DO RECOVERY PROCESS IN A SQUARE EMBAYMENT CONNECTED TO AN OPEN-CHANNEL FLOW

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ABSTRACT

This study highlights a DO recovery process in embayment connected to a straight main-channel. Our field survey results in that the DO is larger in opened condition to the mainstream than that closed condition without no mass / momentum exchanges with the mainstream. Hence, the mass exchange between the mainstream and the embayment is decided by the embayment opening. To reveal the relation between DO recovery and embayment opening, we conducted laboratory experiments to measure time-variation of the DO value and horizontal velocity vectors in the model embayment. Finally, we proposed a prediction formula of the recovery time related to reaeration through free-surface and DO supply from main-channel.

Keywords: DO transport, lateral embayment in river, field observation and laboratory experiment

1. INTRODUCTION

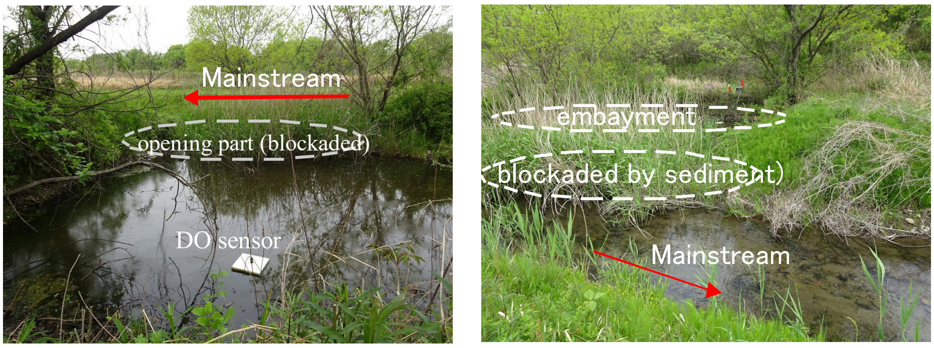
Several sources can supply DO to a natural embayment: 1) transfer from the air through the free surface, 2) convective transfer from the mainstream through the embayment opening, and 3) generation by photosynthesis due to aquatic vegetation and microbes. The first source is called re-aeration, the efficiency 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 or the surface divergence on gas transfer.

In natural conditions, an embayment is not necessarily perfectly open owing to local sedimentation and overgrowth by vegetation. The current distribution and mass transport in a partly closed embayment have been studied experimentally and numerically by Savvidis et al. (2017). 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 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.

2. FIELD OBSERVATION IN NATURAL LATERL EMBAYMENT

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. 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 minutes. 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



(a)Embayment (Apr. 2016) (b)Opening part (Apr. 2016)

Figure 1. Natural lateral embayment for field observation

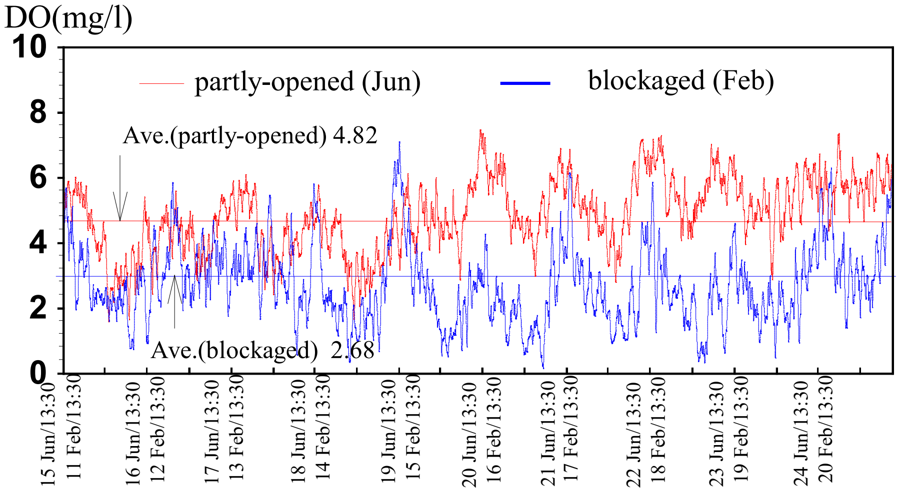


Figure 2. DO time-cycle in natural lateral embayment

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 2015to 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.

Fig. 2 shows an example of the time variation of DO within the natural embayment in the partially open case (June) and in the blocked (closed) case (February). The results indicate that a daily oxygen cycle exists irrespective of the opening condition. During nighttime, the respiration of aquatic plants, fish, etc., significantly reduces the DO because of the lack of photosynthesis.

By contrast, photosynthesis and interfacial transfer from the air increase the DO during the daytime, with the result that the DO recovers, reaching a maximum around 1:00 pm to 2:00 pm. The mean DO value is much smaller in the closed case than in the partially open one. The saturated DO value also is generally larger in colder water. Thus, larger DO values are expected during the winter season, which corresponds to the closed case. However, the lack of mass exchange with the mainstream and the very slow circulation actually induce a hypoxic environment in the embayment.

3. LABORATORY EXPERIMENT

We conducted our laboratory experiments in a 16 m-long, 40 cm-wide, 50 cm-high, circulating, tank-type channel. A sketch of this model embayment is shown in Fig. 4, in which B = 20 cm is the main-channel width, and Δ is the length of the opening. The embayment zone, which is a square L = 20 cm on a side, was situated 10 m downstream from the inlet honeycomb. Mass and momentum exchanges occur through an opening on the downstream side of the mainstream/embayment boundary. We varied the opening length systematically by

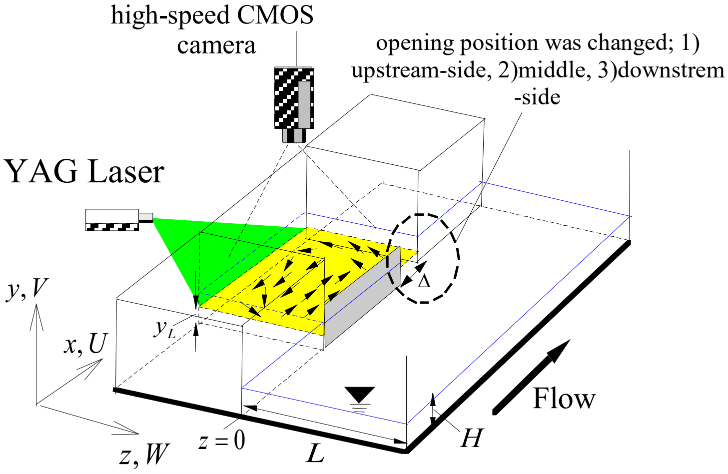


Figure 3. PIV measurement setup for laboratory embayment

using a 3 mm-thick acrylic plate from Δ = 1 to 100 mm (Δ/L = 0.5% to 50%). We chose three different opening positions: on the downstream side, in the middle, and on the upstream side of the embayment.

Fig. 3 shows the experimental setup and the coordinate system. The quantities x, y, and z are the streamwise, vertical, and spanwise coordinates, respectively. The vertical position $y = 0$ is the channel bed, and the spanwise location $z = 0$ is the embayment/mainstream boundary. The quantities U, V, and W are the corresponding time-averaged velocity components, and H is the water depth.

Table 1 shows the hydraulic conditions we considered, with different bulk-mean velocities U_m, H, and Δ. We conducted two kinds of experiments, namely, measuring the velocity and measuring the DO recovery.

The horizontal velocity components (U, W) were measured by means of the PIV technique. A laser-light sheet was projected into the water body in the embayment from the glass side-wall of the flume. We chose three projection elevations: $y_L/H = 0.1$ (near the bottom), 0.5 (mid-depth), and 0.99 (near the free surface). Images of the illuminated horizontal plane were recorded by a downward-looking high-speed CMOS camera placed over the free surface of the flume.

The mass-transfer flux F through the embayment/mainstream boundary can be defined in terms of the lateral mean velocity as follows:

$$F = H\int_0^H \int_{L-\Delta}^{L} |W(x,y,z=0)| dxdy \cdot \tag{1}$$

Given that the present study measured the horizontal velocity components (U, W) at three elevations, namely, $y_L/H = 0.1$, 0.5 and 0.99, we calculated the depth-averaged flux $\langle F \rangle$ as follows:

$$\langle F \rangle = \frac{1}{3} H \sum_{i=1}^{3} \int_{L-\Delta}^{L} |W(x,y,z=0)| dx \tag{2}$$

We expect the mass flux evaluated from the spanwise velocity W to have some relationship to the mainstream velocity. Fig.4 shows the variation of $\langle F \rangle$ with the bulk-mean velocity U_m in the main channel for the downstream-opening position, with $H = 5.0$ cm. It is generally accepted that the spanwise velocity in the cavity opening is significantly correlated with the mainstream velocity. Hence, this result implies that the mass flux increases—i.e., the mass-exchange efficiency is improved—for larger mainstream velocities. It is particularly significant that a larger aperture ratio significantly increases the mass transfer at the embayment/mainstream boundary. This effect is caused both by the larger contact area of the opening and by the larger momentum exchange between the embayment and the mainstream.

The influence of the opening position on the mass flux is also interesting, as shown in Fig.5, in which the results are compared for Δ/L = 25% and $H = 5.0$ cm. A larger momentum transfer occurs from the mainstream to the embayment with the upstream opening because of the small reduction in the streamwise velocity by the downstream lateral wall in the embayment, as discussed in the previous section.

These results suggest that the mass-transfer flux can in fact be modeled using the bulk-mean velocity, the aperture ratio, and the opening position. Furthermore, these parameters are expected to be important for predicting DO recovery in the embayment.

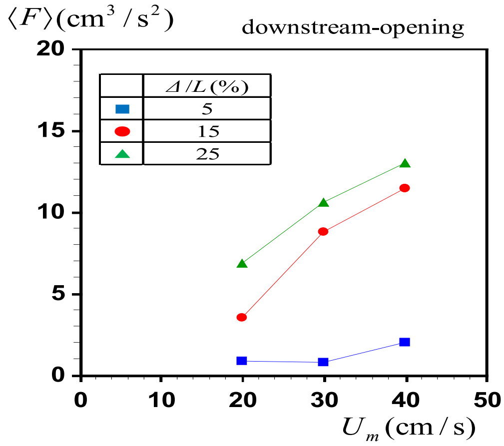


Figure 4. Relationship between the bulk-mean velocity and the mass flux through the embayment / mainstream boundary; influences of aperture rate

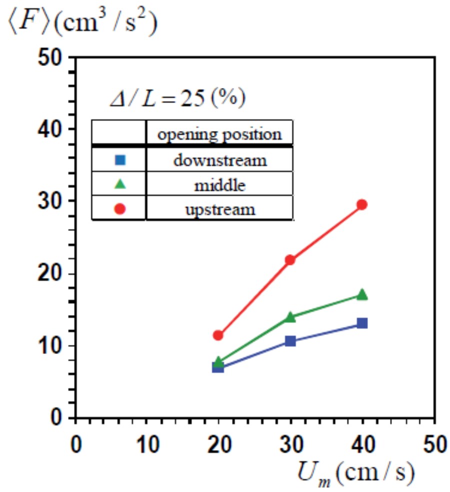


Figure 5. Relationship between the bulk-mean velocity and the mass flux through the embayment / mainstream boundary; influences of opening position

The main channel was saturated and the embayment zone was initially de-aerated in our DO experiment.. The initial time $t = 0$ corresponds to the removal of the splitter plate. The DO concentration retains its initial value as long as the sodium sulfite used for degassing is still present. Let us define T_{lag} as the time when the DO starts to increase and T_r as the timescale on which the DO attains saturation, i.e., the recovery time. We evaluated T_r by fitting the measured data for the DO concentration C with the following exponential function:

$$\frac{C - C_0}{C_{sat} - C_0} = 1 - \exp\left(- \frac{t - T_{lag}}{T_r} \right), \qquad (3)$$

where the subscripts 0 and *sat* mean the initial stage and the saturated stage, respectively. Uijittewaal et al. (2001) and Tominaga and Nugroho (2009) used this same function to measure the dye-exchange rate across the boundary between a main channel and a side cavity. All results were found to be well fitted by Eq. 3

The time variations of DO are compared for varying aperture ratios in Fig. 6, for the case $U_m = 40$ cm/s and $H = 5.0$ cm downstreamwise - opening. The result for the closed condition, $\Delta = 0$, is also included for reference. For the closed condition, we found that it takes more than 50 hours until the DO saturates because DO in this case is only supplied by molecular diffusion through the free surface. By contrast, a larger aperture ratio shortens the saturation timescale significantly, and the time lag T_{lag} between the start of DO exchange and the beginning of the rise in DO decreases. Note that DO is supplied through the free surface even if mass exchange with the mainstream dominates, i.e., the DO recovery process discussed here includes supply from both the mainstream and the air. Fig. 7 shows the variation of T_r normalized by T_c, the recovery time for the closed-embayment case given by Eq. (3), in downstreamwise – opening. When the aperture ratio exceeds 15%, the DO recovers in only 2% of the time required for the closed embayment irrespective of the mainstream velocity U_m. It is significant that the recovery time is reduced by 15% to 20% when we choose only a 1% aperture ratio.

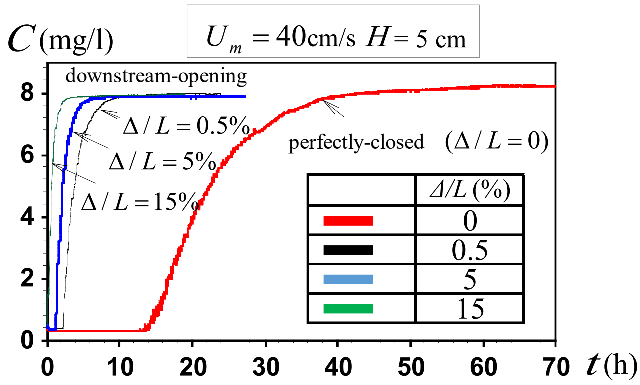


Figure 6. Time-variation in DO recovery process with the different aperture rate in downstream – openings

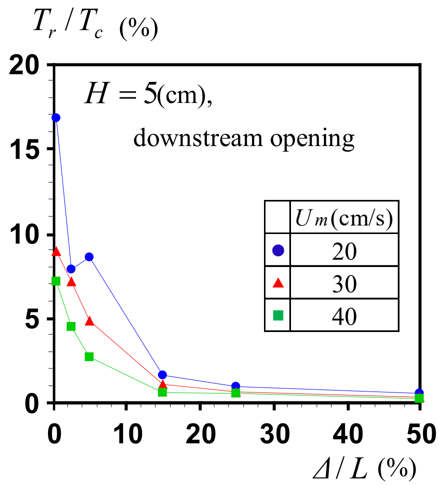


Figure.7 Effects of aperture rate on recovery time-scale in downstream - openings

The DO recovery rate can be expressed as the inverse of the recovery time scale, T_r^{-1}. The recovery rate is controlled both by the mass-transfer flux from the mainstream and the re-aeration flux through the free surface. More detailed measurements are required to evaluate these contributions separately. However, Fig. 14 suggests that T_r^{-1} can be predicted using only the mass flux through the embayment/main-channel boundary when there is some streamwise velocity in the main channel.

As mentioned above, the mass flux F is strongly correlated with the bulk-mean velocity in the mainstream. However, the mass flux are hard to obtain directly from natural-field measurements. Hence, we seek a practical model of the gas-recovery rate T_r^{-1} based on the bulk-mean velocity in the mainstream.

The mass flux F is proportional to the lateral mean velocity W in the boundary along the embayment opening. Assuming a proportionality between W and the bulk-mean velocity U_m, we obtain the following linear relation:

$$T_r^{-1} \approx F / V = F / (AH) \approx W(z=0)\Delta / A \propto U_m \Delta / A \quad (4)$$

Fig. 8 compares the relationship given by Eq. (4) with the present experimental data, taking T_r^{-1} to be evaluated as explained in Fig. 14. This results in the following fitting equation:

$$T_r^{-1} = 0.0154 \cdot U_m \Delta / A . \quad (5)$$

This equation indicates that the gas-recovery process is controlled by the bulk-mean velocity and the aperture ratio of the embayment opening; the correlation coefficient is R_2 = 0.8374. Although this is already a comparatively large correlation, information about the opening position is not included in this model.

When we considered separately the correlation properties for different opening positions, the present results yield a gradient of the fitting lines that depends on the opening position. All cases were found to have strong correlations, with R_2 larger than 0.9. In particular, the downstream-opening case has the strongest correlation, R_2 = 0.9663. These fitting relations are as follows:

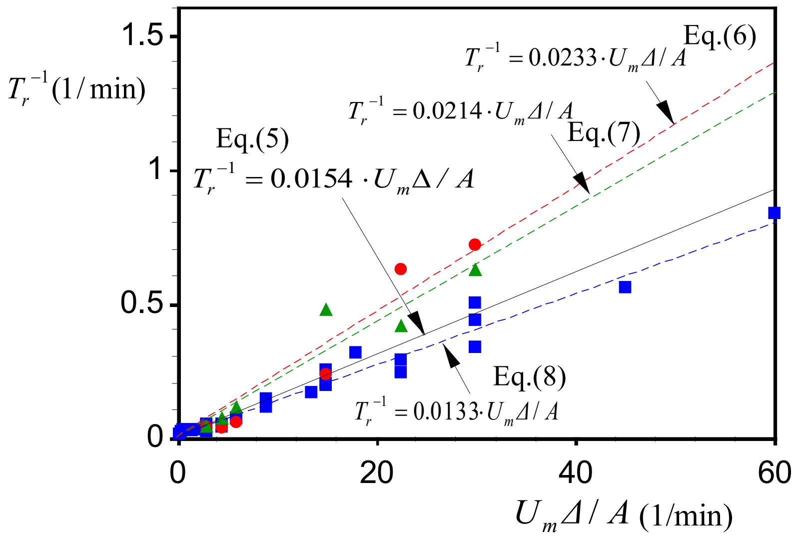


Figure.8 Linear formulae in prediction of recovery rate

$$T_r^{-1} = 0.0233 \cdot U_m \Delta / A \quad \text{(upstream opening)}, \tag{6}$$

$$T_r^{-1} = 0.0214 \cdot U_m \Delta / A \quad \text{(middle opening)}, \tag{7}$$

$$T_r^{-1} = 0.0133 \cdot U_m \Delta / A \quad \text{(downstream opening)}. \tag{8}$$

The proportionality coefficient that corresponds to the DO transfer efficiency into the embayment varies with the opening position. In the experiments, the DO transfer increases as the opening position is shifted upstream. This tendency coincides with the velocity distribution obtained by the PIV, which implies that the mass flux and momentum transfer through the embayment/mainstream boundary depend significantly on the opening position.

5. CONCLUSIONS

The present study has clarified DO recovery in an embayment zone open to the mainstream. We performed velocity and DO measurements, varying systematically the mainstream velocity, the aperture ratio, and the opening position. We investigated in particular how these factors influence the circulation and the DO recovery rate. Detailed discussion including theoretical expansion were reported in Sanjou et al. (2018).

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