


## Application of the Streeter-Phelps model for evaluating the wastewater treatment plant effluent impact on the receiving river water quality

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### ABSTRACT

Water is considered one of the most important natural resources on Earth. Rivers are the main source of freshwater in many countries around the world. However, these rivers are exposed to pollution due to several factors, the most significant of which is the direct discharge of partially treated or untreated municipal wastewater into receiving rivers. This leads to an increase in the river carbonaceous biochemical oxygen demand (CBOD), which in turn causes a decrease in the dissolved oxygen (DO) levels. In this study, the Streeter-Phelps model was used to evaluate the impact of the Al-Muamirah Wastewater Treatment Plant on the water quality of the Hilla River in central region of Iraq and to monitor the variation in the CBOD and DO values over distance from the wastewater discharge point. The results indicated that very good accuracy was achieved by the developed model compared to field data. The highest CBOD value was at the wastewater effluent location, leading to a direct decrease in the DO levels. Subsequently, the river experienced a self-purification process that restored oxygen levels to its background value. However, the high CBOD values caused that oxygen concentrations at some distances have fallen below the permissible limit, with the lowest dissolved oxygen concentration of 4.7 mg/L recorded at 20 km from the wastewater discharge point. The results also showed that the highest acceptable 5-day CBOD value of wastewater effluent that can be discharged into the river water without lowering the dissolved oxygen level below the minimum permissible value, was 8.4 mg/L, making the minimum level location (at about 15 Km) closer to the effluent outfall. Furthermore, the river oxygen sag curve was very sensitive to the CBOD decay and oxygen reaeration coefficients variation. Accordingly, the study recommended continuous monitoring of CBOD levels in the treated wastewater effluent and implementing additional treatments, when necessary, to ensure the preservation of water quality and to prevent any adverse impacts on its environmental conditions.

**Keywords:** BOD, CBOD, dissolved oxygen, river water quality, Streeter-Phelps model, wastewater treatment plant, water quality modeling, effluent impact.

### INTRODUCTION

Rivers are one of the most significant freshwater ecosystems for securing human drinking and irrigation water needs, and they provide a wide variety of biodiversity. Nonetheless, in

recent decades, these ecosystems have increasingly been in danger by human-induced activities, particularly by the release of untreated or partially treated sewage. One such environmental problem is the pollution of water with organic matter, raising the carbonaceous biochemical

oxygen demand (CBOD) of the water and causing a reduction in the dissolved oxygen (DO) concentrations, which are critical for the survival of the living organisms. Fish and other species can experience possibly fatal conditions when DO falls below 4–5 mg/L (Lung, 2023). CBOD is an essential index indicating the degree of organic pollution in water, which reflects the amount of oxygen needed by microorganisms to decompose organic matter. It represents the presence of decomposable organic matter and how the breakdown of this organic matter in the water consumes dissolved oxygen (Yavuz et al., 2025). The inverse relationship of CBOD and DO is well established, such that the greater the organic load in a river, the lesser the dissolved oxygen content in the receiving water (Saeed et al., 2024). Hence, assessment of this balance is a key tool for river ecosystem restoration and water quality monitoring.

The relationship between organic matter decomposition and dissolved oxygen depletion has been of a major concern, and a number of models have been developed including the Streeter-Phelps model. This model represents the reduction of DO in a river when organic pollution is discharged, and therefore it considers the balance between two processes that work in opposite directions: The removal of DO via CBOD decomposition event and the reaeration process which is oxygen uptake from the atmosphere. It predicts the downstream distance of river recovery and the minimum oxygen concentration after the effluent point (Streeter and Phelps, 1925; Vigiak et al., 2019). Hence, this model is one of the essential modeling tools in the branch of environmental engineering for evaluating the self-purification capacity of a river and wastewater discharge in rivers.

Although different modeling approaches can be used with wide range of complexities (Al-Zubaidi and Wells, 2020; Wu and Yu; 2021), the Streeter-Phelps model has been implemented widely. The model has effectively been applied to many regions around the world as a means of river ecosystem behavior simulation. For instance, Yavuz et al. (2025) implemented an enhanced Streeter-Phelps model in four large rivers across Turkey using revised temperature, and current velocity. They found that increased water temperatures stimulate microorganisms, thereby speeding up organic matter degradation. At the same time, the high temperature decreases

river water oxygen solubility and dissolved oxygen concentrations. On the other hand, greater flow velocities improve reaeration and reduce the effluent concentration impact on the receiving water. Lung (2023) reviewed the BOD-DO modeling in the US and emphasized that the Streeter-Phelps model remains important for environmental policies, such as the Clean Water Act. Moreover, recently the model has developed to include dynamic simulations that can be used to challenge more complicated issues such as hypoxia in urban and agriculture sites. Vigiak et al. (2019), by using a model of CBOD distribution in freshwaters, found that more than 12% of streams in Europe were at a level of greater than 5 mg/L BOD threshold. The research underlined the importance of monitoring BOD-DO modeling as a tool to evaluate wastewater management practices and compliance with regulations. Also, Saeed et al. (2024) modeled the Danube River based on empirical information and Streeter-Phelps model. The results indicated the noticeable effect of organic load from urban wastewaters on the DO sag curve close to wastewater treatment plant outfalls. The study recognized that only biotechnological enhancement could safeguard the integrity of ecosystems downstream. In South Asia, Muyen et al. (2016) conducted similar studies on BOD and DO simulation in the Old Brahmaputra River in Bangladesh and indicated a very serious depletion of dissolved oxygen, impacting the river ecosystem. Their application of the Streeter-Phelps model accurately simulated the observed DO sag and they suggested that upgrading sewage disposal facilities could greatly enhance river water quality.

In the region of Iraq, Abbas (2021) also used Streeter-Phelps model to the Diyala River after the several wastewater outfalls in the Baiquba region. However, the lowest DO was found to be below the level of 4 mg/L, and CBOD was as high as 10 mg/L, indicating cumulative oxygen depletion effects with high organic load and low self-purification capacity. Similarly, Hama Salih et al., (2021) confirmed natural self-purification over a distance of 15 km along the Tanjero River in the Kurdistan Region by applying the model to determine DO and CBOD levels, where a gradual recovery occurs in DO and a gradual decreasing pattern occurs in the CBOD towards downstream. Obaid (2021) studied the seasonal dynamics of DO and BOD in the Hilla River. It was revealed that the river had higher levels of

CBOD in summer months, causing large DO deficits that harm aquatic lives. Also, the QUAL2K model was applied by Al-Dalimy and Al-Zubaidi (2023) to simulate the CBOD and DO concentration in the Hilla River. The field data were collected during low and high flow seasons. The CBOD values were between 0.745–3.075 mg/L and the DO levels were between 9.5–10.65 mg/L. The results indicated acceptable water quality levels, with minimal seasonal variations in DO due to the flow conditions.

The main objectives of this study were: (1) to apply the Streeter-Phelps model for the purpose of evaluating the impact of the Al-Muamirah Wastewater Treatment Plant, situated in the Hilla City (Iraq), on the Hilla River as a result of discharging treated wastewater into the river; (2) to evaluate the river water quality responses to the plant discharge based on DO and 5-day CBOD values. Hence, the changes in their values downstream the discharge point were explored whether the treated wastewater, discharged from the wastewater treatment plant, significantly affects the self-purification capacity of the river and whether the river water quality remains within the permissible limits; (3) to determine the maximum permissible 5-day CBOD concentration in the wastewater that can be discharged into the river water without falling the dissolved oxygen concentration below the minimum permissible limits; and (4) to highlight the CBOD decay as well as oxygen reaeration coefficients variation impact on the river oxygen sag curve

## MATERIALS AND METHODS

### The study area description

The Hilla River is a branch of the Euphrates River, located in Iraq (Figure 1), passing through the Hilla City. The length of the Hilla River is about 104 Km, and its flow rate ranges from about 200 m<sup>3</sup>/s to 45 (Abd Ulameer and Al-Sulttani, 2023). Downstream the discharge point, samples were taken at different distances along the river to measure DO and 5-day CBOD concentrations. Six locations including the outfall were considered for sampling (Figure 1). These field data measurements were used to build the Streeter-Phelps model in this application. The river serves as a key source of water for irrigation, drinking and industry in the city. Within the city, the treated effluent from the Al-Muamirah Wastewater Treatment Plant, about 6 km south of city, can be discharged into the river. This discharge can change the physical and chemical parameters of the river downstream the discharge point, such as biochemical oxygen demand (BOD) and DO, which are important water quality parameters. This plant was constructed in 1977 with a design capacity of 12,000 m<sup>3</sup>/day (Alanbari et al., 2015), and it practices conventional activated sludge processes for the municipal sewage treatment. Hence, the plant effluent has residual organic material and nutrients that will affect the receiving river ecological balance (Abbas and Hadi, 2023). In addition, the river is sensitive to point and non-point sources of pollution along its length due to its low flow rate, especially during the dry seasons, affecting its capability for self-purification (Obaid, 2021).

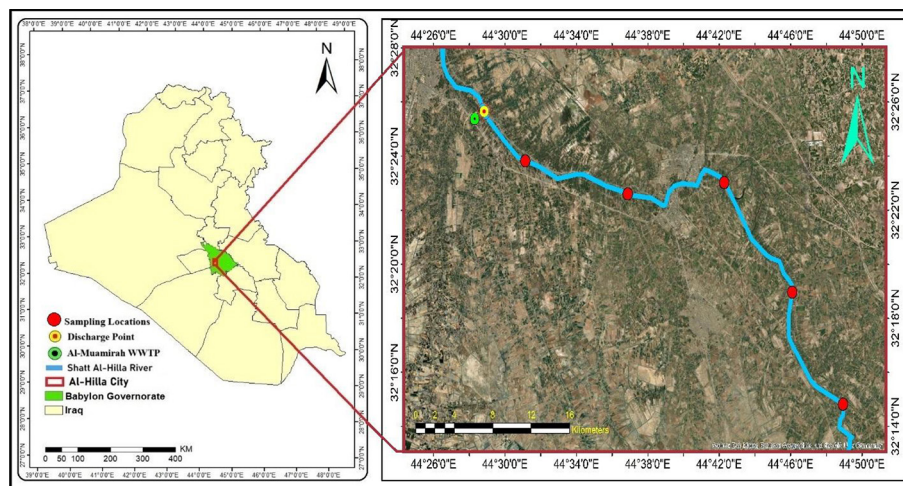


Figure 1. The Al-Muamirah wastewater treatment plant, receiving river, and sampling stations location

### Description of the Streeter-Phelps model and field data measurements

In order to provide an analytical framework for exploring the decomposition of organic matter and oxygen deficit downstream the discharge point along the receiving river, the Streeter-Phelps equations were used to model a river reach with a CBOD single point-source. Accordingly, it was assumed that the reach is under steady state conditions with constant hydrology and geometry, and the reach flow is following the plug-flow river characteristics. The Streeter-Phelps model can be described by using Equations 1 and 2 (Streeter and Phelps, 1925; Fan et al., 2012):

$$L = L_0 e^{-\frac{kd \cdot x}{u}} \quad (1)$$

$$D = D_0 e^{-\frac{ka \cdot x}{u}} + \frac{kd \cdot L_0}{ka - kd} \times (e^{-\frac{kd \cdot x}{u}} - e^{-\frac{ka \cdot x}{u}}) \quad (2)$$

where:  $L$  is the oxidizable organic matter concentration expressed as  $O_2$  (mgO/L) at any distance along the river reach  $x$  (m),  $L_0$  the ultimate CBOD concentration (mixed concentration) at the point source outfall expressed as  $O_2$  (mgO/L) and calculated by Equation 3 (Chapra, 2008) based on 5-day CBOD concentration ( $CBOD_5$  in mgO/L),  $D$  is the dissolved oxygen deficit (mg/L) at any distance along the river reach  $x$  (m),  $D_0$  is the initial oxygen deficit at the point source outfall (mg/L) and calculated by Equation 4 and 5 (de Moura et al., 2020),  $DO_s$  is the saturation concentration of dissolved oxygen in the river reach (mg/L) at water temperature  $T$  (°C),  $DO_0$  is the mixed dissolved oxygen concentration at the point source outfall (mg/L),  $u$  is the river reach average flow velocity (m/s),  $ka$  is the oxygen reaeration coefficient at any temperature (1/day), and  $kd$  is the CBOD decay coefficient at any temperature (1/day).

$$L_0 = \frac{CBOD_5}{(1 - e^{-5kd})} \quad (3)$$

**Table 1.** The plant effluent and receiving water characteristics, measured at the study area location on March 2<sup>nd</sup>, 2025

Value	Plant effluent	River reach
Flow (m <sup>3</sup> /s)	0.4398	73
CBOD <sub>5</sub> (mgO/L)	10	2
DO (mg/L)	5.2	5.62
T (°C)	29.7	29.7

$$D_0 = DO_s - DO_0 \quad (4)$$

$$DO_s = 14.6 \cdot e^{-(0.027767 - 0.00027 \times T + 0.000002 T^2)} \quad (5)$$

To close the problem, the plant effluent and the receiving water characteristics that are required to apply the Streeter-Phelps model are listed in Tables 1 and 2. In addition,  $ka$  and  $kd$  are usually measured at 20 °C. Therefore, they can be calculated at any temperature based on 20 °C using the Arrhenius equation specifications (Chapra, 2008; Fan et al., 2012) as shown in Equation 6, where  $\theta$  is 1.047 for CBOD and 1.024 for DO, and  $k$  represents any value of  $ka$  and  $kd$ . Table 3 displays the final values of  $ka$  and  $kd$  that were used to run the final model after the calibration and validation process.

Furthermore, using a river average flow rate ( $Q$ ) of 73 m<sup>3</sup>/s passing through a cross-sectional area ( $A$ ) of 60 m wide and 5 m depth (The Water Resources Directorate, Hilla City, Iraq), Equation 7 was used to calculate the river average flow velocity ( $u$ ).

For the worst-case scenario, it was assumed that no mixing (zero dilution) occurs between the wastewater discharge into the river and the river water itself at the discharge point. The no mixing assumption prioritizes the near-field aquatic system to account for the maximum oxygen deficit without considering the significant river assimilation capacity. Hence, the minimal mixing is a pollutant conservative approach compared to the complete mixing approach (U.S. EPA, 1991).

$$k = k_{(20)} \theta^{(T-20)} \quad (6)$$

$$u = Q/A \quad (7)$$

**Table 2.** The DO and L data measurements below the discharge point

River distance (km)	05	15	25	35	45
DO (mg/L)	5.3	4.5	5.5	6	7.5
L (mg/L)	10	9	5.5	3	0.8

**Table 3.** Values of final  $k_a$  and  $k_d$  used to run the model in this study

Value (1/day)	20 °C	29.7 °C
$k_a$	0.8	1.0
$k_d$	0.2	0.3

### The modeling conceptual framework

Figure 2 outlines the general conceptual framework used to run the Streeter-Phelps model in this application. Equation 3 to 7 are used to calculate the parameters of Equations 1 and 2 based on the information in Tables 1 to 2. The modeling framework starts by calculating  $L_0$  and  $D_0$  at the point source outfall, which is the discharge point of the plant effluent at the receiving water, from Equations 3 and 4, respectively. Then,  $L$  is calculated from Equation 1 followed by  $D$  from Equation 2. In addition, the dissolved oxygen concentration (DO, mg/L) at any distance downstream the discharge outfall was determined as shown in Equation 8 (Chapra, 2008; de Moura et al., 2020). During the model calibration, the mean

absolute error (MAE) metric (Robeson and Willmott, 2023), Equation 9, was utilized to evaluate and validate the model predictions of Equations 1 and 8 based on  $N$  comparisons related to the field data measurements of DO and  $L$ .

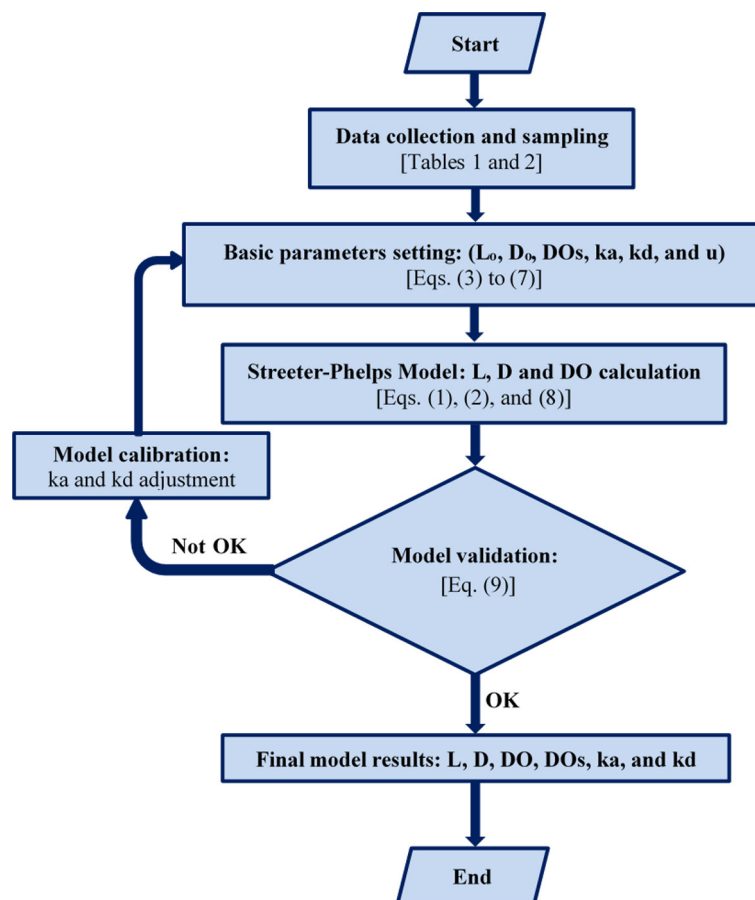
$$DO = DO_s - D \tag{8}$$

$$MAE = \frac{\sum_{i=1}^N |(Model\ prediction\ value)_i - (Field\ data\ measurement\ value)_i|}{N} \tag{9}$$

## RESULTS AND DISCUSSION

### The model computations of oxygen deficit and dissolved oxygen

The plant effluent impact on the water quality of receiving river was explored using the Streeter-Phelps model. Equations 3 to 7 were employed to determine the basic parameter values required to run the final model of Equation 1, 2, and 8 as depicted in Table 4. As a result, the concentrations of the oxygen deficit ( $D$ ) and dissolved oxygen (DO) along the river reach,



**Figure 2.** The Streeter-Phelps model conceptual framework

**Table 4.** The Streeter-Phelps model core parameters

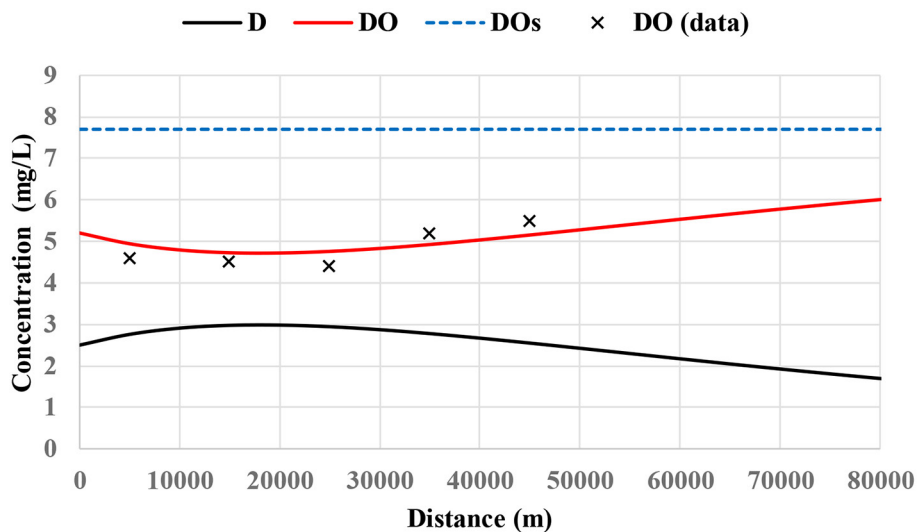
Parameter	Value	Equation
$L_o$ (mg/L)	12.87	Equation 3
$D_o$ (mg/L)	2.5	Equation 4
DOs (mg/L)	7.7	Equation 5
$k_a$ (1/day)	1.0	Equation 6
$k_d$ (1/day)	0.3	Equation 6
$u$ (m/day)	21,024	Equation 7

starting from the wastewater discharge point and extending over distance, were determined and presented as shown in Figure 3. Hence, very good agreement was achieved by the DO developed model compared to the field data with low MAE of 0.31 mg/L.

Figure 3 illustrates the variation in concentrations of oxygen deficit and dissolved oxygen along the river from the point of discharge of the treated wastewater. The deficit value starts at 2.5 mg/L at the discharge point ( $x=0$  m) and gradually increases until it reaches a peak of 2.98 mg/L at a distance of about 20 km from the discharge point, which represents the point where the difference between the oxygen consumption rate and reaeration rate is at its maximum value. Thereafter, the system balance shifts in favor of oxygen recovery, as the curve gradually decreases toward near zero upon reaching the end of the reach. On the other hand, the dissolved oxygen curve (sag curve) starts with a value of (5.2 mg/L) at the discharge point, and it then declines to a minimum value of approximately 4.7 mg/L at a distance of 20 km,

followed by a gradual recovery, until it exceeds 6.0 mg/L near the end of the reach. This pattern is due to the rapid decomposition of organic matter at the discharge point, leading to increased oxygen consumption and deficits upstream. Meanwhile, reaeration processes gradually restore oxygen over time and distance, contributing to the return of dissolved oxygen concentrations to acceptable levels and a decrease in deficit values.

The behavior of D and DO results is consistent with the classical curve described by the Streeter-Phelps model, where a minimum decrease in DO occurs at a certain distance from the discharge point, followed by a recovery path extending downstream. The location and amplitude of the peak depend on the decomposition and reaeration coefficients, as well as the hydrodynamic characteristics of the river, such as flow velocity, cross-section depth and width, as well as temperature (Lung, 2023). Nuruzzaman et al. (2018) reported a similar pattern in their study of a Bangladeshi River using the Streeter-Phelps model, where the DO values decreased immediately after the discharge point and gradually recovered due to re-oxygenation. Hama Salih et al. (2021) confirmed the same behavior in their study on the Tanjero River in the Kurdistan Region, where a significant decrease in DO was observed after the discharge location, followed by a gradual increase due to river self-purification. Similarly, Kulkarni (2017) demonstrated that the recovery of the original oxygen concentration took approximately 100 km beyond the discharge point, attributing the length of the peak distance to the local characteristics of



**Figure 3.** Variation in oxygen deficit (D) and dissolved oxygen concentration (DO) with distance (x) along the river reach; MAE=0.31 mg/L

the river, as increased flow velocity or shallower sections enhance re-oxygenation rates. From an ecological perspective, this pattern suggests that the pollutant effect extends a significant distance beyond the discharge point before the river’s natural processes can gradually restore ecological balance (Yavuz, 2025). The low DO levels also lead to a decline in aquatic biodiversity and abundance. Reduced species richness and populations have been documented in oxygen-deficient environments, reflecting a negative environmental impact on the aquatic food chain. Similarly, aquatic plants may also be affected. Photosynthesis and growth rates decrease due to the lack of oxygen required for their metabolic processes. This impairs the endogenous oxygen production within the water body and exacerbates the DO deficiency (Nodo et al., 2023). Thus, such water ecosystem needs to be monitored regularly by decision-makers.

### The model computations of oxidizable organic matter

Figure 4 shows an exponential decreasing behavior of oxidizable organic matter concentrations ( $L$ ) along the river distance ( $x$ ), starting from the treated wastewater discharge point. Also, low MAE of 0.94 mg/L was the model accuracy compared to field data. The values start at (12.87 mg/L) at the discharge point ( $x=0$ ), then collapse rapidly over distance, reaching approximately (4.1 mg/L) at the end of the reach, and continue to decline toward zero eventually. This pattern matches the basic assumption of the Streeter-Phelps model, which

assumes that the organic matter concentration decreases with time and distance due to microbial activity and biodegradation of first-order decay rate, leading to a rapid decline in its concentration in the sections close to the discharge point, followed by a slower rate of decline when less biodegradable materials remain (Fan and Wang, 2008; Li et al., 2012). These results are similar to those obtained by Yoon et al. (2008) in their study on the Nakdong River system in Korea, where they confirmed that the degradation rates varied depending on local conditions, but remained exponential in general. Furthermore, regional studies in Iraq showed a similar trend of decreasing organic matter concentrations after discharge with distance, although the rates and absolute values varied depending on the load intensity and stream characteristics (Hama Salih et al., 2021).

The high CBOD values increase respiratory stress on aquatic biological communities. The elevated levels of organic compounds worsen oxygen deficiency as well as cause severe stress or death in many sensitive fish and aquatic lives. Furthermore, high CBOD is often accompanied by rapid algal growth (eutrophication). The more algae growth requires more oxygen for decomposition after the algae dies, impairing DO deficiency and promoting the formation of deadly zones that negatively impact the river water ecosystem (Bashir et al., 2020). Consequently, this decay simulation (Figure 4) is linked to the DO sag curve (Figure 3) and can be implemented for making decisions about the river remediation process to balance the ambient water quality.

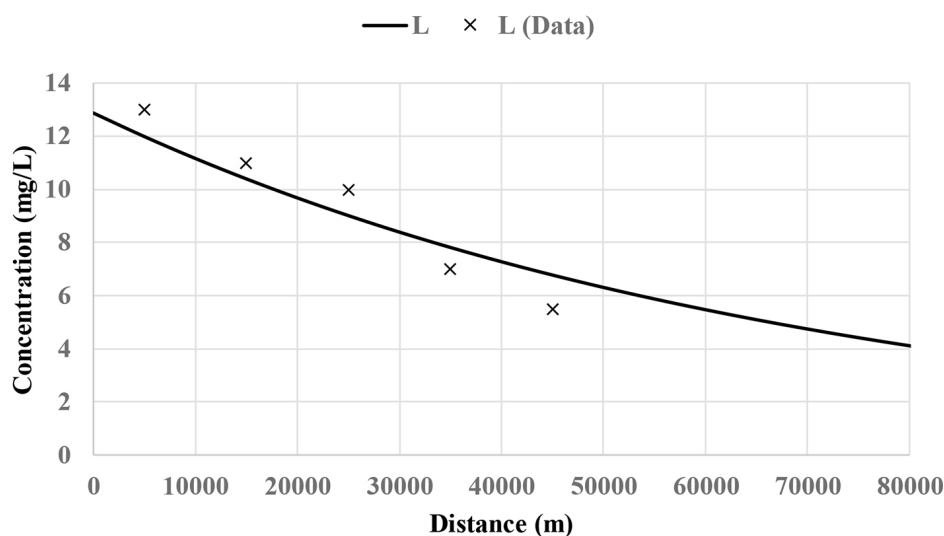


Figure 4. Variation in oxidizable organic matter concentration ( $L$ ) with distance ( $x$ ) along the river reach; MAE=0.94 mg/L

### The river self-purification capacity

On the basis of the above, it is clear that the Hilla River has a clear capacity to self-purify and restore dissolved oxygen levels to environmentally acceptable limits. However, the results indicate that the CBOD<sub>5</sub> value in the treated wastewater discharged into the river led to a decrease in dissolved oxygen concentration to levels as low as 4.7 mg/L within 20 km of the discharge point. This value falls slightly below the river minimum permissible limit, which is 5 mg/L (Abdul-Aziz and Gebreslase, 2023). To determine the maximum permissible CBOD<sub>5</sub> concentration in the wastewater that can be discharged into the river in which the dissolved oxygen concentration does not fall below the minimum permissible limits, several experiments were conducted using the Streeter-Phelps model, fixing all parameters in the model and testing different CBOD<sub>5</sub> values to determine the optimal permissible concentration. The results showed that the CBOD<sub>5</sub> value of 8.4 mg/L, which when converted to the ultimate CBOD (i.e., L<sub>0</sub>) value using Equation 3 is equivalent to 10.81 mg/L, represents the highest permissible CBOD<sub>5</sub> concentration in treated wastewater to be spilled continuously into the river. This value ensures that the dissolved oxygen concentration in the river water remains at the minimum permissible limit ( $\geq 5$  mg/L). The model simulation results are depicted in Figures 5 and 6.

Figure 5 illustrates the change in dissolved DO and D concentrations along the river after applying the imposed CBOD<sub>5</sub> value of 8.4 mg/L. The curve shows that the general behavior of the change is similar to that in the former case, with the deficit gradually increasing after the discharge point and then gradually decreasing with increasing distance due to the effectiveness of river self-purification processes. However, the key difference in this case is that the river DO reached its lowest value, approximately 5.005 mg/L, at a distance of approximately 15 km from the discharge point, a value that remains within acceptable environmental limits. This demonstrates that reducing the organic load discharged into the river to this CBOD<sub>5</sub> value ensures that dissolved oxygen levels remain within safe limits, ensuring the continuity of biological decomposition in the river system. Accordingly, Figure 6 clarifies the change in the CBOD<sub>5</sub> values along the river path. The curve shows that the general behavior of the decrease in L values with distance is similar to that observed in Figure 4, but the main difference is the change in the initial L value, which is approximately 10.8 mg/L instead of 12.7 mg/L in the previous case. This change in the initial value reflects the effect of reducing the organic load on mitigating the sharp decline in dissolved oxygen concentration, which contributes to enhancing the ability of the river to maintain a better ecological balance.

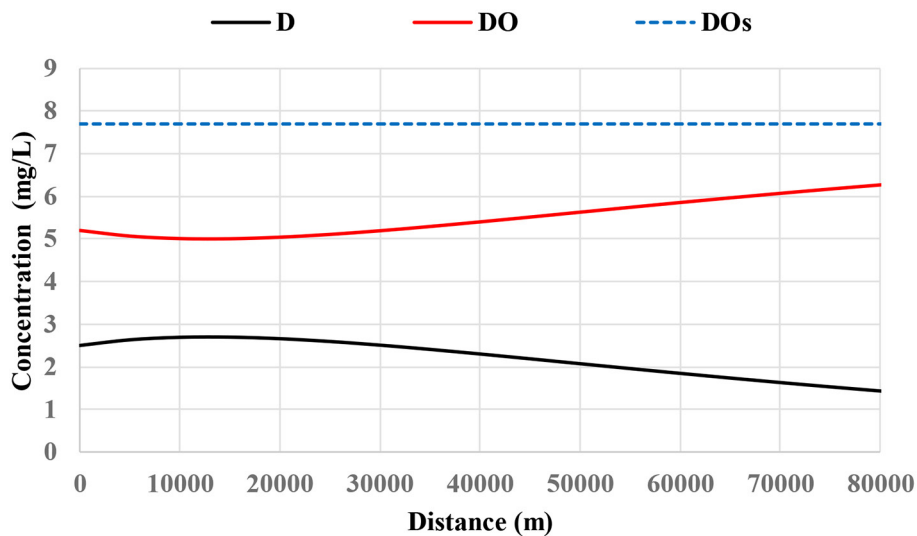
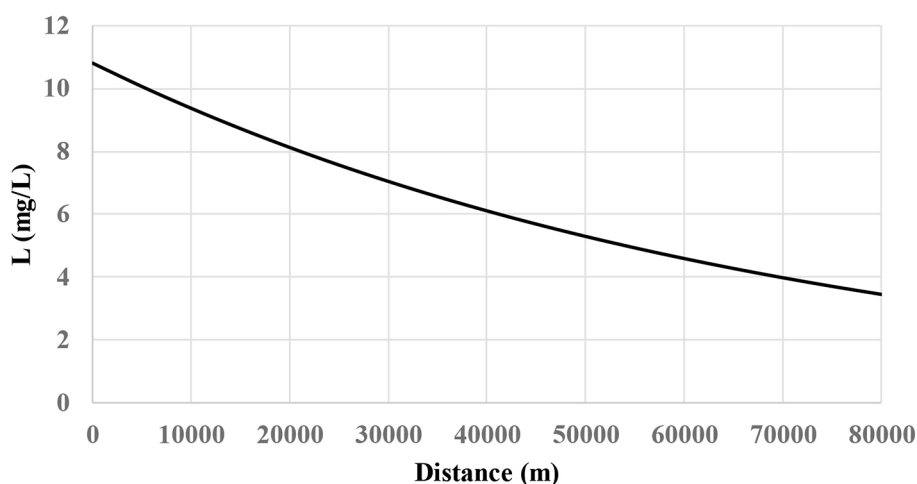


Figure 5. Variation in deficit oxygen (D) and dissolved oxygen concentration (DO) with distance (x) along the river reach in which the river minimum DO is  $\geq 5$  mg/L



**Figure 6.** Variation in oxidizable organic matter concentration ( $L$ ) with distance ( $x$ ) along the river reach in which the river minimum DO is  $\geq 5\text{mg/L}$

### Model sensitivity to change the CBOD decay and oxygen reaeration coefficients

To understand the effect of changes in the CBOD decay coefficient ( $k_d$ ) on the behavior and distribution of dissolved oxygen along the river, several values of  $k_d$  were tested [ $k_d=0.3, 0.4, 0.5,$  and  $0.9$  (1/day)] with fixed oxygen reaeration coefficient ( $k_a$ ) of 1 (1/day), keeping all other parameters the same. These values were used in the Streeter-Phelps model (Figure 7). The model predictions of DO using  $k_d=0.3$  (1/day) and  $k_a=1.0$  (1/day) resulted in the best distribution of dissolved oxygen compared to field data as depicted in Figure 3, with the lowest dissolved oxygen value of approximately 4.7 mg/L occurring at a distance of about 20 km from the discharge point. As  $k_d$  values increase, dissolved oxygen levels gradually decrease and its minimum value becomes closer to the discharge point. As a result, the minimum DO level reached a value of 2.3 mg/L at a distance of 17.5 km from the discharge point when  $k_d$  increased to 0.9 (1/day). Hence, the high  $k_d$  value leads to a greater rate of decline in dissolved oxygen levels along the river. This behavior is scientifically expected since the increase in  $k_d$  reflects a higher rate of organic matter decomposition and leads to increase dissolved oxygen consumption (Chapra, 2008).

On the other hand, the oxygen reaeration coefficient ( $k_a$ ) variation effect on the dissolved oxygen sag curve was explored by fixing the value of the CBOD decay coefficient ( $k_d$ ) at 0.3 (1/days) and changing the oxygen

reaeration coefficient ( $k_a$ ) using several values [1.0, 1.1, 1.2, and 1.3 1/day] as shown in Figure 8. A gradual improvement in dissolved oxygen levels was observed with increasing the  $k_a$  values compared to the validated model [ $k_d=0.3$  (1/day) and  $k_a=1.0$  (1/day)]. The lowest value of the reaeration coefficient ( $k_a = 1.0$ ) resulted in the greatest decrease in the dissolved oxygen levels along the river. Results showed that the best dissolved oxygen distribution was recorded using a  $k_a$  value of 1.3 (1/day) with minimum dissolved oxygen concentration of approximately 5.1 mg/L located at about 10 km from the discharge point. Accordingly, the high  $k_a$  values reduce the severity of the decline in dissolved oxygen levels, while the low values are associated with a greater drop in DO values. This behavior is reasonable because a higher oxygen reaeration rate indicates that the river has more capability of compensating the consumed oxygen result from the decomposition of organic matter (Nodo et al., 2023).

Additionally, it is worth noting that  $k_d$  and  $k_a$  are both functions of temperature as displayed in Equation 6. In natural waters, the reaction rates become higher as water temperature increases (Chapra, 2008). This temperature dependency causes changes in both of the CBOD and DO concentration along the river. As temperature has a significant influence on both coefficients, the seasonal variations of CBOD and DO in the river, which lead to temperature differences, are already reflected in this sensitivity analysis. The presence of organic matter in the river is different during the year seasons. For instance, Al-Dalimy

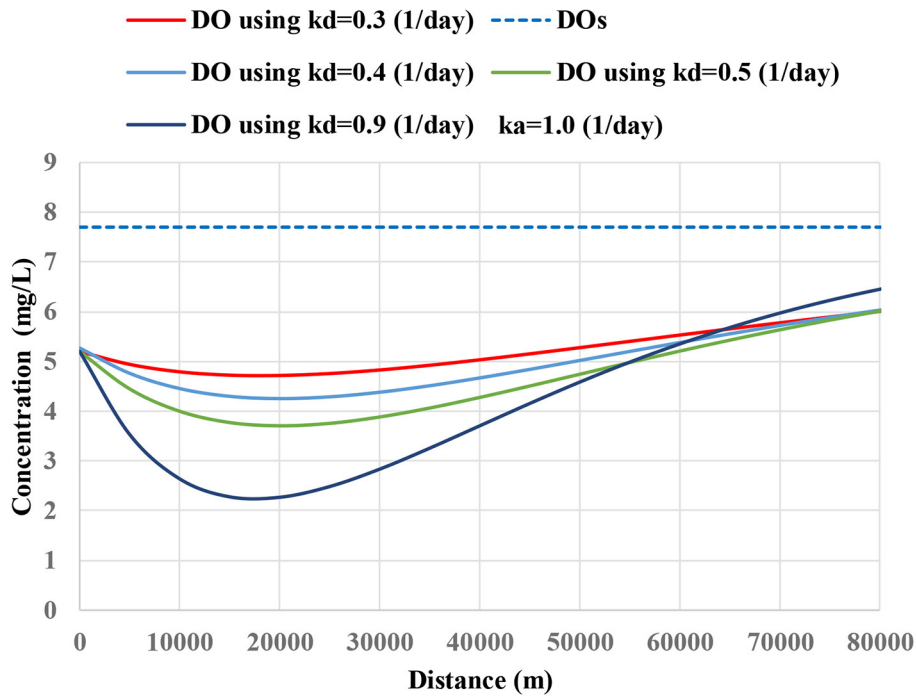


Figure 7. Effect of kd coefficient value on the dissolved oxygen concentration (DO) along the river reach

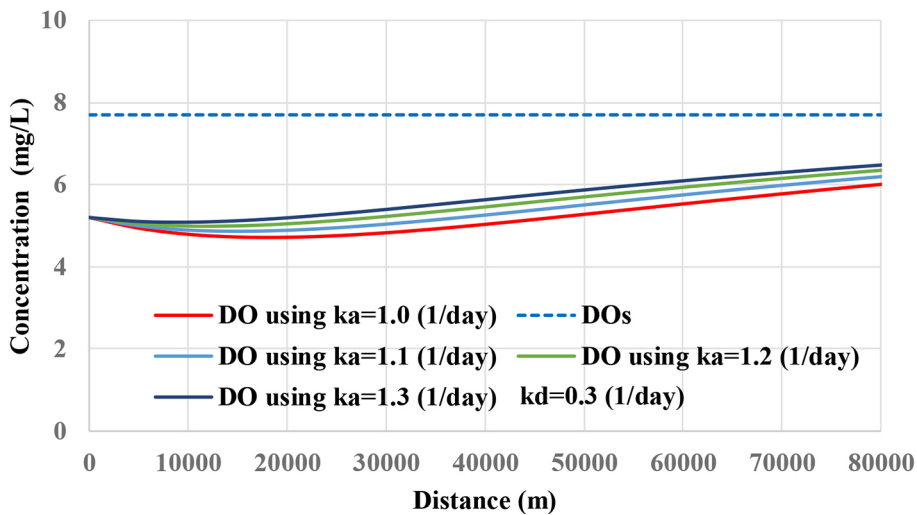


Figure 8. Effect of ka coefficient value on the dissolved oxygen concentration (DO) along the river reach

and Al-Zubaidi (2023) highlighted the seasonal change of ultimate CBOD before the discharge point during the low and high flow conditions by using the QUAL2k model. The range of ultimate CBOD at 23 °C during the summer season (low flow conditions) was between 1.425 to 3.075 mg/L, while at 14 °C during the winter season (high flow conditions) it was between 0.745 to 2.0 mg/L. Accordingly, this impacts the DO levels inversely depending on water temperature variation in which high CBOD amount is associated with

low DO levels due to the high organic matter decay rate.

Finally, it can be concluded that the Hilla River has a good ability to self-purify and restore dissolved oxygen concentrations within permissible limits. However, high CBOD values may cause dissolved oxygen concentrations to fall below the standard permissible levels. Therefore, it is recommended to conduct additional wastewater treatment before discharging it into the river to ensure minimal negative environmental impacts on the

river system such as using adsorption or electro-coagulation (Ahmed et al., 2020; Samaka et al., 2022), advanced wastewater treatment methods. The Streeter-Phelps model has also proven its effectiveness as a reliable scientific tool for assessing rivers affected by treatment plant point discharges, due to its ability to predict changes in dissolved oxygen and organic matter over long distances.

## CONCLUSIONS

In this study, the Streeter-Phelps model was used to assess the impact of the Al-Muamirah Wastewater Treatment Plant effluent on the water quality of the receiving river by monitoring changes in dissolved DO and carbonaceous biochemical oxygen demand (CBOD) along the river after the discharge point. The main modeling findings revealed that: (1) The developed model predicted the DO and CBOD distribution after the discharge point efficiently based on field data measurements and mean absolute error (MAE) metric. Hence, good agreement was accomplished between data and model with very low MAE; (2) discharging treated wastewater directly into the Hilla River led to a decrease in the river dissolved oxygen concentration below the permissible limit at a distance of about 20 km from the discharge point. However, the river demonstrated a good capacity for self-purification, gradually restoring oxygen levels toward the river downstream. Oxidizable organic matter (L) also showed an exponential decrease with distance along the river reach. This confirms the effectiveness of biodegradation processes within the river; (3) reducing the effluent 5-day CBOD concentration to 8.4 mg/L would enable the maintenance of dissolved oxygen concentration above the minimum acceptable limit at a distance closer to the discharge point. Therefore, it is crucial to adhere to the CBOD permissible limit of wastewater treatment plant effluent before discharging it into the river to prevent the dissolved oxygen concentration from falling below acceptable levels; and (4) the CBOD decay and oxygen reaeration coefficients play a major role in the dissolved oxygen concentration distribution after the discharge location downstream the river. The higher the CBOD decay coefficient, the higher drop in the dissolved oxygen concentrations is, and the closer minimum dissolved oxygen level location is. In contrast, higher oxygen reaeration coefficients improve the river water quality.

## REFERENCES

1. Abbas, M. M. (2021). Dissolved oxygen sag curve for Diyala River at Baquba City. *IOP Conference Series: Materials Science and Engineering*, 1076(1), 012117. <https://doi.org/10.1088/1757-899X/1076/1/012117>
2. Abbas, N. A., Hadi, N. S. (2023). Performance assessment of Al Muamirah wastewater treatment plant “using statistical analysis” at Hilla city, Iraq. *Journal of University of Babylon for Engineering Sciences*, 68–78.
3. AbdUlameer, A. H., Al-Sultani, A. O. (2023). Evaluation of the minimum instream flow: A case study of Shatt-Al Hillah river in Babylon governorate. *International Journal of Design & Nature and Ecodynamics*, 18(2), 485–491. <https://doi.org/10.18280/ijdne.180229>
4. Abdul-Aziz, O. I., Gebreslase, A. K. (2023). Emergent scaling of dissolved oxygen (DO) in freshwater streams across contiguous USA. *Water Resources Research*, 59(2), e2022WR032114. <https://doi.org/10.1029/2022WR032114>
5. Ahmed, S. et al. (2020). Improvement of organic matter removal in water produced of oilfields using low cost Moringa peels as a new green environmental adsorbent. *Global NEST Journal*, 22(2). <https://doi.org/10.30955/gnj.003098>
6. Alanbari, M., Alazzawi, H., Al-Ansari, N., Knutson, S. (2015). Environmental assessment of Al-Hilla City wastewater treatment plants. *Journal of Civil Engineering and Architecture*, 9(6), 749–755. <https://doi.org/10.17265/1934-7359/2015.06.013>
7. A. M. Al-Zubaidi, Hussein, Wells, S. A. (2020). Analytical and field verification of a 3D hydrodynamic and water quality numerical scheme based on the 2D formulation in CE-QUAL-W2. *Journal of Hydraulic Research*, 58(1). <https://doi.org/10.1080/00221686.2018.1499051>
8. Al-Dalimy, S. Z., Al-Zubaidi, H. A. M. (2023). One-dimensional model predictions of carbonaceous biological oxygen demand and dissolved oxygen for Hilla river water quality, Iraq. *Ecological Engineering and Environmental Technology*, 24(7). <https://doi.org/10.12912/27197050/170100>
9. Bashir, I., Lone, F. A., Bhat, R. A., Mir, S. A., Dar, Z. A., Dar, S. A. (2020). *Concerns and threats of contamination on aquatic ecosystems*. In Bioremediation and biotechnology: sustainable approaches to pollution degradation (pp. 1–26). Cham: Springer International Publishing. [https://doi.org/10.1007/978-3-030-35691-0\\_1](https://doi.org/10.1007/978-3-030-35691-0_1)
10. Chapra, S. C. (2008). *Surface Water-Quality Modeling*. Inc.: Long Grove, IL, USA.
11. de Moura, L. S., Lopes, R. B., Ribeiro, J. S., Fernandes, G. D. S. T., Almeida, R. M., de Melo, S. G. (2020). Mathematical modeling in the Urumari micro-watershed using Streeter-Phelps mathematical models and the enhanced Do-Bod

- model. *Revista Ibero-Americana de Ciências Ambientais*, 11(6), 332–345. <https://doi.org/10.6008/CBPC2179-6858.2020.006.0027>
12. Fan, C., Wang, W. S. (2008). Influence of biological oxygen demand degradation patterns on water-quality modeling for rivers running through urban areas. *Annals of the New York Academy of Sciences*, 1140(1), 78–85. <https://doi.org/10.1196/annals.1454.031>
  13. Fan, C., Wang, W. S., Liu, K. F. R., Yang, T. M. (2012). Sensitivity analysis and water quality modeling of a tidal river using a modified Streeter-Phelps equation with HEC-RAS-calculated hydraulic characteristics. *Environmental Modeling & Assessment*, 17(6), 639–651. <https://doi.org/10.1007/s10666-012-9316-4>
  14. Hama Salih, N. Y., Mohammad, A. O., Mohammed, F. O. (2021). Study on the self-purification of Tanjaro River. *Tikrit Journal for Agricultural Sciences*, 21(4), 54–62. <https://doi.org/10.25130/tjas.21.4.7>
  15. Kulkarni, S. J. (2017). Analysis of dissolved oxygen deficit in a flowing stream. *Int. J. of Thermal & Environmental Engineering*, 15(2), 97–102. <https://doi.org/10.5383/ijtee.15.02.002>
  16. Li, J., Liu, H., Li, Y., Mei, K., Dahlgren, R., Zhang, M. (2012). Monitoring and modeling dissolved oxygen dynamics through continuous longitudinal sampling: a case study in Wen-Rui Tang River, Wenzhou, China. *Hydrological Processes*, 27(24), 3502–3510. <https://doi.org/10.1002/hyp.9459>
  17. Lung, W.S. (2023). Progression of river BOD/DO modeling for water quality management. *Water Environment Research*, 95(4), e10864. <https://doi.org/10.1002/wer.10864>
  18. Muyen, Z., Rashedujjaman, M., Rahman, M. (2016). Assessment of water quality index: a case study in Old Brahmaputra River, Bangladesh. *Progressive Agriculture*, 27(3), 355–361. <https://doi.org/10.3329/pa.v27i3.30832>
  19. Nodo, P., Childs, A. R., Pattrick, P., Lemley, D. A., James, N. C. (2023). Response of demersal fishes to low dissolved oxygen events in two eutrophic estuaries. *Estuarine, Coastal and Shelf Science*, 293, 108514. <https://doi.org/10.1016/j.ecss.2023.108514>
  20. Nuruzzaman, M., Al-Mamun, A., Salleh, M. N. B. (2018). Experimenting biochemical oxygen demand decay rates of Malaysian river water in a laboratory flume. *Environmental Engineering Research*, 23(1), 99–106. <https://doi.org/10.4491/eer.2017.048>
  21. Obaid, Z. H. (2021). Assessing the water quality at Shatt al-Hillah, Iraq, using the biological oxygen requirement BODs. *Natural Volatiles & Essential Oils*, 8(4), 11397–11402.
  22. Robeson, S. M., Willmott, C. J. (2023). Decomposition of the mean absolute error (MAE) into systematic and unsystematic components. *PLoS ONE*, 18(2 February). <https://doi.org/10.1371/journal.pone.0279774>
  23. Saeed, O., Székács, A., Jordán, G., Mörtl, M., Abukhadra, M. R., El-Sherbeeney, A. M., Szűcs, P., Eid, M. H. (2024). Assessing surface water quality in Hungary's Danube basin using geochemical modeling and Monte Carlo simulation. *Scientific Reports*, 14, 18639. <https://doi.org/10.1038/s41598-024-69312-8>
  24. Samaka, I.S., Naje, A.S., A. M. Al-Zubaidi, Hussein (2022). Treatment of saline water using electrocoagulation process with monopolar connection of electrodes. *Nature Environment and Pollution Technology*, 21(2), 795–802. <https://doi.org/10.46488/NEPT.2022.v21i02.044>
  25. Streeter, H. W., Phelps, E. B. (1925). A study of the pollution and natural purification of the Ohio River (*U.S. Public Health Service Bulletin No. 146*).
  26. U.S. EPA. (1991). *Technical Support document for water quality-based toxics control*. Office of Water, Washington, DC. EPA/505/2-90-001
  27. Vigiak, O., Grizzetti, B., Udias-Moinelo, A., Zanni, M., Dorati, C., Bouraoui, F., Pistocchi, A. (2019). Predicting biochemical oxygen demand in European freshwater bodies. *Science of the Total Environment*, 666, 1089–1105. <https://doi.org/10.1016/j.scitotenv.2019.02.252>
  28. Yavuz, V. S. (2025). Impact of temperature and flow rate on oxygen dynamics and water quality in major Turkish rivers. *Scientific Reports*, 15, 22830. <https://doi.org/10.1038/s41598-025-06433-8>
  29. Yoon, Y. S., Yu, J. J., Shin, C. K. (2008). A study of carbonaceous BOD decay rates for the Nakong river water system. *Journal of Environmental Science International*, 17(8), 833–840. <https://doi.org/10.5322/JES.2008.17.8.833>
  30. Wu, J., Yu, X. (2021). Numerical investigation of dissolved oxygen transportation through a coupled SWE and Streeter-Phelps model. *Mathematical Problems in Engineering*, 2021(1), 6663696. <https://doi.org/10.1155/2021/6663696>