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Dissolved oxygen transfer into a square embayment connected to an open-channel flow

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ABSTRACT

We have conducted field and laboratory experiments to determine the rates of processes responsible for the recovery of dissolved oxygen (DO) in an embayment connected to a main channel. We measured the horizontal velocity vectors to evaluate large-scale circulation within the embayment and measured the time series of DO concentrations during the recovery processes promoted by supply from the main channel. In particular, this study has focused on the effects of the aperture ratio of the embayment/main-channel opening. We have developed a practical formula for the DO recovery rate based on the bulk-mean velocity in the main channel, the aperture ratio, and the position of the embayment opening.

1. Introduction

Preserving water quality in a partly open region such as an embayment or cavity zone requires adequate water exchange with the mainstream in the channel. This study highlights the transfer mechanisms by which dissolved oxygen (DO) is transferred within an embayment that is partly open to a natural river, and we consider it from the standpoint of hydraulic engineering and science.

Several sources can supply DO to a natural embayment: (1) transfer from the air through the free surface, (2) convective transfer from the mainstream through the embayment opening, and (3) generation by photosynthesis due to aquatic vegetation and microbes. The present study focused on the first and second sources directly controlled by the fluid motion. The first source is called re-aeration, the efficiency of which depends significantly on the free-surface flow conditions, i.e., high-speed currents and strong turbulence promote DO exchange between the free surface and the bulk layer of water, resulting in quick recovery from a poor-DO condition. The second source depends on the mass-exchange rate between the embayment and the mainstream. This in turn depends upon the form, size, and position of the embayment opening.

The supply of oxygen across a free surface is known to be controlled by turbulent motions on various scales, including viscous-scale vortices and their dissipation, as well as deep coherent gyres. Many physical models have been proposed experimentally, numerically, and theoretically to explain the contributions of the surface renewal rate (Dankwerts [1], Theofanous [2]), or the surface divergence on gas transfer (McCready et al. [3]). In open-channel flows, bed-oriented turbulence has been found to impact free-surface disturbances that promote gas transfer. (e.g., Gulliver and Halverson [4], Komori et al. [5], Moog et al. [6], Banerjee et al. [7], Hasegawa and Kasagi [8] Turney and Banerjee [9], Sugihara et al. [10], Sanjou et al. [11]). By contrast, for scalar exchange such as mass, gas and heat in the ocean, wind and waves induce significant velocity shears accompanied by local turbulence, and substantial surface scalar exchange has been simulated and observed (e.g., Turney et al. [12], Takagaki et al. [13], Kurose et al. [14], Szeri [15]).

Supply across an embayment/main-channel opening is controlled by shear instability and vortex shedding. Furthermore, horizontal, large-scale circulations are formed in the embayment because of the momentum supply from the mainstream. These circulations convey the mass to inner zone of the embayment and return it to the mainstream. Therefore, they are responsible to the mass renewal in the boundary. In particular, the cavity geometry—such as the aspect ratio of the cavity length to the cavity width—influences large-scale gyres within the cavity (e.g., Booij [16], Mignot et al. [17]). A natural embayment observed in a river basin is a kind of horizontal side cavity. Many hydraulic researchers have studied the matter transport, related turbulence structure, and retention properties of dissolved nutrients and sediments in such embayments (e.g., Uijttewaal et al. [18], Mizumura & Yamasaka [19], Weitbrecht et al. [20], Sanjou and Nezu [21], Hill [22], Mignot et al. [23], Sanjou & Nezu [24]). Weitbrecht et al. [20] and Mignot et al. [17] have evaluated the mass-exchange coefficient k by using

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(1) a dye-release method and (2) a transverse-velocity method. The exchange coefficients evaluated by the former and the later methods are noted k_{con} and k_{vel}, respectively.

The normalize coefficient k_{con} is calculated by using bulk-mean mainstream velocity U_m, spanwise embayment width L_w and residence time τ in the following form (e.g., Jackson et al. [25]),

$$k_{con} \equiv \frac{L_w}{\tau U_m}. \tag{1}$$

By contrast, k_{vel} is calculated by using U_m and exchange velocity V_{ex}

$$k_{vel} \equiv \frac{V_{ex}}{U_m}. \tag{2}$$

Measurements and modellings of k have been intensively conducted, because k is the non-dimensional universal parameter which could be compared among different scale mixing processes. Weitbrecht et al. [20] proposed a linear relationship between the mass-exchange coefficient and morphometric groin field parameter. Mignot et al. [17] examined dependencies of the mass-exchange coefficient on relative water depth and Reynolds number. Jackson et al. [25] measured directly the mass-exchange coefficient of natural lateral cavities in small streams and compared with laboratory measurement data.

Mignot et al. [17] focused on the three-dimensional parameters affecting the mass exchange, i.e., the geometrical aspect ratio of the cavity, the Reynolds number, and the water depth normalized by the cavity length. Standing gravity waves in the cavity are also key issues that significantly affect the shear layer along the cavity opening. Wolfinger et al. [26] pointed out that gravity waves enhance both the production of Reynolds stresses and the mean lateral velocity in the embayment opening. Tuna et al. [27] and Tuna and Rockwell [28] investigated the dependence of the mass-exchange velocity on the oscillation modes of standing waves. Furthermore, they found that such free-surface oscillations—and the related mass-exchange velocities—could be successfully controlled by a single cylinder (Tuna and Rockwell) [29].

In natural conditions, an embayment is not necessarily perfectly open owing to local sedimentation and overgrowth by vegetation. Li and Gu [30] have predicted effects of tidal current on concentration decay cycle within the partly closed harbor. The current distribution and mass transport in a partly closed embayment have been studied experimentally and numerically by Savvidis et al. [31].

They discussed the disposal pattern of groin influences on the mainstream profile near the embayment/main-channel boundary and the related lateral matter transport. They evaluated the timescale for water renewal in a lateral embayment and investigated the relationship between the renewal timescale and the probability of trapping particles with different settling velocities. The findings about lateral mass transfer discussed in the present paper are comparable with other phenomena on different scales than river flows. For example, urban-canyon flows have similar mass exchange in the artificial cavities composed of buildings (e.g., Takimoto et al. [32], Savoy et al. [33], Neophytou et al. [34], Blackman et al. [35], Perret et al. [36]). Although they are vertical rather than horizontal phenomena, the large-scale vortices depend on the cavity geometries and are expected to promote mass and momentum exchanges in the same fashion as for a river embayment zone.

The abovementioned studies have revealed detailed fluid motions, including turbulence structures and mass/momentum transport. However, they still lack information about DO transport in a local embayment with two supply sources: through the free surface and through the cavity opening. In the present study, we have investigated these processes through field studies and laboratory experiments. In the latter, we set up an open-channel flow with a model embayment and compared the contributions of DO supplied from the air and from the mainstream. In particular, we investigated experimentally the geometrical effects due to the position of the embayment opening and the opening width on the embayment current and transfer rate. Furthermore, we have developed a predictive formula for the DO recovery rate by using the experimental results; we expect this formula to be applicable to natural rivers with partly open embayment zones.

2. Field observations and experimental methods

2.1. Field observations

The DO within an embayment is controlled by the balance between the consumption and production of oxygen supplied through the free surface and the opening boundary connecting the embayment to the mainstream, bottom-sediment absorption, and biochemical reactions, as shown in Fig. 1. Before undertaking a detailed investigation of this mechanism in a laboratory flume, we conducted field observations in a natural embayment zone. The target field is situated in the National Aqua Restoration Research Center (NARRC) in Japan, where the embayment is connected to a 2 m-wide small river. We monitored the DO variations in the mainstream and in the embayment by using electrode DO sensors. We controlled the discharge rate in the mainstream by a specially designed pumping system.

Fig. 2 shows the measurement site, with the electrode-type DO sensor (SATOTECH, model WA2017SD-DO) positioned in the center of the embayment by using a floating board. This sensor measured the DO value and water temperature 15 cm below the free surface every 10 min. We conducted the same kind of sampling in the mainstream. Given that it was hard to fix the position of the sensor by using the floating board, we employed a concrete block into which the DO sensor was imbedded and placed it at the bottom of the mainstream 1 m downstream from the embayment opening. We began observations of the embayment starting in December 2015 and initiated measurements for the mainstream in June 2016. We regularly collected the data and cleaned the sensor. From December 2015 to June 2016, the discharge rate was approximately 100 L/s, and the water level was low. During this season, the embayment was closed, without exchange with the mainstream, because the bottom elevation of the embayment opening is higher than in the mainstream. By contrast, beginning in June 2016, the discharge increased to 200 L/s, which resulted in mass exchange between the mainstream and the embayment.

We measured the bottom elevation and the water level in the embayment in September 2016, when the discharge was comparatively large. There exist emergent plants (Phragmites japonica) in the opening. Many willow trees grow by riverside and shade the embayment from sunlight. The opening is situated downstream from the embayment. Although the opening was covered with growing aquatic vegetation, the embayment was nevertheless connected to the mainstream. Hence, the water level of the embayment was almost the same as that in the mainstream. The result obtained by a laser range finder and a leveling rod is indicated in Fig. 3. It was dangerous to measure the upstream side in the embayment because bad footing conditions; thus, we obtained no data there. The water depth was approximately 30–40 cm in the embayment opening, smaller than that in the embayment itself. The bottom elevation of the opening is locally high; thus, we found the embayment to be closed in the low-discharge and low-water-level season.

2.2. Laboratory experiments

We conducted our laboratory experiments in a 16 m-long, 0.4 m-wide, 0.5 m-high, circulating, tank-type channel with a