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The influence of wetlands, decaying organic matter, and stirring by wildlife on the dissolved oxygen concentration in eutrophicated water holes in the Seronera River, Serengeti National Park, Tanzania

Bakari Mnaya[1,*], Ephraim Mwangomo[2] and Eric Wolanski[3]
*[1]Department of Environmental Science and Human Engineering, Saitama Univ., 255 Shimo-okubo, Saitama-shi, Saitama 338-8570, Japan; [2]Tanzania National Parks-Serengeti, P.O. Box 3134, Arusha, Tanzania; [3]Australian Institute of Marine Science, PMB No. 3, Townsville, MC, Queensland 4810, Australia; *Author for correspondence (e-mail: jmnaya@yahoo.com)*

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Abstract

The dissolved oxygen concentration (DO) was sampled during a diurnal cycle in three water holes heavily used by wildlife and with distinctive biological features along the Seronera River. The DO fluctuated widely (by up to 11.5 mg l^{-1}) as a function of time, mechanical stirring and aeration by animals, and the presence of fringing wetlands. The DO cycle was successfully modeled (within 0.3 mg l^{-1}) by assuming that the four dominant processes were photosynthesis and respiration by algae near the surface, trapping by wetlands, decomposition of dead organic matter on the bottom, and stirring/aeration by hippos. The rate of DO decline from the decay of dead organic matter was equal to the rate of DO removal by algal respiration at night.

Introduction

Dissolved oxygen (DO) is found in microscopic bubbles of oxygen that are mixed in the water and occur between water molecules (Murphy 2002). Because DO concentration is affected by many water quality parameters, it is a sensitive indicator of the health of the aquatic ecosystem. In the presence of organic waste in water, the reduction of DO is a consequence of the aerobic respiratory processes in the water column and the anaerobic processes in the sediments. The process of organic matter decomposition, unlike the photosynthesis, takes place both at day and night time and therefore, the influence of organic matter on DO concentration is apparent day and night. Nutrients availability may also promote the role of bacteria that also influence the DO diurnal cycle. As a result of these processes, the concentrations of dissolved oxygen within a water body can experience large daily fluctuations. Aquatic plants and algae produce oxygen as a by-product of photosynthesis by day in the presence of sunlight, and release it into the water, while at night and on very cloudy days they consume oxygen through respiration (Addy and Green 1997).

The availability of safe drinking water to wildlife in Tanzania has become a concern to wildlife managers. The water is ponded for several months of the year (in the dry season) and is heavily eutrophicated by animal dung (Wolanski and Gereta 1999). Poor water quality may contribute to the animal mortality in the Serengeti in the dry season (Mduma et al. 1999; Wolanski and Gereta 2001). Stagnant water holes are scattered all along the rivers and there is considerable variability in water quality between these holes. This variability may be explained by the presence/absence of hippos (*Hippopotamus amphibius*) and of fringing wetlands. Hippos are known to aerate the water and prevent anoxia (Gereta and Wolanski 1998; Wolanski and Gereta 1999), through mechanical aeration which may create waves and disturbances and so increasing DO concentration in water by expanding its surface area for oxygen to enter (Wynne 1998), while wetlands improve the water quality by acting as filters (Coughanowr 1998; Gereta et al. 2004).

The study was carried out in three water holes along the 48 km-long Seronera River in the central grassland plain of the Serengeti National Park. The water holes though heavily eutrophicated by animal dung, were used for drinking by wildlife.

The first hole (site A) had neither wetlands nor hippos; the second hole (site B) was inhabited by hippos but had no wetlands; the third hole (site C) had no hippos but had a fringing wetland. The results were used to calibrate a DO model to quantify the role of hippos and of wetlands in modulating water quality. The model suggests that the key processes controlling the diurnal DO cycle are the photosynthesis/respiration of algae near the surface, the decomposition of organic matter near the bottom, the trapping by wetlands, and the aeration by hippos.

The complex nature of DO, being simultaneously affected by many processes including both physical and biogeochemical, provides a difficult yet challenging task for developing a comprehensive model to understand DO dynamics (Misra and Park 2005).

Method

Field work

Three water holes along the Seronera River, within a few km of each other in similar soil settings, were selected. Each water hole had a maximum depth of about 1 m. Site A was about 20 m in width; it had no hippo and no fringing wetland. Site B was about 40 m in width and had six hippos. Site C was about 10 m in width and had a fringing wetland and no hippos. These water holes were all heavily eutrophicated by animal dung with a floating algal mat.

At each site water was sampled at three depths (near surface −0.1 m, mid-depth −0.5 m; and near bottom −1.0 m) at three hourly intervals over 24 h on January 2–3, 2004. The dissolved oxygen concentration was measured using a temperature-compensated microcomputer model HI 9024. A TPS LC84 salinity conductivity–temperature meter was used to measure salinity and temperature.

Modeling

The main process described by the model is the influence of algae and dead organic matter on dissolved oxygen in the turbid, eutrophicated water holes. Algae produce oxygen during the day time by photosynthesis and consume oxygen by respiration at night. The amount of photosynthetic oxygen released during the daylight is proportional to the productivity of the water (Horne and Goldman 1994). Decaying organic matter near the bottom of the water holes cause a decline in dissolved oxygen, as bacteria consume oxygen during the decomposition process. Decaying organic matter at the bottom causes the decline of DO at the rate k. At the same time floating algae abound in these waters and produce oxygen through photosynthesis process in daytime at a rate A_d and by respiration they remove oxygen at night at a rate A_n, where t is time in days. Because the waters are extremely turbidity (visibility <1 cm) all algae are assumed to be restricted to the near-surface.

Thus in daytime $0 < t < 0.5$

$$\frac{d(DO)}{dt} = -k + A_d \tag{1}$$

and at nighttime $0.5 < t < 1$

$$\frac{d(DO)}{dt} = -k - A_n \tag{2}$$

where t is the time in days.

Integrating Eqs. (1) and (2) over $t = 0$–0.5 and $t = 0.5$–1, respectively, leads to:

$$\langle DO_d \rangle = DO_d - 0.25k + 0.25A_d \tag{3}$$

$$\langle DO_n \rangle = DO_n - 0.25k - 0.25A_n \tag{4}$$

where DO_d is the DO value at dawn, DO_n is the DO value at dusk, and <> indicates the mean value in daytime ($_d$) and nighttime ($_n$).

Since daytime and nighttime have the same duration (0.5), the slopes $d(DO)/t$ in daytime and nighttime must have equal magnitude and opposite sign in order to recover the same oxygen level after a day/night cycle. Therefore adding Eqs. (1) and (2) yield

$$-2k + (A_d - A_n) = 0 \tag{5}$$

Thus the constants can be evaluated from the field data by the following equations:

$$k = 2(\langle DO_d \rangle - DO_d) \tag{6}$$

$$A_d = 3k \tag{7}$$

$$A_n = k \tag{8}$$

The temperature affects the biological processes; therefore k is temperature-dependent.

There is an independent verification of the realism of the model, namely that the observed value of $\langle DO_n \rangle$ should be realistically close to the one predicted by Eq. (4).

Results

At the three sites the temperature fluctuated (not shown) in a diurnal cycle by about 5 °C. The maximum vertical temperature difference was about 3 °C. The maximum temperature was about 28.5 °C around midday.

The DO concentration fluctuated widely between daytime and nighttime at all sites and differed measurably between sites (Figure 1 and Table 1). The DO concentration showed a marked increase at sunrise and a marked decrease at sunset

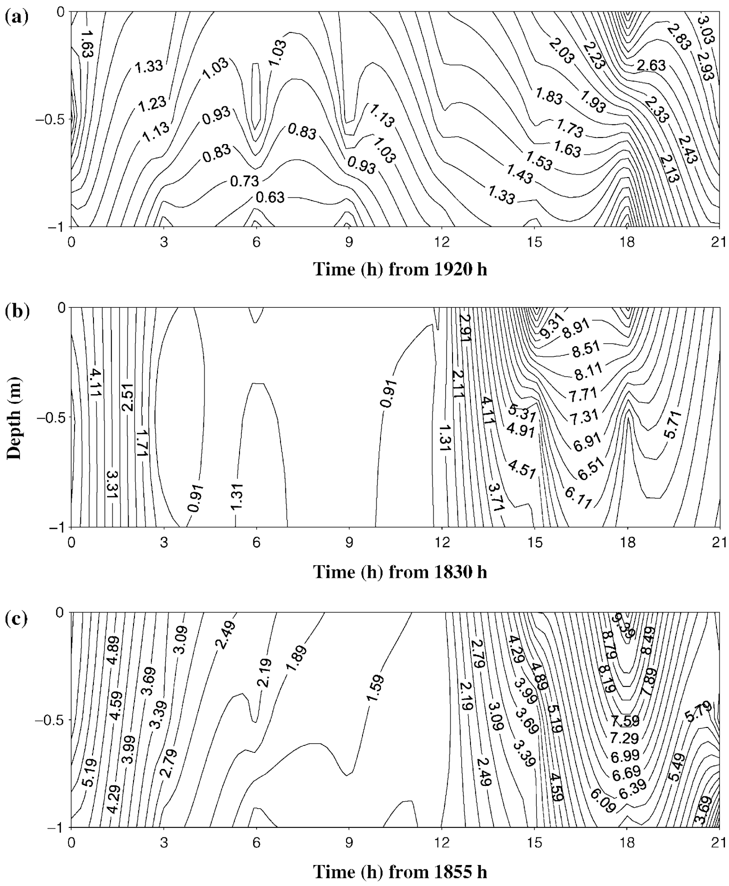

Figure 1. Time-depth plot of the distribution of the dissolved oxygen concentration (DO, in mg l^{-1}) at (a) site A, (b) site B, and (c) site C.

Table 1. Observations of the depth-averaged, dissolved oxygen concentration (DO) at the three sites.

Site	Night/Day time	Time	DO (mg l^{-1})	Mean (mg l^{-1})
A	Night time DO	19:20	1.59	1.13
		22:20	1.08	
		01:01	0.87	
		04:00	0.97	
	Day time DO	07:06	1.42	1.97
		10:00	1.66	
		12:51	1.98	
		16:00	2.81	
B	Night time DO	21:30	1.10	1.14
		0:30	1.31	
		3:30	1.10	
		6:30	1.05	
	Day time DO	18:30	5.17	5.795
		9:33	6.78	
		12:30	6.91	
		15:30	4.32	
C	Night time DO	21:56	3.03	2.00
		0:50	1.88	
		3:45	1.63	
		6:45	1.46	
	Day time DO	18:55	5.95	5.67
		9:50	4.28	
		12:37	8.04	
		15:45	4.41	

and by comparison steadier conditions during daytime and nighttime. This suggests that the system switched in less than 3 h (the sampling interval) from oxygen-producing during the day to oxygen-consuming during the night. This was due to the combined presence of algae near the surface and decaying biological matter (animal dung and dead vegetation) near the bottom. The waters in the site A were nearly anoxic at night, with a minimum DO value of 0.33 mg l^{-1} at 0.1 m depth. The DO values were higher and below saturation in daytime. Significantly higher DO values were measured at sites B and C. Site B was oversaturated in oxygen in daytime with a maximum value of 11.81 mg l^{-1}. Daytime DO oversaturation also prevailed at site B. At sites B and C, the DO decreased at night, to near hypoxia but not anoxia, and more so at site B than at site C.

The model predictions for the DO are shown in Table 2 and compare favorably with the observations.

Discussion

The concentration of dissolved oxygen was higher (by up to 10 mg l^{-1}) in daytime than at nighttime. There was a positive correlation between DO and temperature at sites B and C, contrary to the negative correlation expected from physical processes that should result in smaller DO values (by about 1 mg l^{-1}) with increasing temperature in the range of observations (Addy and Green 1997). Thus the DO fluctuations were controlled by biological processes instead.

The difference between sites A and B was due to the influence of hippos, and between sites A and C to the influence of a fringing wetland. The lowest DO values occurred at site A in the absence of hippos and of a fringing wetland. The data (Table 2) suggest that stirring/aeration by hippos at site B and presence of wetlands at site C contributed to higher DO values than at site A. The addition of hippos increased the biological oxygen demand and the algal productivity by a factor of 2.426 (= 3.76/1.56). The presence of a fringing wetland also increased the biological oxygen demand and the algal productivity by a factor of 3.61 (= 5.6/1.56).

Because the sources and sinks of oxygen (i.e. algae near the surface, and decaying organic matter near the bottom) were physically separated by the water depth, vertical gradients in DO

Table 2. Calculation of the variables in the depth-averaged, dissolved oxygen (DO) model.

	$\langle DO_d \rangle$ observed	DO_n observed	DO_d observed	K	A_d	A_n	$\langle DO_n \rangle$ predicted	$\langle DO_n \rangle$ observed
Site A	1.970	2.200	1.195	1.55	4.65	1.55	1.425	1.13
Site B	5.795	3.135	3.915	3.76	11.28	3.76	1.255	1.14
Site C	5.670	4.490	2.870	5.60	16.80	5.60	1.690	2.00

Because the sampling period was about 3 h, the measured DO_d was calculated as the mean of the last value at nighttime and the 1st value in daytime. The measured DO_n was calculated as the mean of the last value in daytime and the 1st value at nighttime. All DO values are in mg l^{-1}. The last two columns show a comparison between the observed and predicted nighttime-averaged dissolved oxygen concentration ($\langle DO_n \rangle$).

developed. With time the waters were vertically homogenized by a number of mixing processes including convective mixing, wind, and mechanical stirring by animals such as hippos.

The mean value of dissolved oxygen concentration at site C was the highest (3.84 mg l^{-1}) of the three sites (Table 1). The presence of a fringing wetland prevented the occurrence of anoxic condition.

Stirring by hippos at site B aerated the water. The highest dissolved oxygen value (11.8 mg l^{-1}) was recorded during daytime when the hippos were in the water in contrast to night where they leave the water to feed on land.

The DO at site B was higher near the bottom depth than near the surface for 50% of the time. This may be caused by the convective heating generated by organic matter in this case animal dung and aeration may occur due to convective overturning (Wolanski and Gereta 1999; Mnaya and Wolanski 2002).

The DO model is simple, yet it correctly predicts within an error of 0.3 mg l^{-1} the observed nighttime DO. This suggests that the assumption behind the model may be justified, namely that the two key processes of equal importance are the decaying organic detritus near the bottom and the photosynthesis and respiration of algae near the surface. The model suggests that the oxygen cycle was strongly modulated by the presence of a fringing wetland at site C and of hippos at site B, both of which contributed to the improvement of dissolved oxygen.

Hippos improved the DO although nighttime DO values still approach hypoxia. This is believed to be due to the conflicting roles of hippos that aerate the water by mechanical stirring and also increase the biological oxygen demand by releasing dung in the water body and resuspending the dead organic matter on the bottom. Hypoxia occurred at sites A and B, and did not occur at site C (in the presence of a fringing wetland). The higher biological oxygen demand at site C (by a factor of 3.61) may be caused by decay of dead plant matter within the wetland and also due to the exchange of water between the pond and the wetland, where waters are anoxic, and this overwhelms the filtering effect of the wetland.

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