Quantification of Bottom Water Age by Using Temperature Based Age Index Model and Its Relationship with Bottom Water Dissolved Oxygen Concentration in Ise Bay, Japan

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The age of bottom water which indicates the period in which oceanic water stays at the bottom of the inner bay basin after intrusion from the bay mouth was calculated to verify whether the age is a good index for the development of bottom water hypoxia. The spatially distributed water quality data was utilized in this study for three consecutive year in 2012,2013 and 2014. The data was observed monthly on sixteen monitoring stations by Suzuka fisheries laboratory of Mie prefectural government. To calculate the age of bottom water, a temperature-based age index model was used, the model based on the assumption that bottom water in the Ise Bay originates from the bay mouth (Lower strait water) in the predominate stratified period, i.e., summer season and age of the bottom water is the elapsed time from the beginning of intrusion from the bay mouth. From the analysis of age index model, it was found that the age of bottom water was higher in the center of the bay and water can be of 60 days old whereas near the bay mouth it was much younger and its age varied from 0 to 10 days. In September 2014, the entire basin accounted for younger water mass with a maximum age of 10 days at the center as compared to other years. Overall bottom water age in Ise Bay has also been calculated by taking an average of all stations, and it was found that the maximum average age occurred in June 2013 while the minimum one occurred in September 2014. The bottom water oxygen concentration indicated a high average correlation coefficient (R^2>0·70) with bottom water age in June, July, and August, whereas low average correlation coefficient (R^2<0·30) in September.

Key Words: *Age Index Model, Bottom Water Age, Lower Strait Water, Dissolved Oxygen*

1. INTRODUCTION

Oxygen is the most quintessential gas which is required to support life on earth. Oxygen contributes about 21% of the air we inhale, and phytoplankton in the ocean forms more than half of this oxygen [1]. It is essential for all aerobic life to acquire oxygen to harvest energy. In water, oxygen is present in a dissolved form, and it is much more limited as compared to atmospheric oxygen. Sometimes in ocean dissolved oxygen gets so low to have any biological effects and that dissolved oxygen limit is 2 mg/L or less[2),3),4)]. These low DO level zones are called hypoxic zones. The waters with higher bottom water age in the areas of restricted water exchange may experience substantial dissolved oxygen depletion in the presence of oxygen consuming organic matter. The concept of age index is very helpful to understand not only the water exchange process but also the consequences of restricted water exchange such as eutrophication and hypoxia.

Previously, Tanaka et al.[5)] analyzed the flow structure and conforming development of hypoxic water mass in Ise Bay by using the concept of water age based on earlier mentioned methods. It was found that there is a negative correlation between age of oceanic water and dissolved oxygen and older oceanic water coincides with the hypoxic water mass.

Fujiwara et al.[6] proposed, to analyze the development of hypoxia in terms of bottom water age by using only one parameter i.e. water temperature. The author demonstrated the effectiveness of age index model, however with limited data sets. The hypoxic season was also considered up to August contradictory to the actual hypoxic season which lasts up to October. In this study, the age of bottom water was calculated by the same methodology but with the wider data sets from 2012 to 2014, to verify whether the bottom water age is an appropriate index for the development of bottom water hypoxia. The longer hypoxic season was also considered up to October. The temperature-based age index model performance was also evaluated for entire summer hypoxic season instead of a few selected hypoxic episodes.

2. STUDY AREA

Ise Bay is a body of water that is partially surrounded by a coastline, located in the center on the southern coast in Japan and covers an area of 1738 km². It is bordered by Aichi prefecture and Mie prefecture and opened to the Pacific Ocean through a mouth as illustrated in Figure 1. The mouth is sited between Shima peninsula and Atsumi peninsula on the west and east, respectively. Moreover, it shares Chita peninsula to the North-South direction which encloses the Mikawa Bay on one side. Despite having a larger surface area as compared to other semi-enclosed bays in Japan, for instance, Tokyo Bay and Osaka Bay, it has a shallower depth, i.e., 19.50 m. The bathymetry feature of Ise Bay is bowl-shaped. Thus, it has the deepest longitudinal depression in the middle, i.e., approximately 35 m deep as shown in Fig.1. Bay mouth doesn't contain any sills. Although, there are several deep trenches near the bay mouth over 90 m in depth, particularly, the one in the shape of Irago strait. There are many small and medium size rivers flowing into Ise Bay and Mikawa Bay including famous three Kiso rivers, contributing 85% of the total freshwater discharge flowing into the bay system[7].

The Eastern side of the bay mouth is considered much deeper than the western side. There are several small and significantly large islands alongside the bay mouth such as Toshi Island, Suga Island and Kami Island. In Ise bay, a typical tidal current is very different from bay head to bay mouth as 10^{-1} m/sec to 1 m/sec respectively. The tidal current at bay mouth ensures the vertical mixing of heavier bottom water with the lighter surface water and produce intermittent density water[8].

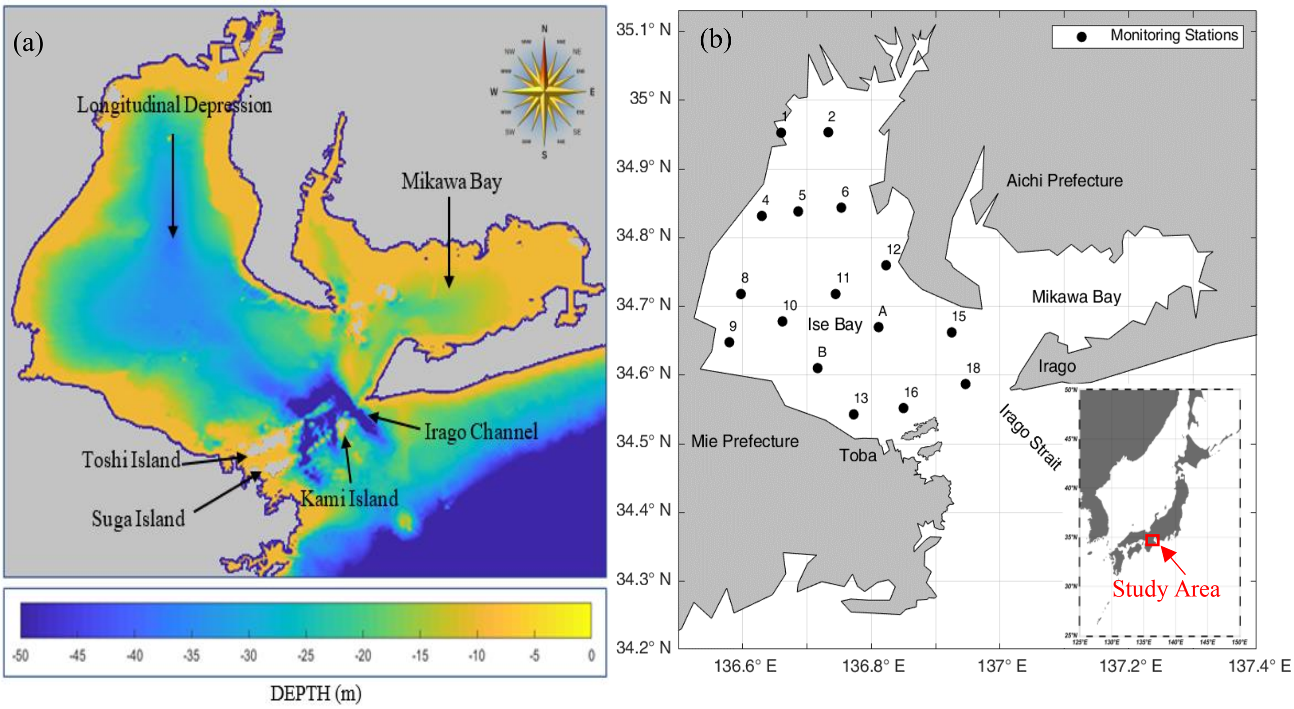

Fig.1 (a) Bathymetry of Ise Bay and its adjacent Mikawa Bay, (b) a map of Ise Bay. In (a), the color specifies the bathymetry with respect to the color bar and showing the location of Islands. In (b), the solid black dots indicate the location of sixteen water quality monitoring stations as set by Suzuka fisheries laboratory of Mie prefectural government Japan.

3. MATERIALS AND METHODS

(1) Data Used

To analyze the water quality and calculate the bottom water age of entire Ise Bay, a spatially distributed data set from Suzuka fisheries laboratory was used for the summer season of three consecutive years 2012, 2013 and 2014. The Suzuka fisheries laboratory observe water quality including temperature, salinity and dissolved oxygen concentration regularly on a monthly basis [9]. Data was observed on sixteen spatially distributed stations throughout the bay body as shown in Fig.1. Dissolved oxygen and water temperature were measured in different layers at 0m, 2m, 5m, 10m, 20m and 30m from the surface layer and 1m above from the bottom, B-1 m. The fundamental purpose of this monitoring system was to understand the short-term and long-term fluctuations in the marine environment, especially the behavior of hypoxic water mass and its impact on fisheries.

(2) Model Description

To calculate the age of bottom water, a temperature-based age index model was used [6]. The model assumes that bottom water in the Ise Bay originates from the bay mouth (Lower strait water) in the predominate stratified period, i.e., summer season and age of the bottom water was the elapsed time τ from the beginning of intrusion from the bay mouth. The bay mouth originated water was being considered as outer water and Station number 18 from Fig.1 was being considered as outer water as it was closed to Ise Bay mouth while rest of all stations were considered as inner bay water. Figure 2 illustrates the intrusion of LSW from deeper layers of bay mouth (depth>20m). Figure 3 illustrates the model parameters, the blue solid line is showing the variation of mean water temperature [T(t)] at station 11, while the red solid line is showing the variation of mean water temperature [To(t)] at station 18. The relationship among two temperatures can be explained by a simple model having water volume V, subjected to water exchange rate Q. Assuming outer water temperature $T_o(t)$ and inner water temperature $T(t)$, increasing linearly with rate α following an initial condition T (0) =T_o (0), the relation among temperatures and water exchange can be expressed as equation (1) and equation (2). After examining the assumption above the equation (1) and equation (2) can be solved easily and yields to equation (3).

$$T_o(t) = T_o(0) + \alpha t \tag{1}$$

$$\frac{VdT}{dt} = Q(T_o - T) \tag{2}$$

$$T(t) = T_o(t) - \alpha\tau + \alpha\tau.\exp\left(-\frac{t}{\tau}\right) \tag{3}$$

where $\tau = \frac{V}{Q}$ is mean residence time and identical to bottom water age.

$T(t)$ = Temperature of Water Parcel Inside the Bay (°C)

$T_o(t)$ = Temperature of Outer Water/ Lower Strait (Irago) Water at Bay Mouth (°C)

α = Temperature Increase Rate of Outer Water (°C/day)

τ = Age of Water Parcel (day)

t = Time

Figure 3, in which solid red line indicates the increase in the temperature of lower strait water and by combining it with initial condition T (0) =T_o (0), and for time scale $t \geq \tau$ the later exponential term from the model disappears and enabling the relatively simple version of it as following equation (4).

$$T(t) = T_o(t) - \alpha\tau \tag{4}$$

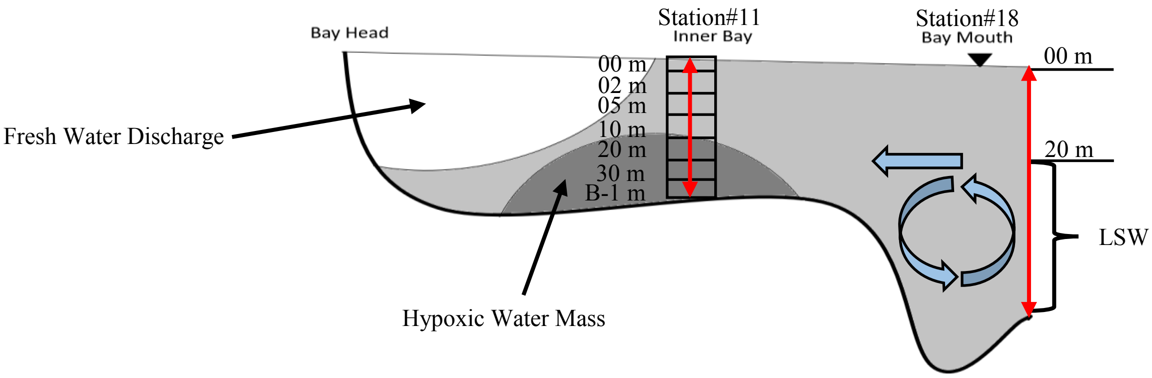

Fig. 2 Explanation of major model assumption. It was assumed that oceanic water intruded from bay mouth lower layer which was being assumed as lower strait water (LSW). The temperature of lower start water was calculated by taking an average of water column temperature from 20 m depth to the bottom.

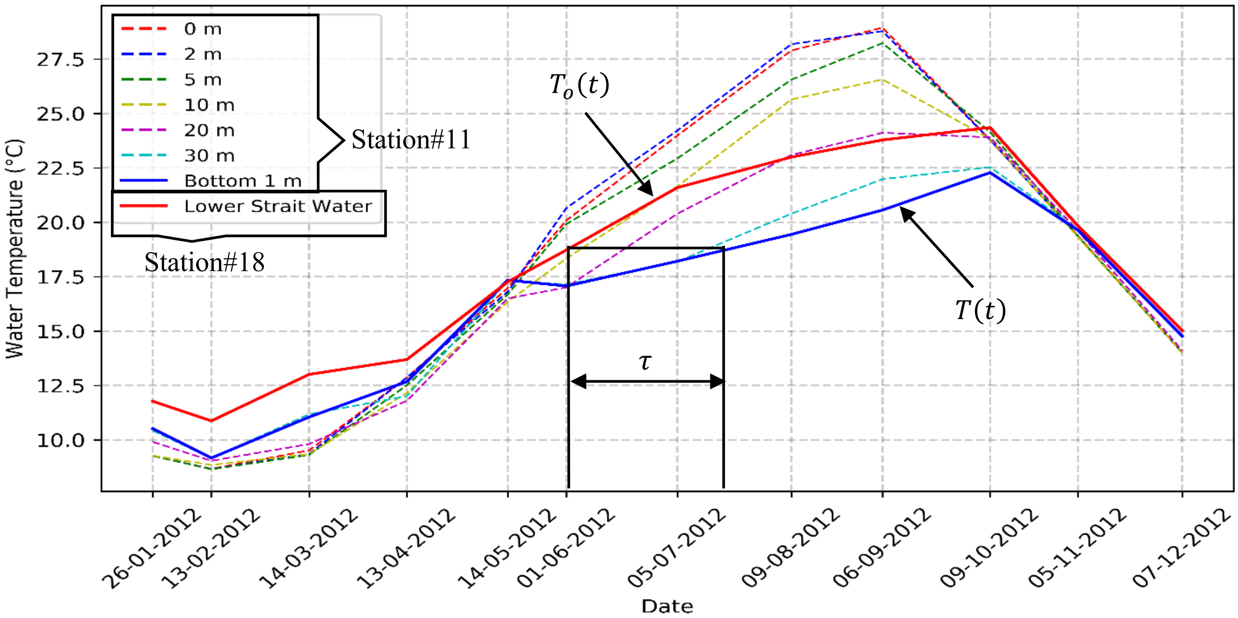

Fig. 3 Illustration of model parameters. Blue solid line is showing the variation of mean water temperate [T(t)] at station 11 over the course of one year while the red solid line is showing the variation of mean water temperature [To(t)] at station 18 for the same duration. Dotted colored lines are indicating the variation in water temperate of the water column at station 11.

4. RESULTS AND DISCUSSION

By comparing the temperature of lower strait water (LSW) water with the temperature of inner bay bottom water, the age of bottom water was calculated. For the input parameters of the model, the temperature increase rate (α) of lower strait water was calculated by dividing the increase of temperature over the summer duration with the period in days (K), taken for the increase of temperature.

From α values, it was found that temperature increase rate was higher in 2012 with a value of 0.0691 °C/day as compared to 2013 and 2014 with corresponding values of 0.0566 °C/day and 0.05422 °C/day respectively. The Summary of α calculation values with corresponding (K) period is shown in Table 1.

Table 1 Temperature Increase rate of summer period for 2012,2013 and 2014.

Parameter	2012	2013	2014
K (days)	146	150	149
α =(T1-T2)/K (°C/day)	0.0691	0.0566	0.05422

After determination of input parameters for age index model such as temperature increase rate and temperature of inner basin bottom water as well as the temperature of lower strait water, the age of bottom water was calculated by using age index model.

The Fig.4(a~i) shows the entire summary of this study, where subplot (a,b & c) is showing the spatial distribution of bottom water DO concentration and subplot (d,e & f) is showing the spatial distribution of bottom water age, while subplot (g,h & i) is showing the relationship between both parameters. From the analysis of age index model, it was found that age of bottom water was higher in center of the bay and water can be of 60 days old while water near the bay mouth was much younger and its age varied from 0 to 10 days. In June 2012 and August 2013, the age distribution was a little bit different, and younger water also existed along the eastern coastline of the bay, meanwhile, on the western side of the bay, there was older (25-40 days) water mass. In September 2014, the entire basin accounted for younger water mass with a maximum center age of 10 days as compared to other years. As age was dependent on water temperature, and if the temperature of the inner bay bottom water was greater than or equal to bay mouth bottom water, the ultimate age of water parcel in the bay was smaller or equal to zero. It was also somewhat astonishing to see that the age of bottom water near the head of the bay was younger as compared to the central part of the bay, even though the bayhead is most distant from the location of Irago strait and it can be seen clearly from Fig. 4 (d,e,f). It can also be associated with the supply of warmer water from the land side. Overall bottom water age was also calculated by taking an average of all stations as shown in Table 2, and it was found that the maximum average age occurred in June 2013 while the smallest one occurred in September 2014.

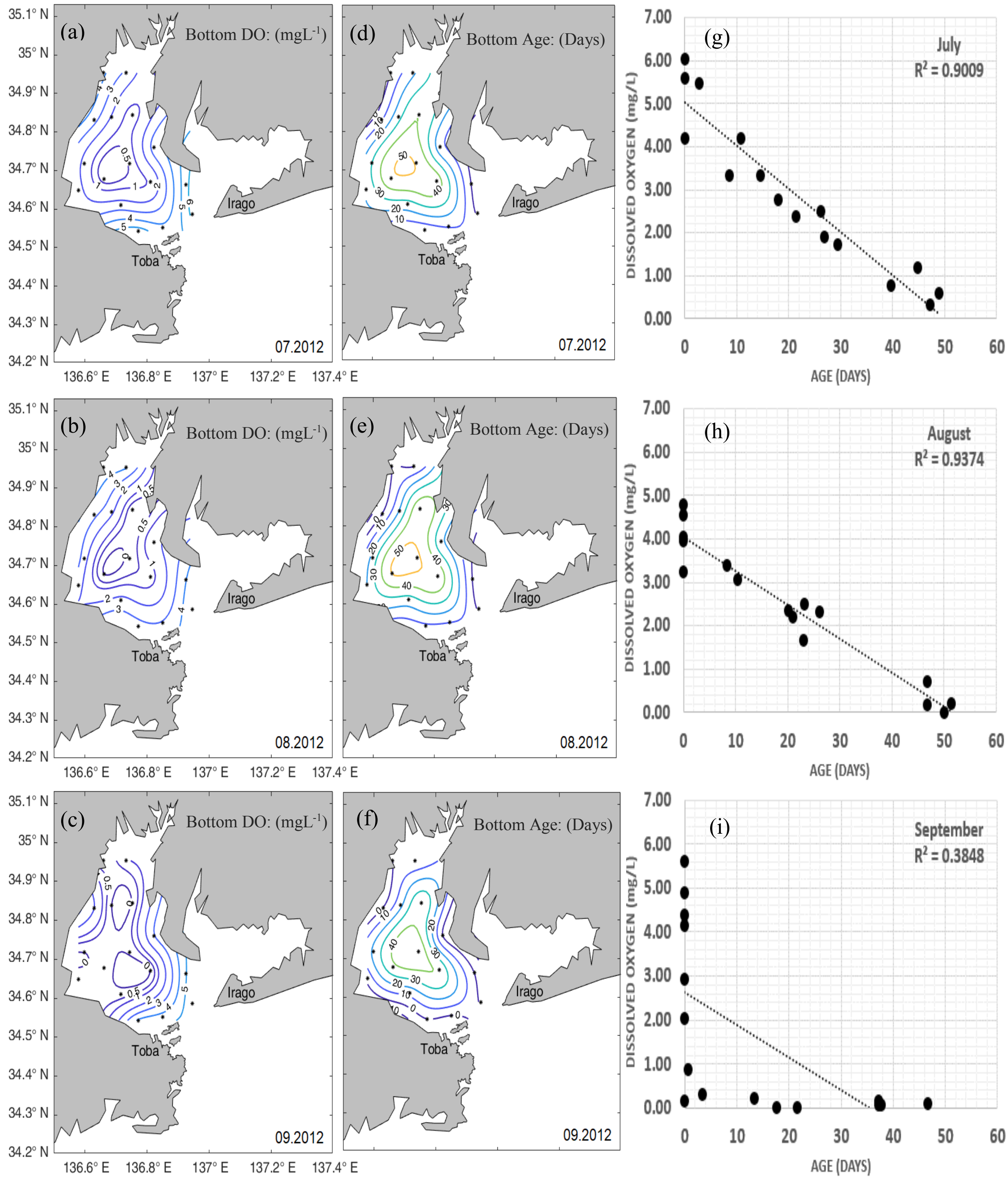

Fig. 4 Horizontal distributions of (a,b,c) bottom water DO and (d,e,f) bottom water age for July, August and September 2012, while (g,h,i) is showing the relationship between bottom water age and bottom DO.

Fig. 5 indicates the model performance in terms of R^2 value. The bottom water oxygen concentration indicated a good correlation with bottom water age in June, July, and August, while the correlation was not good in September. As discussed in chapter 3, the model is based on an assumption of the constant increase rate of LSW. This assumption was valid in the summer season while violated the validity in the autumn by a decline in water temperature due to heat loss from the water surface.

Table 2 Average bottom water age of the entire bay.

Month	2012	2013	2014
June	42.84	56.48	28.18
July	39.48	29.48	31.84
August	43.61	17.96	35.6
September	23.91	34.17	10.33
October	18.63	13.33	10.54

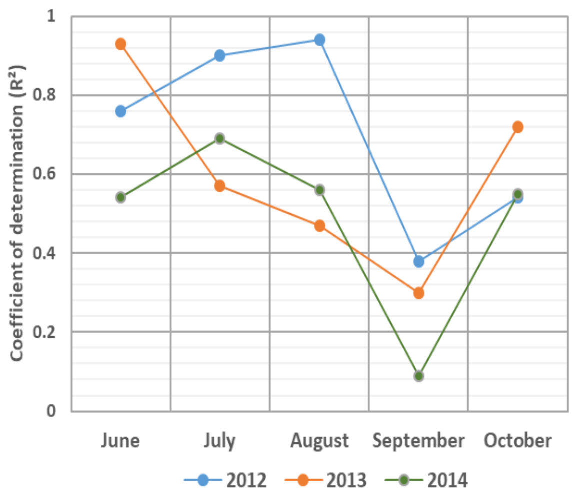

Fig. 5 Coefficient of determination (R^2) between age and DO concentration.

5. CONCLUSION

The concept of water age is very important and easy to understand the replenishment process of bottom water. The temporal change of hypoxia can also be explained by this concept especially in the case of the semi-enclosed water body where the deep-water intrusion is primarily driven from one direction.

In this study, the age of bottom water which indicates the period in which oceanic water stays at the bottom of the inner bay basin after intrusion from the bay mouth was calculated to verify whether the bottom water age is an appropriate index for the development of bottom water hypoxia. The temperature-based age index model performance has also been evaluated for entire summer hypoxic season instead of a few selected hypoxic episodes.

The age of bottom water proved to be a good indicator of bottom water hypoxia development. The bottom water oxygen concentration indicated a good average correlation coefficient (R^2>0·70) with bottom water age in June, July and August which means more than 70% of the variation in hypoxic water mass can be explained by such physical process, while the average correlation was not good in September (R^2<0·30) as some lower age hypoxic water was also detected in the said month. As mentioned in the earlier chapter, the model validity was violated as the fundamental assumption of the constantly increasing rate of temperature was not valid in the autumn season.

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