

ANALYSIS OF CONTRIBUTING FACTORS TO DISSOLVED OXYGEN DEPLETION IN THE ANOXIC ZONE AND THEIR RESPECTIVE CONTRIBUTIONS BASED ON STRATIFIED HYPOLIMNETIC OXYGEN DEPLETION

Análisis de los factores que contribuyen al agotamiento del oxígeno disuelto en la zona anóxica y sus contribuciones con base en el agotamiento del oxígeno hipolimnético estratificado

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ABSTRACT

Hypolimnetic anoxia is often observed in large reservoirs during thermal stratification. In the hypolimnion layer, dissolved oxygen (DO) is continuously consumed by biological and chemical reactions, resulting in a stable anoxic zone at the bottom of the reservoir. The areal hypolimnetic oxygen depletion (AHOD) has been a widely used indicator for hypolimnetic DO depletion, but this indicator could not reflect the DO depletion process at the bottom of deep reservoirs with deposits of pollutant sediments. With Daheiting Reservoir as the study case, the concept of stratified areal hypolimnetic oxygen depletion (S-AHOD) was proposed, and an S-AHOD calculation model was built, which could accurately describe the DO depletion process in the anoxic zone at the bottom of Daheiting Reservoir, identify the DO depletion rate at different water depths in the anoxic zone and quantify the contribution of sediment oxygen demand to the overall oxygen depletion. It was found that sediment oxygen demand contributed considerably (41.4%) to the overall hypolimnetic DO depletion in the reservoir, DO depletion rate varied considerably at different water depths, which increased from the surface to the bottom of the reservoir and reached the maximum at the bottom layer. Finally, based on results of existing works, an AHOD calculation equation applicable to lakes and reservoirs with considerable deposits of heavily pollutant sediments was put forward.

Palabras clave: estratificación térmica, zona anóxica, consumo de oxígeno disuelto, sedimentos contaminantes

RESUMEN

La anoxia hipolimnética se observa a menudo en grandes reservorios durante la estratificación térmica. En la capa del hipolimnion, el oxígeno disuelto (OD) se consume continuamente por reacciones biológicas y químicas, lo que resulta en una zona anóxica estable en el fondo del depósito. El agotamiento del oxígeno hipolimnético del área (AOHA) ha sido un indicador ampliamente, pero este indicador no pudo reflejar el proceso de agotamiento del OD en el fondo de los depósitos profundos con sedimentos contaminantes. Con el embalse de Daheiting como caso de estudio, se propuso el

concepto de agotamiento de oxígeno hipolimnético zonal estratificado (AOHA-E) y se construyó un modelo para el cálculo del AOHA-E, que podría describir con precisión el proceso de agotamiento de OD en la zona anóxica en el fondo del embalse de Daheiting, identificar la tasa de agotamiento de OD a diferentes profundidades de agua en la zona anóxica y cuantificar la contribución de la demanda de oxígeno del sedimento al agotamiento general del oxígeno. Se encontró que la demanda de oxígeno del sedimento contribuyó considerablemente (41.4%) al agotamiento hipolimnético general en el reservorio. La tasa de agotamiento del OD varió considerablemente a diferentes profundidades, aumentó desde la superficie hasta el fondo del depósito y alcanzó el máximo en la capa inferior. Por último, sobre la base de los resultados de las obras existentes, se propuso una ecuación para el cálculo del AOHA aplicable a lagos y embalses con depósitos considerables de sedimentos muy contaminantes.

RESEARCH BACKGROUND

Thermal stratification, a feature common among water ecosystems in lakes and reservoirs, usually affects the water quality and is a main contributor to the changes of water properties in lakes and reservoirs. Widely observed in reservoirs, thermal stratification mainly results from the temperature differences between the upper and the bottom layers of the water body (Boehrer 2013). The layered distribution of temperatures brings about substantial changes to the chemical and physical properties of the water body as well as the distribution of aquatic organisms (Wang 2009). The dissolved oxygen (DO) concentration is among the most deeply affected property of the water body and is an important indicator for the impacts of thermal stratification. During thermal stratification, the thermocline layer precludes mixing of water between the upper layer and the bottom layer of the water body, and isolates the hypolimnion layer from the oxygen produced by reaeration and photosynthesis reactions from the upper layers; meanwhile, the dissolved oxygen in the hypolimnion layer is continuously consumed by the decomposition of organic matters and oxygen-consuming reactions of the sediments at the bottom. Consequently, a steady anoxic zone (DO concentration $< 2.0 \text{ mg/L}$) is formed at the bottom of the reservoir (Wentzky 2019). The anoxic zone will reduce the water quality through a series of chemical and biological processes (Thompson 2013). For instance, the sediments at the bottom of the reservoir will release ammonia and phosphates in an anoxic context, which will contaminate the habitat of aquatic creatures and exacerbate eutrophication (Kang 2018, Ahlgren 1994).

Many indicators and calculation methods have been proposed to identify the oxygen depletion rate and quantify the oxygen depletion degree in the anoxic zone of reservoirs. Thienemann (1926,

1928) assumed that the productivity of surface water (nutritious state) and the morphology of the hypolimnion layer of the lakes and reservoirs would affect the oxygen concentration in the hypolimnion layer. Thienemann indicated that the organic matter would be diluted once falling into a thick hypolimnion, and hence the rate of volumetric hypolimnetic oxygen depletion (VHOD) generated by the decomposition of organic matters in a thick hypolimnion layer was lower than that in a thinner hypolimnion layer. As prior works used to relate the primary productivity of lakes and reservoirs to the oxygen depletion, the impacts of the morphology of the hypolimnion layer, as proposed by Thienemann, would defy any attempt to establish a relationship between the primary productivity and the oxygen depletion rate in the hypolimnion layer (Cornett 1980). Thus, Strom (1931) and Hutchinson (1938) proposed the concept of areal hypolimnetic oxygen depletion (AHOD) to remove the impacts of the morphology of the hypolimnion layer. With four lakes as the study cases, Hutchinson confirmed the feasibility of using AHOD to reflect the productivity and nutritional state of the surface water of the lakes (Hutchinson 1938), but this conclusion failed to win support in later research works (Deevey 1940, Ohle 1956, Lasenby 1975, RAST 1978). Cornett and Rigler (1980) argued that AHOD was not an indicator independent of the status of the lake, and hence AHOD-based measurement of the nutrition condition of a lake would fall short of accuracy. Though taking AHOD as an indication of the nutrition status of water bodies, as stated in Hutchinson's theories, is controversial, AHOD has remained a popular tool in comparative research on the productivity of stratified lakes (Lasenby 1975, Walker 1979, Wentzky 2019). Moreover, many researchers have proposed improved methods for AHOD calculation. Walter (1995) factored in the contribution of inputs

of organic matter to the AHOD rate; Cornett and Rigler (1980, 1979) explored the relations between the AHOD rate and the phosphorus retention rate in the water body; Charlton (2003) considered the impact of the thickness of the hypolimnion layer. Sadeghian et al. (2018) constructed a model to identify the correlation between the chlorophyll concentration and DO depletion. Terry et al. (2017) built a mathematical model to explore the correlation between the sediment oxygen demand (SOD) and the DO concentration in the hypolimnion layer of water bodies. Dong et al. (2020) analyzed the hypolimnetic DO depletion process and the contributing factors to the vertical diffusion of DO in the water body. Kreling et al. (2017) gauged the impacts of vertical diffusion of DO on the DO concentration at the hypolimnion layer of water bodies. Weber et al. (2017) measured the DO depletion rate of unit water column and unit surface area of sediments. Having developed for years, AHOD has become an important indicator for quantifying the primary productivity and the DO depletion process in water bodies.

When the concept of AHOD was introduced to studies on the anoxic zone in reservoirs in China, the following problems were observed. First, though AHOD provides a comprehensive indicator for DO depletion in water bodies, most AHOD-based studies abroad are performed in lakes or reservoirs with clean sediments, where the decomposition of organic matters is the major driver of DO depletion; consequently, in previous works abroad, the calculation of AHOD mainly considers the DO consumed by decomposition of organic matters, but does not factor in SOD. Secondly, the concept of AHOD refers to the DO depletion rate per unit area in the hypolimnion layer, but it cannot well reflect the DO depletion rate at different depths in the hypolimnion layer. When the reservoirs have pollutant sediments, the closer it is to the sediments, the larger the impact of the sediments on the DO depletion. Thus, the single indicator of AHOD cannot clearly reflect the DO depletion level at different depths of the water body. Thirdly, in the AHOD calculation methods proposed in existing works, it was largely assumed that there was no heat and mass transfer between the hypolimnion layer and the above epilimnion and metalimnion layers during thermal stratification, and hence the DO transferred from the upper layers to the hypolimnion layer was largely not considered in the calculation. Nonetheless, it was found in later works that there is a DO flux that migrates from the upper layers to the bottom of the water body during

thermal stratification. Burns (1995), when exploring the contributors to hypolimnetic DO depletion, stated that “though the volume of DO migrated or diffused to the hypolimnion layer of lakes is yet to be determined, this DO flux that migrates downwards should be considered in calculation of AHOD”. Matthews and Effler (2006) reviewed the AHOD calculation methods and proposed that the oxygen flown into the hypolimnion layer due to vertical mixing of DO in the water body would affect the accuracy of the conventional AHOD calculation methods. To sum up, the currently available AHOD calculation methods cannot clearly reflect the hypolimnetic DO depletion in reservoirs or lakes with heavily pollutant sediments, and hence the indicator needs to be improved.

The present work is a case study of Daheiting Reservoir (Daheiting Reservoir is a deep-water reservoir in northern China with serious sediment pollution and a typical hypoxic zone), the source reservoir of the water diversion project from the Luanhe River to Tianjin City. Based on the concept of AHOD, the concept of stratified areal hypolimnetic oxygen depletion (S-AHOD) rate was proposed, and a calculation model was constructed to analyze the hypolimnetic dissolved oxygen depletion in Daheiting Reservoir. The measured high-frequency stratified DO evolution data from the reservoir and the modified AHOD calculation method were used to quantitatively assess the driving factors for hypolimnetic dissolved oxygen depletion in the reservoir, identify the contributors to dissolved oxygen depletion at different water depths, and explore the factors contributing to hypolimnetic dissolved oxygen depletion in the reservoir and their contribution levels. The research results of this paper can significantly improve the understanding of the evolution mechanism of the hypoxic zone of the reservoir, which is of great significance to the management of the water quality of the reservoir.

STUDY AREA AND RESEARCH METHODS

Introduction to the study area

Daheiting Reservoir, located along the mainstream of Luanhe River in Qianxi County of Tangshan City, is a major link in the water diversion project from Luanhe River to Tianjin City. With a capacity of 337 million m³ and a backwater reach stretching 23 km, the reservoir is a Level-II water conservancy project in China. Since it was built in 1986, the reservoir has been a major source of water supply for Tangshan, Tianjin, and other regions in the lower reach of Luanhe River. From the 1980s

to the late 1990s, the water quality of Daheiting Reservoir was good and was rated Class III as per the National Environmental Quality Standards for Surface Water of China (Wang 2003). Amid fast economic growth after 2000, however, the pollution load in the reservoir increased, resulting in poorer water quality; and the wide adoption of cage culturing that grew increasingly popular later led to more serious pollution and increased deposit of pollutant sediments in the reservoir (Wang 2016). After 2016, cage culturing was banned in the reservoir, and the water quality was improved (Wang 2017), but the pollutant sediments generated by massive cage culturing in the past decade remained at the bottom. These sediments lead to considerable hypolimnetic oxygen depletion during thermal stratification each year, and result in hypolimnetic anoxia (Liu 2019) (**Fig. 1**); consequently, more pollutants are released from the sediments at the bottom of the reservoir during thermal stratification, which affects the function of water supply of the reservoir. The hypolimnetic dissolved oxygen depletion process and law of the reservoir during thermal stratification remain unclear now. Thus, to analyze the dissolved oxygen depletion process and influencing factors in the anoxic zone of the reservoir by technical means can help understand the evolution pattern of the anoxic zone and provide a theoretical basis to address pollution problems in the reservoir.

Research method

To unveil the process and pattern of dissolved oxygen depletion during the formation of the anoxic zone in the hypolimnion layer of Daheiting Reservoir, high-frequency monitoring of the vertical dissolved oxygen concentrations at the front of the dam was performed. As per the spatio-temporal evolution pattern of the anoxic zone in this reservoir (Liu 2019), the anoxic zone is formed basically in June each year, about one month after the thermal stratification occurs. To identify the accurate changing pattern of

DO concentrations during the critical period of the anoxic zone formation in Daheiting Reservoir, the DO concentration monitoring technique for oceans which is popular in the field of marine science was employed, and the vertical DO high-frequency monitoring system was developed to perform high-frequency stratified monitoring of DO concentrations in the deep-water zone at the front of the dam of the reservoir. The location of the monitoring system in the reservoir is shown in **figure 2**.



Fig. 2. location of the monitoring system in the reservoir.

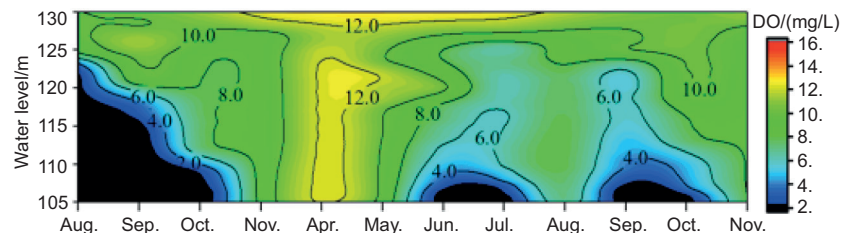


Fig. 1. Temporal evolution features of dissolved oxygen content and the anoxic zone at the front of the dam of Daheiting Reservoir(2017-2018).

The monitoring system consists of observation instruments, a mooring system, and a floating system. The observation instruments include five temperature logging probes (RBR, Canada, Measuring range, -5°C to 35°C , Resolution, $<0.00005^{\circ}\text{C}$), and four temperature and dissolved oxygen concentration probes (HOBO, USA, Measuring range, 0 to 30mg/L , Resolution, $<0.02\text{ mg/L}$); the mooring system and the floating system consist of two 30-kg floating balls, a 20-m steel wire rope, a 25-m mooring chain, a 150-kg anchor block and a chain shackle. **Figure 3** presents a sectional diagram of the monitoring system, and **Table I** shows the location of the probes and the monitoring indicators.

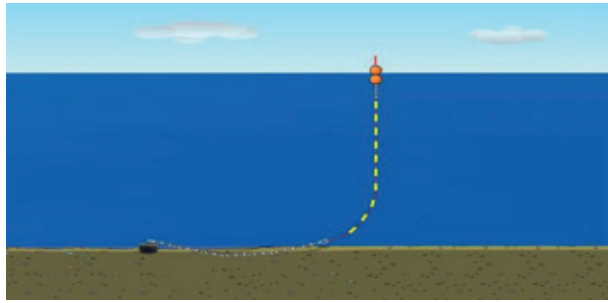


Fig. 3. High-frequency monitoring system of vertical dissolved oxygen concentrations in Daheiting Reservoir.

According to the monitoring results of the dissolved oxygen concentration of Daheiting Reservoir, the hypoxia phenomenon of reservoir generally starts in the middle and late June of the year, enters the development period in July, and is in a stable period in August. Therefore, in order to capture the formation process of the hypoxic zone of the reservoir,

the monitoring system was deployed at the front of the dam of the reservoir on June 3rd, 2018. To obtain high-frequency data of DO concentrations at different water depths in the reservoir, the probes were set to record the data once every 0.5 h. The monitoring started at 9:00 a.m., June 3rd, 2018, and stopped at 10:00 a.m., June 28th, 2018 when a stable anoxic zone occurred at the bottom of the reservoir. During the period of monitoring, each DO detection probe collected 1,202 pieces of data, and hence four probes collected a total of 4,808 pieces of data.

RESULTS AND DISCUSSION

Dissolved oxygen depletion during the formation of the anoxic zone in Daheiting Reservoir

Figure 4 shows the changes in the DO concentration with time at different water depths at the front of the dam of Daheiting Reservoir detected by the four probes. As per the thermal stratification monitoring results in June 2018 in Daheiting Reservoir (Liu 2019), the probe deployed at a depth of 5 m was on the interface between the metalimnion layer and the hypolimnion layer, while the other three probes were within the hypolimnion layer. The data obtained by the deepest probe (18.5 m below the water surface and 1.5 m from the bottom of the reservoir) clearly recorded the continuous depletion of dissolved oxygen in the hypolimnion layer of the reservoir till the layer entered an anoxic state.

As **figure 4** shows, the DO concentration showed no tangible variations along the vertical direction in the early stage of monitoring and stayed between 9 and 12 mg/L . The water at the top of the hypolimnion layer, due to proximity to the oxygen-rich layers above, registered a higher DO concentration, while

TABLE I. DEPLOYMENT DEPTHS OF THE PROBES AND INDICATORS OF THE MONITORING SYSTEM.

Series No.	Instrument	Deployment depth of the probes (m)	Monitoring indicators
1	RBR recording probe (Canada)	3	Temperature
2	HOBO recording probe (USA)	5	Temperature, DO
3	RBR recording probe (Canada)	7	Temperature
4	HOBO recording probe (USA)	9	Temperature, DO
5	RBR recording probe (Canada)	11	Temperature
6	RBR recording probe (Canada)	13	Temperature
7	HOBO recording probe (USA)	15	Temperature, DO
8	RBR recording probe (Canada)	17	Temperature
9	HOBO recording probe (USA)	18.5	Temperature, DO

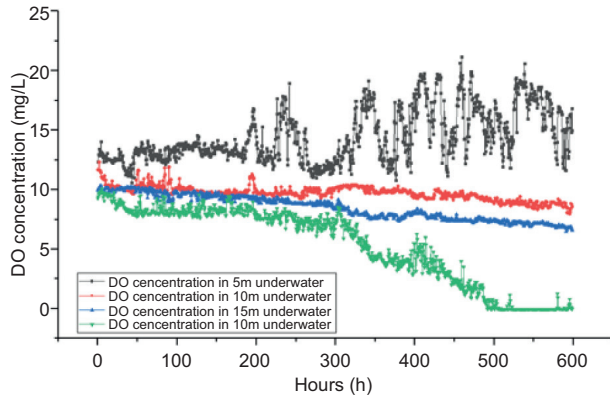


Fig. 4. Variations in the DO concentration at different water depths in front of the dam of Daheiting Reservoir during the anoxic zone formation period.

that at the bottom of the hypolimnion layer was lower, but the overall concentration stayed at a high level. As the thermal stratification developed, the DO concentration began to vary among different layers of the reservoir, resulting in oxygen stratification. In the later stage of monitoring, the hypolimnion layer witnessed a sharp drop in the DO concentration till reaching an anoxic state. The evolution of the hypoxic zone of Daheiting Reservoir began to transition from the formation period to the stable period.

The measured data clearly revealed the DO depletion process in the hypolimnion layer, but the contribution of organic matter decomposition and sediment oxygen demand to the overall oxygen depletion at different depths is yet to be determined. It is necessary to combine the measured data with the DO depletion calculation methods to perform quantitative analysis.

Analysis of contributing factors of dissolved oxygen depletion in the anoxic zone and their respective contributions based on the S-AHOD rate

Conventional AHOD rate calculation methods outside China

Among the many AHOD rate calculation methods proposed by international scholars, the most popular one is the equation proposed by Charlton (2003). Charlton maintained that the AHOD rate was correlated to the primary productivity of the lake (the functions of chlorophyll concentration or the total phosphorus concentration), the thickness of the hypolimnion layer, and the average hypolimnetic temperature. Charlton's equation mainly reflects the process of DO depletion caused by decomposition of

organic matter in the hypolimnion layer. Based on the data from 26 lakes in the USA and Canada, Charlton put forward an AHOD calculation equation:

$$AHOD = 3.80 \left[f(Chla) \frac{\bar{Z}_\eta}{50 + \bar{Z}_\eta} 2^{\frac{\bar{T}_\eta - 4}{10}} \right] + 0.12,$$

where $\bar{Z}_\eta$ refers to the thickness of the hypolimnion layer (m), $\bar{T}_\eta$ is the average hypolimnetic temperature ($^{\circ}\text{C}$), $f(Chla)$ is the chlorophyll concentration function that indicates the primary productivity of the lake, which is expressed as

$$f(Chla) = \frac{1.15Chla^{1.33}}{9 + 1.15Chla^{1.33}}.$$

Charlton employed the equation to calculate the AHOD rate of many lakes for verification, and achieved good results. Charlton's equation has been widely mentioned in later works.

Charlton's equation was employed here to calculate the AHOD rate during the anoxic zone formation period in Daheiting Reservoir. The measured data in June show that the hypolimnion layer was 4.5 m below the water surface, the water was 20 m deep in front of the dam of the reservoir, and hence the thickness of the hypolimnion layer was 15.5 m. The average temperature from the hypolimnetic top to the reservoir bottom was 8.07°C , and the average chlorophyll concentration at the reservoir surface layer was $12.32 \mu\text{g/L}$. Thus, as per Charlton's equation, the mean AHOD rate in Daheiting Reservoir was obtained, i.e., $1.05 (\text{gO}_2 \cdot \text{m}^{-2} \cdot \text{d}^{-1})$.

In fact, Charlton was aware of the impacts of reactions of sediments on the DO concentration aside from the decomposition of organic matter during thermal stratification, and hence indicated that SOD should be considered to improve the equation. Charlton's equation achieved good verification results when applied to most lakes and reservoirs because of the following two reasons. First, the lakes and reservoirs used for verification experienced little pollution, and the sediments make a small contribution to the overall hypolimnetic dissolved oxygen depletion. The intercept in Charlton's equation (0.12) indicates the impacts of the SOD on the AHOD rate. Secondly, in the equation, it is presumed that the sediments account for a very limited proportion of the overall dissolved oxygen depletion because the SOD is limited by DO content in the hypolimnion layer: when the hypolimnetic DO content reaches the threshold, the SOD stops rising. However, these two reasons are exactly what made Charlton's equation inapplicable to Daheiting Reservoir. Due to the massive cage culturing in the

early 21st century, the reservoir witnessed considerable deposits of pollutant sediments that were rich in organic matter, and the SOD contributed much to dissolved oxygen depletion. Meanwhile, in the early stage of the anoxic zone formation, the hypolimnion layer has efficient oxygen flux, which provides sufficient oxygen for the sediments, and the total oxygen content will not limit the contribution of SOD. Moreover, Charlton's equation has not considered the diffusion of DO from upper layers to the hypolimnion layer. Consequently, the AHOD rate obtained by Charlton's equation would differ considerably from the actual situation.

Proposal of the concept of S-AHOD

According to the varied AHOD rates at different water depths in Daheiting Reservoir, we proposed in this work the concept of stratified areal hypolimnetic oxygen depletion (S-AHOD) rate based on the existing concept of AHOD. The concept of S-AHOD presumes that the sediments are large contributors to the overall oxygen depletion in heavily-polluted reservoirs, and the DO depletion rate varies among different water depths in the hypolimnion layer. Thus, the average AHOD rate of the hypolimnion layer cannot serve as an indicator for the impacts of pollutant sediments on the overall oxygen depletion. The S-AHOD rate, however, provides a metric to assess the respective DO depletion rate at different layers in the reservoir and a comprehensive indicator for the DO depletion of the reservoir.

Analysis of contributing factors to dissolved oxygen depletion and their respective contributions based on the S-AHOD rate

Theoretical model for S-AHOD calculation

Only one monitoring line was deployed in front of the dam of Daheiting Reservoir for high-frequency DO monitoring, and when the obtained data were used to calculate the S-AHOD of the reservoir, the following assumption was made: when the anoxic zone occurred within a given range, the vertical distribution pattern of DO concentrations remained the same on any horizontal plane (Within a certain water area, the water depth, water quality, sediment pollution, meteorological conditions, dynamic conditions, etc. of the reservoir are basically the same, so the vertical dissolved oxygen structure will be basically the same). This assumption could be verified by the spatial evolution features of the anoxic zone and the correlations between the anoxic zone and the local topography (Liu 2019). Therefore, the data obtained from one single monitoring line are enough

to represent the hypolimnetic DO depletion in front of the dam of the reservoir.

Based on this assumption, a theoretical model was proposed and used for calculation of S-AHOD (**Fig. 5**). The high-frequency DO monitoring data were analyzed, and as per the assumption, the DO concentration within a given range around the monitoring line showed largely the same distribution pattern, and thus a standard water column with a section area of 1 m² was defined first in the conceptual model. The depth of the column was the same as the water depth of Daheiting Reservoir in June, and the four monitoring probes were deployed 5 m, 10 m, 15 m and 18.5 m below the water surface, with the deepest one staying 1.5 m from the reservoir bottom. As **figure 5** shows, each probe could obtain data of the AHOD rate of specific layers within the column. This rate would reflect the impacts of DO concentration changes in lower layers and hence could reflect the contribution of SOD to the DO concentration in the specific layer.

Our proposed model also considered the diffusion of DO from upper layers to the hypolimnion layer, and the diffused content of DO was calculated by the equation proposed by David et al. [28], which directly converted the vertical diffused DO into the AHOD. David et al. maintained that the

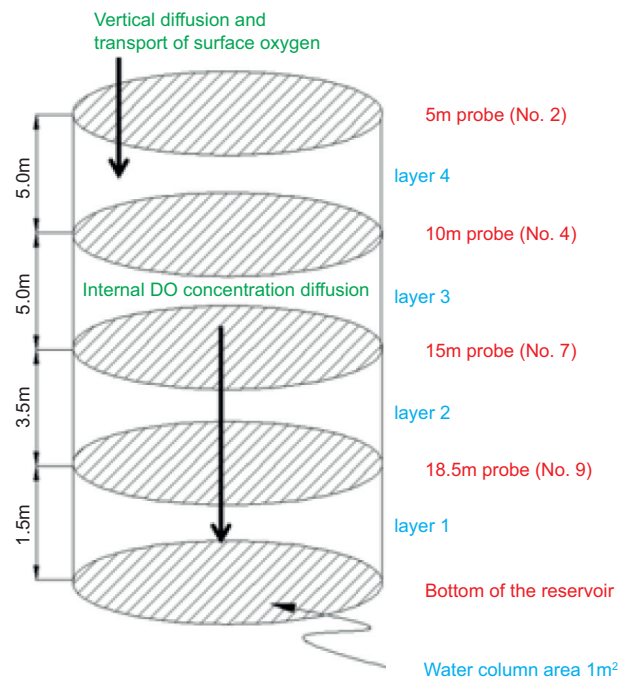


Fig. 5. Conceptual model for S-AHOD calculation in Daheiting Reservoir.

vertical diffusion of DO would affect the AHOD rate, and hence it would necessary to modify the AHOD calculation as per the specific conditions. They assumed that the rate of DO depletion caused by vertical DO diffusion was a function between the vertical heat transfer coefficient and inter-layer difference of DO concentrations:

$$DO_{flux} = v_t (DO_u - DO_d),$$

where DO_{flux} is the DO depletion rate post inter-layer oxygen diffusion ($gO_2 \cdot m^{-2} \cdot d^{-1}$), v_t is the vertical heat transfer coefficient ($m \cdot d^{-1}$), DO_u is the DO concentration of the upper layer (mg/L), and DO_d is the hypolimnetic DO concentration (mg/L). v_t is obtained by the following equation:

$$v_t = \frac{V_h}{A_t t_s} LN \frac{T_{h,i} - \bar{T}_u}{T_{h,s} - \bar{T}_u},$$

where V_h is the volume of the hypolimnion layer (m^3), A_t is the area of the hypolimnion layer (m^2), is the duration of the DO depletion process (d), $T_{h,i}$ is the initial temperature of the hypolimnion layer ($^{\circ}C$), $T_{h,s}$ is the temperature of the hypolimnion layer when the monitoring stopped ($^{\circ}C$), and $\bar{T}_u$ is the average temperature of upper layers of the reservoir ($^{\circ}C$).

S-AHOD calculation result and analysis of hypolimnetic dissolved oxygen depletion mechanism

Table II shows the S-AHOD rates at different water depths calculated based on the measured data from Daheiting Reservoir (statistics for lakes outside China were provided for comparison (Kalff 2011)). By combining our calculated results with those obtained by Charlton's equation, we could obtain the contribution of organic matters and sediments at different layers to the overall dissolved oxygen depletion.

The calculated results reveal the following findings:

- 1) Compared with lakes outside China, Daheiting Reservoir is more eutrophic and sees more deposits of pollutant sediments at the bottom. As a result, the reservoir has a higher AHOD rate than other lakes, and the hypolimnion layer is more likely to see oxygen depletion during thermal stratification.
- 2) The AHOD of Daheiting Reservoir showed considerable difference among layers: the rate was the maximum at the bottom, and decreased upwards. The AHOD rate obtained based on the measured data was larger than that calculated by Charlton's equation, which indicates that the measured data reflected the impacts of organic matter and sediments on the dissolved oxygen depletion in the hypolimnion layer, while the Charlton's equation considered only the impacts of organic matters while left out the dissolved oxygen consumption mechanism during the anoxic zone formation period.
- 3) The difference between our result and that obtained by David's equation is the contribution of SOD to the dissolved oxygen depletion. The sum of the difference and the intercept in Charlton's equation (the intercept partly reflects the contribution of SOD to the overall dissolved oxygen depletion) is the contribution of SOD to the dissolved oxygen depletion rate at different water depths in the hypolimnion layer of the reservoir. The contribution of SOD reveals that sediments account for a large proportion of hypolimnetic oxygen depletion in Daheiting Reservoir, reaching 41.4% (while the rest is credited to decomposition of organic matters). As the water depth decreases, the contribution of sediments to the hypolimnetic dissolved oxygen depletion reduces, reaching 24.7% at a depth of 15 m and 13.0% at a depth of 10 m. This indicates that the impact of SOD on the DO depletion in the reservoir decreases as the water depth reduces, and its impact is mainly observed at the bottom of the reservoir (when the distance from the sediments

TABLE II. S-AHOD RATES OF DIFFERENT LAYERS IN DAHEITING RESERVOIR.

Layers	S-AHOD	AHOD calculated by Charlton's equation	AHOD obtained by David's improved equation	Difference	Contribution of SOD
1	1.86	1.05	1.21	0.65	41.4%
2	1.45			0.24	24.7%
3	1.25			0.04	13.0%
Mean	1.52			0.31	28.3%

AHOD rates of lakes in North America: Superior Lake (0.40); Lake Ontario (1.25); Central area of Lake Erie (0.33), Eastern area of Lake Erie (0.61), Lake Michigan (0.88).

approaches infinity, the impacts of SOD on the DO depletion moves towards 0; in this case, the AHOD rate moves infinitely closer to the value obtained by Charlton's equation, which confirms the feasibility and accuracy of Charlton's equation in calculating the DO depletion caused by decomposition of organic matter).

- 4) The formation of an anoxic zone in Daheiting Reservoir during thermal stratification is a result of joint action of decomposition of organic matter and SOD, but the effects of these two actions vary at different depths of water. The sediments play an essential role in the formation of the anoxic zone (the mean value reveals that the dissolved oxygen consumed by sediments accounts for 30% of the overall hypolimnetic oxygen depletion).

Modified Charlton's equation applicable to reservoirs with heavily pollutant sediments

Based on the results obtained above, we propose a modified Charlton's equation applicable to the critical period of anoxic zone formation in reservoirs with heavily pollutant sediments:

$$SAHOD = 3.80 \left[f(Chla) \frac{\bar{Z}_\eta}{50 + \bar{Z}_\eta} 2^{\frac{\bar{T}_\eta - 4}{10}} \right] +$$

$$AHOD_{flux} + 0.0005Z^{2.479} \quad (R^2 = 0.943),$$

where Z is the water depth at the hypolimnion layer (m), $AHOD_{flux}$ is the rate of DO depletion caused by vertical diffusion of DO.

It should be noted that the correlation coefficient in the equation is determined based on the measured data from Daheiting Reservoir, and when applied to other reservoirs or lakes, the equation will need to be adjusted (Calculate the vertical diffusion of DO based on the measured dissolved oxygen data of the reservoir, and modify the coefficient and index of the water depth Z). This equation is expected to provide a new method and a research direction for AHOD calculation in similar lakes or reservoirs. We propose the equation to highlight the need of stratified analysis in calculation of AHOD in reservoirs with highly pollutant sediments and the necessity to consider the contribution of vertical DO diffusion to the hypolimnetic oxygen depletion.

CONCLUSIONS

The major conclusions of the present work are as follows.

- 1) Though cage culturing has been banned in Daheiting Reservoir, the sediments from cage culturing in the past decade remain at the bottom of the reservoir. These sediments cause serious hypolimnetic anoxia in the reservoir during thermal stratification each year, and the resultant anoxia leads to substantial release of pollutants from the sediments, which affects the role of the reservoir in water supply. However, the process and mechanism of hypolimnetic dissolved oxygen depletion in the reservoir during thermal stratification remain to be determined.
- 2) In reservoirs with heavily pollutant sediments, the sediments contribute considerably to the overall oxygen depletion. The dissolved oxygen depletion rate shows substantial differences among different depths within the hypolimnion layer, and the average AHOD rate for the whole hypolimnion layer will not be enough to reflect the impacts of sediments on the overall dissolved oxygen depletion. With Daheiting Reservoir as the study case, the concept of S-AHOD was proposed and a conceptual model for its calculation was established. The dissolved oxygen depletion at different depths of the hypolimnetic layer in the reservoir was quantified to accurately demonstrate the dissolved oxygen depletion rate at different water depths and the contributions of organic matter and sediments to the overall oxygen depletion.
- 3) The AHOD rate within the hypolimnion layer in Daheiting Reservoir shows considerable variations at different water depths: the rate reaches the maximum at the bottom, and decreases upwards. The sediment oxygen demand accounts for a large proportion (41.4%) in the hypolimnetic dissolved oxygen depletion of Daheiting reservoir, and the proportion is 24.7% and 13.0% at a depth of 5 m and 10 m, respectively. It reveals that the impact of sediment oxygen demand on the dissolve oxygen depletion declines as the water depth reduces, and the impact is mainly observed at the bottom of the reservoir.
- 4) In the reservoir with strong eutrophication and substantial deposits of highly pollutant sediments, it is likely to observe a high dissolved oxygen depletion rate and formation of a stable anoxic zone during thermal stratification. When an anoxic zone is taking form in the hypolimnion layer, the sediment oxygen demand accounts for the major contributor to the formation process, and the impact of sediments on the oxygen depletion process should be noted.

- 5) This article only proposes the SAHOD calculation formula based on the measured dissolved oxygen concentration change data of Daheiting Reservoir. In future research, monitoring of the dissolved oxygen concentration and the evolution of the hypoxic zone should be carried out in more reservoirs, and the relevant parameters of the formula should be further optimized to increase the applicability of the formula.

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