WATER QUALITY CHARACTERISTICS AND MITIGATING OF HYPOXIA VIA THE INTRODUCTION OF EXTERNAL WATER IN THE HIGASHI-YOKOBORI AND Dotonbori RIVERS

Yusuke NAKATANI1, Shuzo NISHIDA2 and Naomi INOUE3

1Member of JSCE, Assistant Professor, Dept. of Civil Eng., Osaka University
(2-1 Yamadaoka, Suita, Osaka 565-0871, Japan)
E-mail: nakatani@civil.eng.osaka-u.ac.jp

2Member of JSCE, Professor, Dept. of Civil Eng., Osaka University
(2-1 Yamadaoka, Suita, Osaka 565-0871, Japan)
E-mail: nishida@civil.eng.osaka-u.ac.jp

3Member of JSCE, Graduate Student, Dept. of Civil Eng., Osaka University
(2-1 Yamadaoka, Suita, Osaka 565-0871, Japan)
E-mail: inoue_n@civil.eng.osaka-u.ac.jp

In the Higashi-Yokobori and Dotonbori Rivers, water quality is controlled by the inflow of relatively clean river water from above the upstream floodgate and outflowing polluted water to below the downstream floodgate. However, a hypoxic water mass occurs during high-temperature periods; therefore, there is room for further water quality improvement. In this study, field surveys, laboratory experiments, and simulations were conducted to determine the water quality characteristics of these two rivers.

The impacts of these water quality improvements resulting from the exchange of the water mass with water from outside the floodgates were evaluated, and more effective methods were proposed. It was shown that the main factor leading to hypoxia was dissolved oxygen (DO) consumption in the water. In order to maintain a satisfactory DO environment in the summer, it would be necessary to continuously allow water to enter from above the upstream floodgate at a rate of more than 2.0 m³/s.

Key Words: urban tidal river, hypoxia, Higashi-Yokobori River, Dotonbori River, floodgate

1. INTRODUCTION

In many coastal urban areas, economic and cultural development is supported by transportation on waterway networks. In these areas, human interest in waterfront areas has diminished, with buildings and streets typically built facing away from rivers. This is largely a result of the construction of storm surge barriers, the reclamation of waterways (associated with the decline in waterway transportation), and the deterioration of water quality owing to the inflow of excess domestic and industrial effluents.

Water quality is an important basic environmental component of rivers. In the Higashi-Yokobori and Dotonbori Rivers in Osaka, Japan, which are the focus of this study, water pollution is a concern. The annual average biochemical oxygen demand (BOD) exceeded 30 mg/L in the 1970s as the pollution load increased with the rapid urbanization1). Many measures for improving the water quality, such as the development of sewerage systems or the dredging of sediments, have been implemented over many years2,3). As a result, the water quality has recovered and has now achieved the B-type environmental standard for BOD (3 mg/L) as prescribed in the Environmental Basic Law throughout the year1).

Regarding dissolved oxygen (DO), although an annual average value of 5 mg/L has been achieved, which is the environmental standard value, there are many occasions in the summer in which this standard is not met and a hypoxic water mass (DO < 3 mg/L) becomes prevalent4,5). Various measures for resolving the issue of hypoxia have been assessed and implemented over many years. However, owing to the lack of data and knowledge related to the mechanisms of hypoxia, it is difficult to perform an adequate verification of the improvements potentially offered by such measures.

Figure 1 shows the target area of this study. The Higashi-Yokobori and Dotonbori Rivers are artificial
waterways created by excavation and located in the tidal area downstream of the Yodo River Basin. They flow through the center of the city of Osaka. The two rivers form a sequence that is usually closed by floodgates located at the upstream and downstream edges. Therefore, water exchange occurs temporarily only when a drainage operation is conducted. The flow is limited to one direction (i.e., from the Higashi-Yokobori River to the Dotonbori River).

As a measure for improving the water quality in these rivers, a water pollution cleanup operation is performed by opening and closing the floodgates according to the tidal cycle, as explained in detail in the next section. Although this cleanup operation is performed on the basis of a predetermined operation rule, in reality, this largely depends on human judgment. In addition, the water quality of the inflowing water mass is not evaluated; as a general rule, gate opening and closing are based only on the water level outside the floodgates. Moreover, because there is little data on the inflow water quality through the gates, a quantitative evaluation of the effect of water quality improvements resulting from the cleanup operation is not presently possible.

There have been many studies on the water quality of urban tidal rivers. In particular, recent studies in Japan that investigated the effects of water quality improvement by the introduction of external water include, for example, Sugihara and Nakatsugawa, Takeda et al., and Uno et al. However, as water-quality characteristics vary from river to river, a detailed field survey of the target river is necessary to quantitatively evaluate the effect of water-quality improvement.

In this study, the water-quality characteristics of (i) the Higashi-Yokobori and Dotonbori Rivers and (ii) the water mass introduced through the floodgates are determined using field surveys and laboratory experiments. Furthermore, we quantitatively evaluated the potential inhibition of hypoxia following the introduction of “external” water into the rivers.

2. STUDY AREA

(1) Overview of the study area

As shown in Fig.1, the Higashi-Yokobori River flows from the north to the south, with a total length and width of about 3.0 km and 25–35 m, respectively, with most of the water covered by an elevated highway. From the southern end, the river becomes known as the Dotonbori River, which flows about 2.5 km west and then joins the Kizu River at its downstream end. The width of the Dotonbori River changes near the Daikoku Bridge (Sta. 2); the width of the eastern and western sections is about 25 m and 40–45 m, respectively. In all sections, riverbanks are built on a concrete upright bulkhead. There are few aquatic organisms on the riverbanks. Although the presence of both brackish and freshwater fish has been confirmed and a basic habitat for fish is provided, it is not a river environment where fish can complete their life cycle.

The flow structure of these rivers is very complex. Although the main factor is one-dimensional advection in the longitudinal direction owing to water intake and drainage, it is also affected by factors such as density flow due to intrusion of seawater, wind-driven current, and vertical disturbance due to ship navigation.

In the Higashi-Yokobori and Dotonbori Rivers, combined sewage overflow (CSO), which occurs...
during rainy weather, is a serious cause of water pollution.\textsuperscript{13,14} However, since the beginning of the operation of the underground water reservoir (the Kitahama–Ousaka storage pipeline) in March 2015, no CSO has occurred for the 10-year rainfall probability.\textsuperscript{15}

The Higashi-Yokobori River branches from the Tosabori River, with the Oh River and Neya River joined in the upper region. The water discharge from the Oh River is about 80 m\textsuperscript{3}/s, with an annual inflow average flow rate of about 40 m\textsuperscript{3}/s from the Neya River. While the water of the Oh River, which branches from the Yodo River, is relatively unpolluted, the Neya River is polluted owing to the inflow of large amounts of sewage treatment water and untreated sewage. All of the study areas are located in a tidal region, and seawater from Osaka Bay can reach near Kyobashi (Sta. 6).

(2) Water pollution cleanup operation

As mentioned above, floodgates that open and close electrically are located upstream of the Higashi-Yokobori River and downstream of the Dotonbori River, as shown in Fig.2. One lock gate comprising a radial gate and a miter gate in series is installed at the upstream end of the Higashi-Yokobori River. On the other hand, at the downstream end of the Dotonbori River, two gates are installed in the transverse direction: one is a lock gate comprising a radial gate and a miter gate, and the other is a slide gate used for drainage operation. The main roles of these gates are (i) protection against storm surges and tsunamis, (ii) control of inner water levels, (iii) lock operation for ship navigation, and (iv) water exchange with “external” water to enable cleanup based on wise use of tide. Since both gates are usually closed, water exchange with the water outside the gates occurs only when the water is purposely imported or exported (i.e., the flow is stagnant at other times). Water exchange occurs mainly during water pollution cleanup operations; the amount of water exchanged for ship navigation and water-level adjustment is less than that for the cleanup operation.

A schematic diagram of the water pollution cleanup operation is shown in Fig.3. The aim of this operation is to selectively introduce only an unpolluted water mass by considering the tidal effects on the water quality above the upstream gate. Above the gate, there are two water masses originating from the Oh and Neya Rivers, for which the BOD averages in 2013 were 0.77 and 3.18 mg/L, respectively.\textsuperscript{4} Near high tide, the downstream water level rises, so the water of the Neya River, which has a low discharge, can scarcely flow down owing to the backwater, and only the Oh river water exits near the upstream gate. Considering these flow characteristics, near high tide, the upstream gate is opened to import external water (i.e., Oh River water), which is relatively unpolluted. On the other hand, at ebb tide (immediately after high tide), the inner water is exported by closing the upstream gate and opening the downstream gate to prevent the inflow of polluted water from the Neya River. The cleanup operation is mainly conducted during the spring tide period. Water imports and exports are often carried out as a series of operations.

There are three approaches for importing and exporting water: (i) opening and closing the gates located in the river channel, (ii) transporting water through a bypass tube installed on the riverbank by utilizing the difference in the water level inside and
outside the gate, and (iii) transporting water through the bypass tube using an electric pump. While these three methods have all been used at the upstream gate, pipe transport based on water-level difference is not used at the downstream gate.

3. METHODS

(1) Field surveys of water quality

In order to elucidate the longitudinal structure of water quality in the rivers, we measured the vertical profiles of water quality by collecting water samples at the 17 bridges that span the Higashi-Yokobori and Dotonbori Rivers. The measured variables, that is, water temperature, electrical conductivity, DO, turbidity, and fluorescence intensity, were assessed using a multicomponent water-quality profiler (AAQ-170 and AAQ-1183H, JFE Advantech; DS5X and Quanta-G, Hydrolab). A temperature-corrected electrical conductivity value at 25°C (EC25) was used. The surveys were conducted from September 2013 to September 2017. The survey frequency was once every two months from September 2013 to December 2014; once every two weeks from August 2015 to March 2016; and once a week from July 2016 to September 2016 and from July 2017 to September 2017. The chemical forms of nitrogen, phosphorus, silicon, and organic carbon were determined for all water samples. An autoanalyzer for nitrogen, phosphorus, and silicon (AACS-V, BLTEC) using the continuous flow analysis method and an organic carbon meter (TOC-V, Shimadzu) using the combustion catalytic oxidation method were used for the water-quality analyses. The water samples were filtered through glass fiber filters (<0.65 μm retention; GS25, Advantec Toyo).

In addition, a long-term continuous measurement of water quality in the rivers was performed using memory-type instruments (COMPACT and INFINITY series, JFE Advantech). The measured variables were water temperature, electrical conductivity, DO, turbidity, and fluorescence intensity. The monitoring sites and periods are shown in Table 1. Electrical conductivity (and salinity calculated from electrical conductivity and water temperature) was measured at 10-min intervals in continuous mode. DO, turbidity, and fluorescence intensity were measured at 10-min intervals in burst mode (1 s × 10 samples). Water temperature was measured in the same mode for all instruments.

In order to clarify the short-term variations in the water quality around the upstream gate before and after the cleanup operation, one-hour continuous water sampling was performed at Stas. 4, 5, and 6. At Sta. 4, river water in the middle layer was taken using an automatic portable water sampler (900MAX, HACH) from 0:00 to 23:00 on November 4, 2013. At Stas. 5 and 6, the surface water was collected using a bucket sampler from 19:00 on November 4, 2013, to 8:00 the next day. For these samples, as well as the samples taken in the longitudinal water quality survey, the quality of the water was analyzed.

Table 1 Measurement periods and sampling layers for long-term water-quality monitoring at fixed locations. “U”, “M”, and “L” indicate the upper (0.5 m below the surface), middle (half of the water depth), and lower layers (0.5 m above the bottom), respectively. In addition, “Sal.”, “Tur.”, and “Flu.”, indicate salinity, turbidity, and fluorescence intensity, respectively. Although water temperature is omitted in this table, it was also measured along with all items.

| Site (transverse mean water depth) | Measurement period, sampling layer, and measured variable |
|-----------------------------------|----------------------------------------------------------|
| Sta. 1 (3.4 m)                    | 2013/11/25 to 2014/12/1 M (DO, Tur., Flu.) L (Sal.) L (DO, Sal.) L (DO, Sal.) Not measured |
| Sta. 2 (3.2 m)                    | Not measured L (DO, Sal., Tur., Flu.) M (DO) L (DO) |
| Sta. 3 (2.7 m)                    | Not measured M (DO, Sal., Tur., Flu.) M (DO) |
| Sta. 4 (3.2 m)                    | M (DO, Sal., Tur., Flu.) M (DO, Sal., Tur., Flu.) M (DO, Sal., Tur., Flu.) |
| Sta. 5 (3.2 m)                    | U (Sal.) L (Sal.) M (DO, Sal., Tur., Flu.) M (DO, Sal., Tur., Flu.) M (DO) |

Although water temperature is omitted in this table, it was also measured along with all items.
(2) Laboratory experiment on sediment characteristics

In order to understand the rate of oxygen consumption by the river sediment, we conducted a laboratory experiment using local materials. On December 1, 2014, undisturbed columnar sediment and bottom-layer water were collected at Stas. C and M. Core samples were collected in an acrylic cylinder (pipe diameter: 11 cm, cylinder height: 50 cm) using an HR-type sampling system and transported to the laboratory under cold and dark conditions. After filtration and aeration of the bottom-layer water, changes in the DO concentration were measured for 24 h in the shade at 20°C and 30°C. The oxygen consumption rate \( k_{sed}, \text{day}^{-1} \) was calculated using the following equation:

\[
DO(t) = DO_{t=0}e^{-k_{sed}t},
\]

where \( DO(t) \) and \( DO_{t=0} \) are the amounts of DO (g/m²) in the water at time \( t \) and at the start of the experiment, respectively.

(3) Collection and analysis of data and documents

We obtained records related to the cleanup operation, as well as water-level monitoring data, from the River and Ferry Administration Office of Osaka City Construction Bureau. The time and method of water import and export, water level before and after the operation, and the operation details were taken from the cleanup operation record table. The water-level monitoring data provided temporal values (10 min intervals) measured above and below the upstream gate.

4. RESULTS AND DISCUSSION

(1) Characteristics of the river water quality

a) Long-term variation characteristics of the river water quality

The long-term variations in water temperature, EC25, and DO concentration at Sta. 4, together with salinity at Sta. 1, are shown in Fig. 4. EC25 typically showed the lowest value of about 0.3 mS/cm (or less) throughout the year, only temporarily exceeding 0.5 mS/cm. There were three water masses flowing into Sta. 4: the Oh River water with low EC25 (0.1–0.2 mS/cm) and high DO, the Neya River water with high EC25 (0.3–0.4 mS/cm) and low DO, and seawater from Osaka Bay with remarkably high EC25 compared with the river waters. Considering the EC25 range of each river water, it is considered that Sta. 4 usually receives water either from one or both rivers, with the temporarily intruded seawater also a component of the mix.

The DO concentration at Sta. 4 changed markedly over a short period of time. As described below, this was influenced by the biological oxygen consumption processes below the gate and the introduction of external water. Over a long time scale, the DO concentration showed low values during high-temperature periods. Particularly from early May to early November, it was observed that hypoxic conditions (i.e., DO concentrations of less than 3 mg/L) occurred frequently.

At Sta. 1, the salinity of the lower layer fluctuates greatly between 0 and 28 throughout the year. As such, it is evident that seawater flows in and out with the opening and closing of the downstream floodgate. On the other hand, because no high salinity is observed in the middle layer, it is considered that the seawater enters and spreads through a relatively thin layer when the downstream gate is opened; as such, strong salinity stratification is formed.

b) Short-term variation characteristics of river water quality during hypoxic periods

The short-term fluctuations in salinity and DO at Stas. 1–5, the fluorescence intensity at Stas. 2 and 3,
and the tide level at Osaka Port in the summer (September 1–30, 2015), during which hypoxia occurred, are shown in Fig.5. In the figure, the periods during which the cleanup operations were performed are shown by green bars. For each operation, the intake of water at the upstream gate and the drainage operation at the downstream gate were performed either in series or simultaneously.

At Sta. 1, in consideration of the fact that salinity fluctuated greatly in the range of 0–26 over the short term when the water cleanup operation was conducted, it is evident that the salinity fluctuation was strongly influenced by the saltwater intrusion from the downstream gate and the outflow of freshwater at the upstream gate. The DO concentration remained close to 1 mg/L and a hypoxic water mass occurred during most periods. There are two possible reasons for this: strong oxygen consumption at the bottom sediment and intrusion of low-DO seawater from outside of the gate. After September 23, although the
salinity decreased and the DO concentration increased as a result of the inflow of freshwater from the upstream side, the DO concentration decreased immediately and recovery of the DO concentration as a result of the cleanup operation was temporary.

At Sta. 2, a periodic variation in salinity of about two weeks was observed, with salinity mainly tending to rise during neap tide periods with a low number of cleanup operations. This is because saltwater intrusion from downstream is suppressed in the spring tide period when the water cleanup operation is performed frequently; whereas saltwater intrusion is likely to increase during the neap tide period when the number of operations is low. During the neap tide period in late September, since the fluorescence intensity, DO concentration, and salinity were high, it is presumed that the primary production of brackish phytoplankton was activated and DO was generated by photosynthesis owing to the strong retention in the water.

At Sta. 4 (near the upstream gate), the DO concentration varied markedly according to the cleanup operation. In many cases, it was observed that the DO concentration increased owing to the intake of water with a high DO concentration from the Oh River. Although the same tendency was observed at Sta. 3, the variation in the DO concentration at Sta. 3 was smaller than that at Sta. 4. Although salinity was low (below 0.2) for most of the period, it increased to about 1.0 after September 21, and the DO concentration decreased at this time. The reason for this is that seawater entering through the downstream floodgate intruded upstream of the river channel bottom layer as a density flow; whereas DO was consumed owing to the influence of the sediment. No increase in the fluorescence intensity was observed at Sta. 3 in late September (as what was seen at Sta. 2). This may have been because the amount of light reaching the Higashi-Yokobori River is low owing to the expressway overpass (the coverage rate of water surface by the expressway is approximately 80%).

At Sta. 5 (located outside the upstream gate), the variation in the DO concentration was similar to that at Sta. 4 and changed markedly in response to the cleanup operation. Since the DO concentration fluctuates during the operation, it appears that it is difficult to control the quality of the water mass imported through the upstream gate by monitoring only the water quality at Sta. 5. Salinity temporarily rose to about 3.0 on September 29. This was because the seawater intruded to above the upstream gate.

As described above, the variation characteristics of water quality in the Higashi-Yokobori and Dotonbori Rivers vary greatly depending on the location. The biological and chemical processes in the river strongly influence the water quality at locations distant from the gates; whereas the water quality near the floodgates is directly affected by the water cleanup operations. By comparing the monitoring results of the DO concentration at Sta. 4 and the salinity at Sta. 1 obtained from November 2013 to November 2014 with the cleanup operation records, we calculated the frequency of the introduction of lower-DO water mass at the upstream gate and the intrusion of saltwater at the downstream gate. Accordingly, it was estimated that an external water mass with a lower DO concentration was introduced at a frequency of about 20% at the upstream gate; whereas intrusion of saltwater occurred at a frequency of about 40% at the downstream gate.

c) Spatial distribution of river water quality

As described above, the water-quality structures are quite different between the Higashi-Yokobori River and the Dotonbori River. As a typical distribution that was often observed, the vertical longitudinal distributions of EC25 on July 11, 2017, are shown in Fig.6(a). The range of EC25 is limited to the value of freshwater (<0.5 mS/cm), so as to allow the observation of mixing between the water masses of the Neya and Oh Rivers. In the Higashi-Yokobori River, the water quality is uniform in the vertical direction; therefore, it is presumed that the water mass in the river is gradually pushed out by the external mass imported from above the upstream gate. Various water masses are distributed in the longitudinal direction depending on the water quality of the imported water mass.

On the other hand, in the Dotonbori River, the water quality was very different between the upper and the lower layers. The vertical longitudinal distributions of water quality on July 11, 2017 (spring tide), are shown in Figs.6(b)–6(d). Around Sta. 2, the density difference in the vertical direction is caused by the intrusion of saltwater through the downstream gate, which leads to the formation of salinity stratification; moreover, the fluorescence intensity and DO concentration are high in the upper layer. Although the cause of this is not clear, it is presumed that there is vigorous photosynthesis by brackish water phytoplankton intruding through the downstream gate; this is also affected by the strong stagnation of the river channel.

As described above, since the water-quality structure is different between the upstream and the downstream regions of the Higashi-Yokobori and Dotonbori Rivers, it is considered that the factors that exert a dominant influence on the water quality are different in each water region.

d) Net decline rate of DO concentration

Using the monitoring data at Sta. 4 from November 25, 2013, to December 1, 2014, the net decline rate (k_{net}, day^{-1}) of DO was determined by dividing
the change in the DO concentration by the time taken for the concentration change to become settled during the cleanup operation periods. However, in order to remove the effect of the concentration change resulting from the mixing with seawater transported from downstream, only data for the period in which seawater intrusion was not confirmed were used. The $k_{\text{net}}$ rate includes not only the effect of DO being consumed via the mineralization of organic matter in the water and sediment, but also the effect of DO being supplied via photosynthesis and reaeration.

The monthly average values of $k_{\text{net}}$ and water temperature ($T$) are shown in Fig.7. In the figure, the standard deviations of $k_{\text{net}}$ are also given, and a threshold of 3 mg/L was used to distinguish the hypoxic from the non-hypoxic periods based on the annual variation in the DO concentration at Sta. 4, as shown in Fig.4. $k_{\text{net}}$ showed a range of 0.1–0.5 day$^{-1}$. As positive values are shown throughout the year, it is evident that DO consumption is greater than DO generation regardless of the season in the Higashi-Yokobori River. As with water temperature, $k_{\text{net}}$ showed a tendency to increase during the period of hypoxia. This suggests that not only the quality of the water introduced from above the upstream gate but also consumption via biological and chemical processes in the river channel has a significant effect on hypoxia.

The hypoxic and nonhypoxic periods were separated on the basis of the threshold of $k_{\text{net}} = 0.20–0.25$ day$^{-1}$. The following equation for the relationship between $k_{\text{net}}$ and $T$ was obtained with a high coefficient of determination ($R^2 = 0.91$):

$$k_{\text{net}} = 0.242 \times 1.076^{T-20}. \quad (2)$$

c) Change in water quality around the upstream gate during the cleanup operation periods

Figure 8 shows the fluctuations in the water level and water quality around the upstream gate (Stas. 4, 5, and 6) on November 4 and 5, 2013. Here, we show the TOC concentration as an index of organic matter,
which influences the DO consumption process. During the survey period, the water-quality cleanup operation was performed twice in the morning and afternoon of November 5, with the water level inside the gate changing as follows: 1.6 m → 1.9 m → 1.6 m.

At Sta. 6, the TOC concentration was lower than 2.0 mg/L at high tide. This rose to about 4.0 mg/L during falling tide to low tide, before dropping again at rising tide. This is because the water from the Oh River flows up to Sta. 6 at high tide; whereas the water is removed from falling tide to low tide and the polluted water mass from the Neya River basin flows downstream.

At Sta. 5 (located at the confluence of the Higashi-Yokobori and Tosabori Rivers), a trend similar to that observed at Sta. 6 is seen (i.e., the TOC concentration was low at high tide and high during rising tide to low tide). However, since the variation at Sta. 5 is not as clear as that at Sta. 6, it is considered that either one of the Oh River water and Neya River water is not present at Sta. 5. The TOC concentration changes in response to changes in the mixing ratio of the river waters at Sta. 5, which changes according to the tide.

Focusing on Sta. 4 inside the gate, it can be confirmed that the TOC concentration increased at the same time as water intake from outside the gate was performed at around 8:00 on November 5. Since the TOC concentration immediately after the water intake was almost identical to the value at Sta. 5, it is thought that the water mass present outside the gate was transported inside the gate by the water intake operation.

In this paper, although only TOC is shown, the same variation was confirmed for TN and TP. From these results, it is apparent that the water mass, which was more polluted than that inside the gate, was removed by the cleanup operation during this study.

**f) Oxygen consumption rate by sediment**

The oxygen consumption rates by the sediment \( k_{sed} \) obtained in the laboratory experiment are shown in Table 2. The oxygen consumption rate varied depending on the temperature and sampling location. The rate ranged from 0.285 to 0.772 day\(^{-1}\). Although the experimental method was different, this value was greater than that obtained for the sediments of the Neya River and the Kanzaki River (from 0.046 to 0.068 day\(^{-1}\)), where pollution has increased\(^6\).

Since the value is the same as that for the net decline rate in DO \( k_{net} \) obtained from the continuous measurement data, it is presumed that the contribution of the sediment to hypoxia is not small. From these results, it is thought that dredging and improvement of riverbed quality are effective for the suppression of hypoxia in the summer. In the case of dredging and bottom improvement, a secondary effect, such as the suppression of primary production, can be expected owing to a reduction in the amount of nutrient elution.

**Table 2** Experiment results for the oxygen consumption rate by sediment.

| Sampling site | Temperature (°C) | \( k_{sed} \) (day\(^{-1}\)) |
|---------------|-----------------|---------------------------|
| Sta. M (The Higashi-yokobori River) | 20 | 0.417 |
| | 30 | 0.772 |
| Sta. C (The Dotonbori River) | 20 | 0.285 |
| | 30 | 0.392 |

![Fig.9](image-url) Relationships between net DO decline rate and (i) the longest retention period and (ii) the lowest introduced flow rate.

(2) Proposal for the improvement of the water cleanup operation

a) A simple simulation for the inhibition of hypoxia

We analyzed the gate operation record for one year from December 1, 2013, to December 1, 2014. It was found that the water intake at the upstream gate was performed 316 times and the annual water intake amount was approximately \( 1.47 \times 10^7 \) m\(^3\)/year (equal to 0.47 m\(^3\)/s). Considering that the volume of water in the Higashi-Yokobori and Dotonbori Rivers is \( 4.4 \times 10^5 \) m\(^3\) on average over the year (O.P. + 1.59 m), it is calculated that the water exchange in the rivers was performed at a frequency of 33.6 times a year (i.e., once every 11 days).

Figure 9 shows the relationships between the decline rate of the DO concentration \( k_{net} \) and (i) the maximum retention time and (ii) the minimum water intake amount required to maintain a nonhypoxic condition (DO > 3 mg/L). The figure shows that it is necessary to reduce \( k_{net} \) to 0.10 day\(^{-1}\) via some measure (e.g., improvement of intake water quality or improvement of sediment quality) in order to suppress hypoxia under the condition of the current
average residence time (about 11 days).

Moreover, the figure also shows that it would be necessary to keep the number of retention days below about 2.5 in order to suppress hypoxia in August, when hypoxia is most serious as the DO concentration decreases at a rate of $k_{net} = 0.40 \text{ day}^{-1}$ (see Fig.7). In order to achieve this, it is necessary to always allow in a water volume of about 2.0 m$^3$/s or more, which is equivalent to a water exchange rate that is more than four times the current rate. It would be difficult to realize such a rate of water exchange when we consider that there is a limit to the performance of the installed pumps and that the water mass containing much of the Neya River water is present outside the upstream gate during falling tide to low tide.

If it was possible to create a new aqueduct and intake water directly from the Oh River, it can be seen from Fig.9 that it would be necessary to allow in such water at more than about 2.0 m$^3$/s at all times in order to suppress hypoxia in August.

b) Relationship between the water quality of intake water and tide condition

As shown above, with the current water-cleanup operation, water masses with better water quality than that of the Higashi-Yokobori River are not necessarily allowed in. Therefore, we analyzed the change in the water quality inside the upstream gate before and after the water intake operation during the period of hypoxia from May to October 2014. Data related to the influence of saltwater intrusion from the downstream gate were excluded from this analysis.

The relationship between the change in the DO concentration and EC25 at Sta. 4 before and after the water intake is shown in Fig.10. In this figure, the positive value of the DO change indicates that the DO concentration at Sta. 4 increased with water intake. In the case of approximately 77% of all water intake operations, the DO concentration at Sta. 4 increased after water intake. As there are few data points in the third quadrant, it would be possible to raise the DO concentration of the river if the EC25 outside the gate was relatively low compared with that inside the gate.

The water levels at low tide, which occurs twice a day, are different owing to the daily tidal inequality of this water. In Fig.10, the plots are distinguished according to whether the low tide occurring just before high tide (when water intake is conducted) is “high” low water or “low” low water. Since about 90% of the data points are in the first or fourth quadrant in the case of high tide just after the “high” low tide, it was possible to allow in a water mass with a relatively high DO concentration. On the other hand, in the case of the high tide just after the “low” low tide, the water mass containing a large amount of Neya River water or seawater was incorporated in more than 30% of the total number of cases.

From the above results, it is possible to increase the probability of taking in the water mass with high DO concentration by further classifying the tidal periods during the water intake operation.

5. CONCLUSIONS

In this study, we clarified the characteristics of water quality in the Higashi-Yokobori and Dotonbori Rivers and evaluated the mitigation of hypoxia by the water-quality cleanup operations. The main conclusions obtained in this study are as follows:

(1) In the Higashi-Yokobori River, the water is a mixture of water masses from the Neya River and the Oh River and the water quality is vertically uniform. In the Dotonbori River, saltwater spreads thinly through the bottom layer, leading to salinity stratification.

(2) The water quality of the Higashi-Yokobori and Dotonbori Rivers varied under the influence of the water masses inflowing from the upstream and downstream floodgates, respectively.

(3) The main factors leading to hypoxia in this water were the low-DO water mass allowed in through the gates, the oxygen consumption by the bottom mud, and the biochemical processes in the river water.

(4) In the water cleanup operation performed between November 2013 and November 2014, low-DO water masses were allowed in through the upstream gate with about 20% frequency; whereas saltwater entered from the downstream gate with about 40% frequency.

(5) In order to increase the probability of allowing in a water mass containing a large volume of relatively non-polluted water, it is effective to classify the tidal periods during the water intake.
operations based on more detailed tidal indicators.

(6) For an optimal cleanup operation, it is necessary to keep the number of retention days below about 2.5 in order to suppress hypoxia in the summer; however, it is considered that this would be difficult to realize in practice. If it was possible to take water from the Oh River, it is considered that it would be possible to suppress hypoxia in the summer by taking the water at a rate of more than 2.0 m³/s.

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