.60	0.44	0.58	3.42	147
1,3	1480	0.086	28.82	4.11	7.60	3.49	0.093	2.33	0.42	0.45	0.59	3.52	16
1,4	2406	0.139	28.78	4.15	7.61	3.46	0.186	2.68	0.57	0.45	0.59	3.16	47
1,6	3138	0.182	28.71	4.20	7.62	3.42	0.412	3.15	0.58	0.45	0.59	3.22	70
2,4	1665	0.096	28.77	4.18	7.61	3.44	0.137	2.81	0.69	0.45	0.59	2.62	65
2,6	2396	0.139	28.68	4.23	7.62	3.39	0.363	3.31	0.66	0.45	0.59	2.86	90
3,6	1658	0.096	28.62	4.28	7.63	3.36	0.319	3.77	0.71	0.45	0.58	2.96	119
7,6	2268	0.131	29.06	4.57	7.57	3.00	0.027	2.16	0.50	0.45	0.60	4.87	69
6,4	732	0.042	28.82	4.59	7.60	3.02	0.004	2.04	0.55	0.45	0.59	4.25	204
4,3	926	0.054	28.92	4.71	7.59	2.88	0.239	1.78	0.55	0.45	0.60	3.42	177
3,2	738	0.043	28.85	4.87	7.60	2.73	0.088	1.56	0.70	0.45	0.59	3.48	36
7,4	3000	0.174	29.00	4.57	7.58	3.00	0.031	2.13	0.51	0.45	0.60	4.72	102
7,3	3926	0.227	28.98	4.61	7.58	2.98	0.270	2.05	0.52	0.45	0.60	4.41	120
7,2	4664	0.270	28.96	4.65	7.59	2.94	0.358	1.97	0.55	0.45	0.60	4.26	106
6,3	189	0.096	28.88	4.65	7.60	2.94	0.243	1.89	0.55	0.45	0.59	3.79	189
6,2	142	0.139	28.87	4.72	7.60	2.88	0.332	1.79	0.60	0.45	0.59	3.69	142
4,2	114	0.096	28.89	4.78	7.60	2.81	0.327	1.68	0.62	0.45	0.59	3.45	114

Table 4: Variables considered in equation (2) for the determination of reaeration coefficient by boat activities

Segments	*1/D.(ΔDO/Δt)*	*Kd.(CBOD/D)*	*Kn.(NBOD/D)*	K_u *(day^{-1})*	K_b *(day^{-1})*
1,2	0.32	0.31	0.05	0.23	0.44
2,3	0.30	0.29	0.09	0.50	0.19
3,4	0.51	0.43	0.14	0.51	0.56
4,6	1.62	0.60	0.11	0.34	1.99
1,3	0.31	0.30	0.07	0.33	0.36
1,4	0.39	0.35	0.10	0.38	0.45
1,6	0.66	0.41	0.10	0.37	0.80
2,4	0.41	0.37	0.12	0.51	0.39
2,6	0.77	0.44	0.11	0.44	0.88
3,6	0.99	0.50	0.12	0.42	1.19
7,6	0.07	0.33	0.10	0.20	0.29
6,4	0.03	0.30	0.11	0.25	0.20
4,3	1.55	0.28	0.11	0.34	1.60
3,2	0.76	0.26	0.15	0.33	0.84
7,4	0.06	0.32	0.10	0.21	0.27
7,3	0.40	0.31	0.10	0.23	0.58
7,2	0.45	0.30	0.11	0.24	0.62
6,3	0.86	0.29	0.11	0.29	0.97
6,2	0.83	0.28	0.12	0.30	0.93
4,2	1.21	0.27	0.13	0.34	1.27

theory assumes that oxygen dissolves into water through the air-water interface since the gas film has lower resistance compared to the liquid film on the interfaces. However, in the case of reaeration due to boat traffic, high-speed boats break the continuous "films" on the air-water interface and create strong turbulence in the water. This not only leads to rapid gas transfer from the air to the water due to strong entrainment near water surfaces in the form of a large number of bubbles, but also significantly increases oxygen transfer efficiency in the water. Due to this, the water parcels with strong turbulence carry the air bubbles away and distribute oxygen to ambient and deep waters rapidly. On the other hand, Equations (2), (4) and (7) are all one-dimensional. Oxygen dissolved from the water surface must be averaged with the whole depth. That is why both K_u and K_b are reversely proportional to water depth, H.

Regression analysis (Figure 4) shows that the data fit to a power function equation as:

$$K_b = 0.0769\left(\frac{N}{H}\right)^{0.690} \tag{12}$$

Comparing with Equation (7), α is equal to 0.0769 with 95% confidence interval that the value lies between

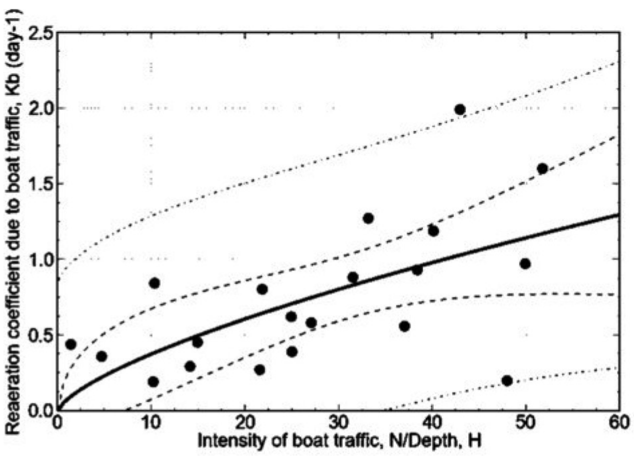

Figure 4: Measured K_b as a function of N/H (dots), power function fitted curve (solid line), confidence band (dashed line) and prediction band (dashdot line).

–0.0897 and 0.243 and β is equal to 0.690 with 95% confidence interval that the value lies between 0.0846 and 1.296. Although the observed data points were scattered, most of them lie within the 95% confidence interval band. This predictive equation can be used to estimate K_b so as to estimate the purification capacity of a river with additional sources of oxygen from boating activities. In water quality modelling, the predictive equation can be added into DO mass balance equation as a source of oxygen besides natural reaeration.

Conclusions

Based on in-situ monitoring, a predictive equation for reaeration coefficient due to boat traffic, K_b was developed in this study, which is a power function of the ratio of *N/H*. It indicates that K_b is proportional to the number of boats in a unit area during unit time (number/hectare/hour) but reversely proportional to water depth. This finding can assist a water quality manager to correctly analyse the water quality of a river that is highly impacted by boat traffic. It can also be introduced into numerical modelling as an additional source of reaeration when appropriate. Although Equation (12) is a one-dimensional equation, it should also be applicable for two-dimensional analysis and modelling due to the definition of *N* and *H*. Nevertheless, since the real case is always three-dimensional, it is believed that a three-dimensional survey can further improve accuracy of the predictive equation.

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