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Assessment of Thermal Pollution at Selected Stretch of Tigris River in Baghdad by Field Observations and Numerical Simulations

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ABSTRACT

Although many technological improvements are occurring in power production worldwide, power plants in third world countries are still using old technologies that are causing thermal pollution to the water bodies. Power facilities that dump hot water into water bodies are damaging aquatic life. In the study, the impact of the Al Dora thermal power plant on a nearby stretch of Tigris River in Baghdad city was assessed by measuring the temperature of the disposed of hot water in various cross-sections of the selected stretch of Tigris River, including measuring the thermal mixing length. The measurements were conducted in winter, spring, and summer. For field measurements, it was found that the impact of recovery distances extended to 1500, 1810, and 2450 m in winter, spring, and summer seasons, respectively. Also, the impact of the thermal pollution was simulated using the CFD COMSOL model. When these values were compared with the predicted values, the measured values were found smaller than the predicted by using the heat equation for temperature recovery distances. Also, the simulation included the impact of reducing the velocity of the disposed of hot water on the temperature distribution and mixing length in the studied stretch of Tigris River. Simulation results show that when the velocity of the disposed of hot water was reduced from 1.6 to 0.5 m/s, the thermal mixing in the Tigris River improved. The estimation of dissolved oxygen concentrations was found to range from 6.9 to 10.7 mg/l, which is higher than the critical concentration of 5 mg/l, which is required for aquatic life.

Keywords: Thermal pollution, Tigris River, Field measurement, Simulation.

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تقييم التلوث الحراري في مقاطع مختارة لنهر دجلة في بغداد من خلال الملاحظات الميدانية والمحاكاة العددية

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الخلاصة

على الرغم من وجود العديد من التحسينات التكنولوجية في عملية إنتاج الطاقة في جميع أنحاء العالم ، إلا أن محطات الطاقة في دول العالم الثالث لا تزال تستخدم التقنيات القديمة التي تسبب التلوث الحراري للمسطحات المائية. تؤدي هذه المحطات الكهربائية التي تصب المياه الحارة في الأنهار الى أضرار بالحياة المائية. في هذه الدراسة ، تم تقييم تأثير محطة الدورة الحرارية لتوليد الكهرباء على نهر دجلة في مدينة بغداد من خلال قياس درجة حرارة الماء الساخن المصرف منه خلال مقاطع النهر بما في ذلك قياس مسافة الخلط الحراري. أجريت القياسات الحقلية في الشتاء والربيع والصيف ووجد أن تأثير مسافات الاسترداد للحرارة امتدت إلى 1500 و 1810 و 2450 م في مواسم الشتاء والربيع والصيف على التوالي. وتم عمل محاكاة تأثير التلوث الحراري باستخدام نموذج CFD COMSOL. عندما تمت مقارنة هذه القيم مع القيم المتوقعة، القيم المقاسة أصغر من المتوقع باستخدام معادلة تغير الحرارة لمسافات استعادة درجة الحرارة. كما تضمنت المحاكاة تأثير تقليل سرعة تصريف الماء الساخن على توزيع درجة الحرارة ومسافة الخلط في النهر. عندما انخفضت سرعة تصريف الماء الساخن من 1.6 إلى 0.5 م/ث ، تحسن المزج الحراري في نهر دجلة. وجد أن تقدير الأكسجين المذاب يتراوح من 6.9 إلى 10.7 ملغم/لتر وهي أعلى من التركيز الحرج البالغ 5 ملغم/لتر المطلوب للحياة المائية.

الكلمات الرئيسية: التلوث الحراري, نهر دجلة, قياسات موقعية, محاكاة

1. INTRODUCTION

Pollution of water bodies is occurring due to various reasons, both natural and manmade (**Peters et al., 2019**). The key emission forms are water pollution, air pollution, and soil pollution, biological and nuclear pollution. Thermal pollution is the deterioration of water quality caused by a process that alters the ambient water temperature. (**Cuttler and Pollycove, 2009; Khadim and Oleiwi, 2021)**. Power plants often cause thermal contamination. The rapid temperature rise reduces the oxygen supply and affects the environment as water is retrieved in nature at high temperatures as a coolant. Fish and other organisms adapted to specific temperature ranges will be wiped out by the sudden rise in water temperature (**Dodds and Whiles, 2010**). Thus, the abrupt change in water temperature can kill fish and other species that have adapted to the specific temperature range when they first open or shut down for reparation or other purposes (**Dodds and Whiles, 2010**).

When the temperature rises as low as 1 or 2 °C, the fish, shellfish, and plants can be killed or expelled by the sudden shift in water temperature (Thermal shock). In Iraq, six thermal plants are situated on the Tigris River. These energy plants use a lot of water to cool the units and release hot water at a higher temperature back into the Tigris River. The running of a power plant is also related to major problems in a specific area. The disposal of heated water in the Tigris River is affecting flora and fauna and causing thermal pollution. The power plants, generally situated in the river region, use a massive volume of water for cooling. In Iraq, electric power generation is rising increasingly, which means that the Tigris River receives more heated water. Currently, no data on the Tigris River's thermal pollution, including the extent to which it extends downstream and the level of water quality degradation. It is essential to monitor the thermal pollution in the Tigris River, particularly at the site of the thermal power plants that dispose of the hot water in the river continuously. The present study focused on the field measurements and numerical modeling of thermal pollution in a selected stretch of Tigris River at the Baghdad Al Dora thermal power plant site.

2. MATERIALS AND METHODS

The methodology used in the current study includes several stages implemented to obtain adequate results on the impact of thermal pollution on the Tigris River by the hot water released from the Al-Dora power plant in the Tigris River. The steps have been arranged in the form of a flowchart shown in **Fig. 1**.

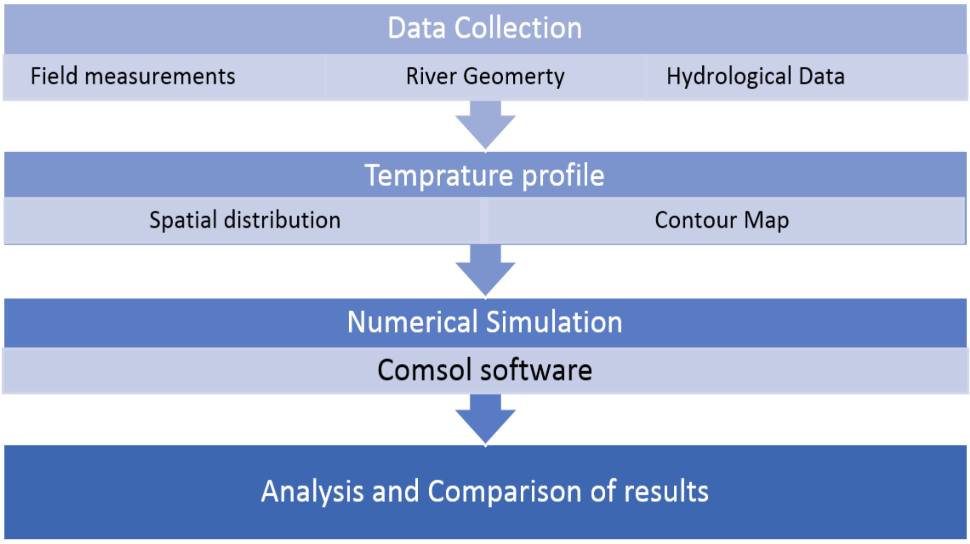

Figure 1. Flowchart for the methodology assessment

2.1 Al-Dora thermal power plant

AL Dora thermal power station is located on the right bank of the Tigris south of Baghdad. AL Dora power plant comprises steam turbine units with a nominal capacity of 160 MW per unit. The AL Dora plant uses an open (unique) system to cool the condensers. Spot cooling requires a large amount of water, which Tigris River supplies. After the cooling process, hot water is poured into the river. The average rate of water used to cool the condenser is 40000 m^3/hr. **Fig. 2** shows the plan of the Al-Dora power plant, with the outfall to Tigris River.

2.2 Fieldwork

The fieldwork included the water temperature measurements of Tigris River near the Al-Dora power plant, particularly upstream the location of the plant, at the plant, and downstream of the plant. The water temperature measurements for the sections were taken one time during winter, spring and summer. The temperature field measurements were taken at different points in the river sections (**Fig**. **2**) by using temperature and humidity meter type HTC -2 with an accuracy of 0.1^{o}C. A wire, which is ended by a sensor, was linked to the meter and the meter gave a digital reading for the water temperature. Based on the location of the section from the disposal point, the section was divided into grids of points in which the temperature was measured. For lateral distance, the temperature was measured every 5 m at points near the hot water disposal site and 25 m for points located far from the disposal site. The temperatures of the disposed of hot water and at different sections of the Tigris River stretch were measured. Geometry Data of the Tigris River for different cross-sections upstream and downstream of the Al-Dora thermal power plant were collected from the Ministry of Water Resources, General Survey Authority. **Fig. 2** shows the sections with their locations. The hydrological data was collected from the National Center for Water Resources Management, Ministry of Water Resources.

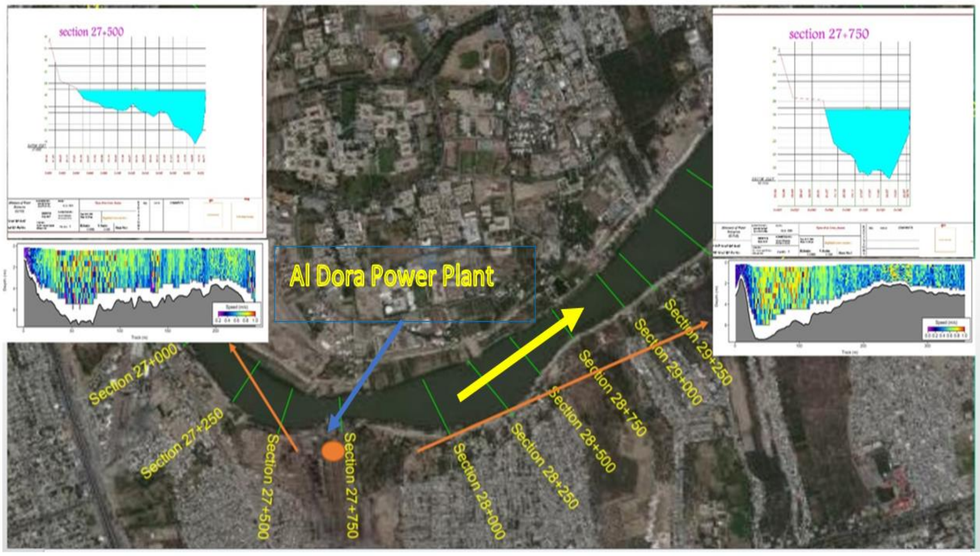

Figure 2. Cross-sections of Tigris River stretch near the power plant

2.3 Numerical simulation

The first step is to create a mesh that accurately captures the input domain geometry of the studied stretch of Tigris River near the Al Dora power plant with high-quality (well-shaped) cells. The mesh should also be fine (small elements) in important areas for the subsequent calculations (**Fig. 3**).

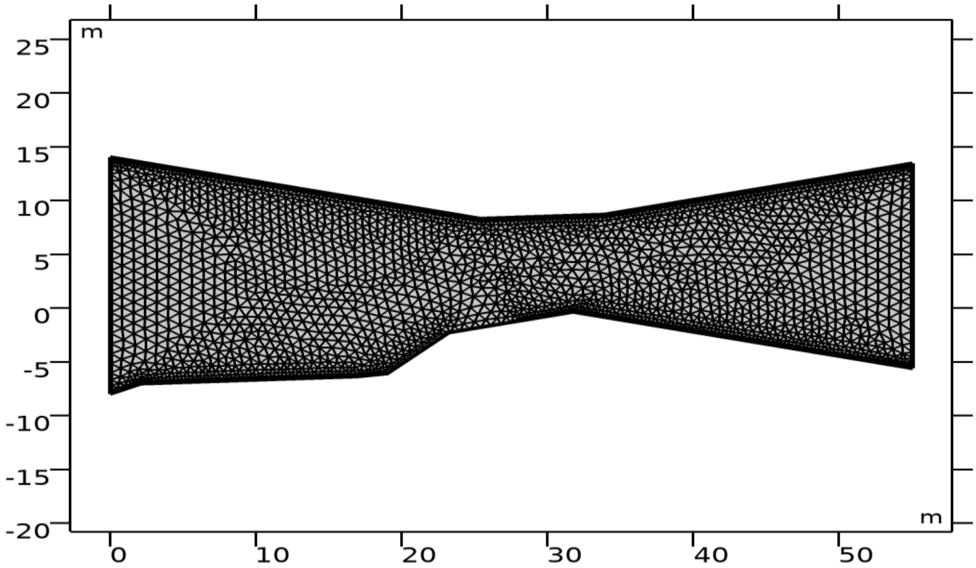

Figure 3. Mesh cells for the studied stretch of Tigris River

The COMSOL simulation model solves the Navier-Stokes continuity and thermal conduction equations with initial, hypothetical, and appropriate boundary conditions. Fluid is taken as water in the model and considered stable and laminar. The water density was considered constant, so an approximation of an incompressible fluid is valid. **Table 1** shows the water properties used in the COMSOL model. **(Khan et al., 2008, and Negi, 2013)** used the same assumption. When compared to convection-diffusion heat transfer, radiation heat transfer was ignored, and insulated walls were taken for granted all over the place except the input and exit borders (**Erickson et al., 1985; Negi, 2013**). Boundary Condition represents the temperature of the water discharged from the Dora station, as well as the shoulders of the river, which are considered heat insulators, and the transfer and change of temperature are with the direction of water flow in the Tigris River. The results obtained from the numerical model were compared with field measurements. Also, various scenarios to study the impact of the disposal hot water velocity on mixing length were demonstrated. **Fig. 4** shows a flow chart for the simulated conditions**.**

Table 1. Various properties of water used in COMSOL

Water Properties	Value
Dynamic viscosity(μ)	0.0008509 Pa s
The ratio of specific heats (γ)	1.0
Heat capacity at constant pressure(C_p)	4186 J/kg K
Density(ρ)	996.59 kg/m^3
Thermal conductivity(k)	0.6 W/m K

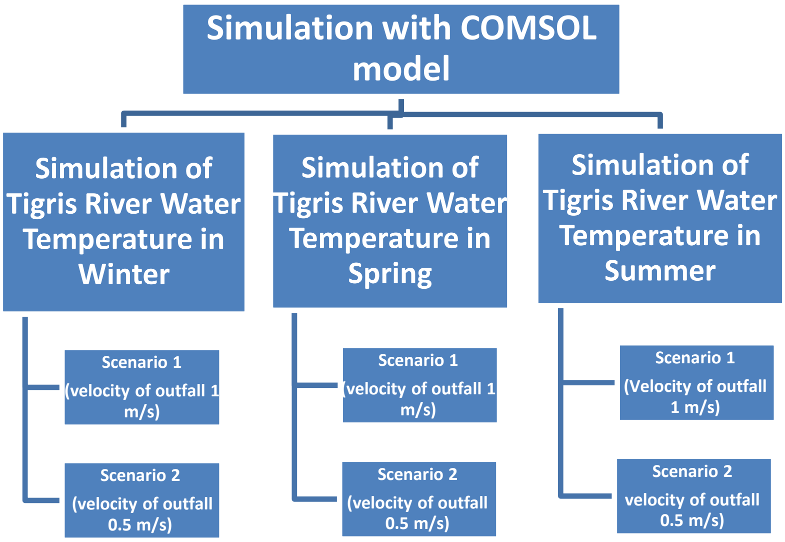

Figure 4. Flowchart for the simulated conditions in this study

3. RESULTS AND DISCUSSION

The field measurements for the temperature of the Tigris River stretch were conducted in winter, spring, and summer. Stream and rivers temperatures are crucial, especially at the locations of hot water disposal from power plants that endanger aquatic life. The field measurements showed a high-temperature difference between the flowing water in the Tigris River and the disposed hot water from the Al Dora power plant. **Table 2** shows the differences between the measured temperature of the disposed hot water and that of the Tigris River near the disposal site in various seasons. The maximum difference in temperature was 10.4°C, recorded during the summer season, while the minimum difference was 5.5°C, measured in winter. The difference in measured temperatures was enough to cause environmental pollution that affected the fish population in the Tigris River. According to **(Rosen et al., 2015**), any river is considered thermally polluted if the difference in temperature between the outfall water and the river flowing water is 5°C or more.

Table 2. The measured temperature at the disposal site of Al Dora power plant

Season	River flow rate m^3/s	Date of field measurements	The temperature of disposal water from the Al Dora power plant, °C	The temperature of water in Tigris River, °C	Difference in temperature
Winter	624	16-1-2021	18.4	12.9	5.5
Spring	608	23-5-2021	36	27.6	8.4
Summer	576	2-8-2021	41	30.6	10.4

The distribution of water temperature in the studied stretch of Tigris River due to the hot water disposal from the Al Dora power plant was simulated by the COMSOL model. **Figs. 5 and 6** show simulation results of temperature distribution in the Tigris River stretch in winter and summer. In addition, many scenarios were simulated to demonstrate the impact of the disposed hot water velocity from the Al-Dora power plant on temperature distribution and mixing length in the studied stretch of Tigris River. To simulate the scenarios, the required data on outfall water temperature from the Al-Dora power plant, the velocity of the disposed of hot water, and the other required boundary conditions such as velocity and temperature at specific locations in the stretch of Tigris River were used as input U/S. The temperature of the disposed water and that in various depths of Tigris River sections were measured locally by a digital thermometer, while the velocity of the disposed hot water was determined by applying the continuity equation after knowing the discharge from the plant. The daily discharge of the hot water from the Al Dora power plant was given as 40,000 m^3/day. The simulation was based on the actual value of the disposed hot water velocity from the Al-Dora power plant, determined and found to be 1.6 m/s. The simulation results show that the temperature distribution in the Tigris River stretch in the winter, spring, and summer seasons .

The temperature difference in the contact area between the river and the discharge point of the AL Dora power plant was higher than the allowable limit, which is less than 5^{o}C. The velocity of the disposed hot water plays an important role in mixing between the disposed hot water and river water. At high velocity, the flowing hot water from the outfall causes accumulation of a large volume of hot water in the river region near the outfall. While at smaller velocity, the mixing between the disposed hot water and the river water is improved. The effect of the disposed hot water velocity from Al Dora power plant on the thermal mixing in Tigris River stretch was simulated using the COMSOL program. Two scenarios were tested in which the velocity of the disposed hot water from the Al Dora power plant was reduced two times (one time was taken as 1m/s, and another time was taken as 0.5 m/s). The results of the scenarios can be used to reduce the impact of thermal pollution from the Al Dora power plant on the Tigris River stretch at that site .

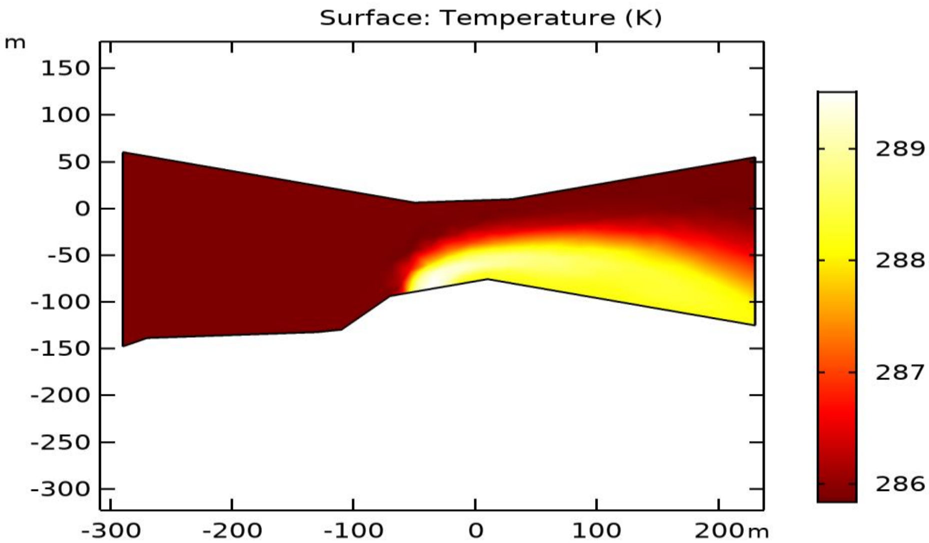

Figure 5. Simulation of Temperature distribution in Tigris River stretch due to hot water disposed from the AL Dora power plant in winter with a discharge of 624 m^3/s.

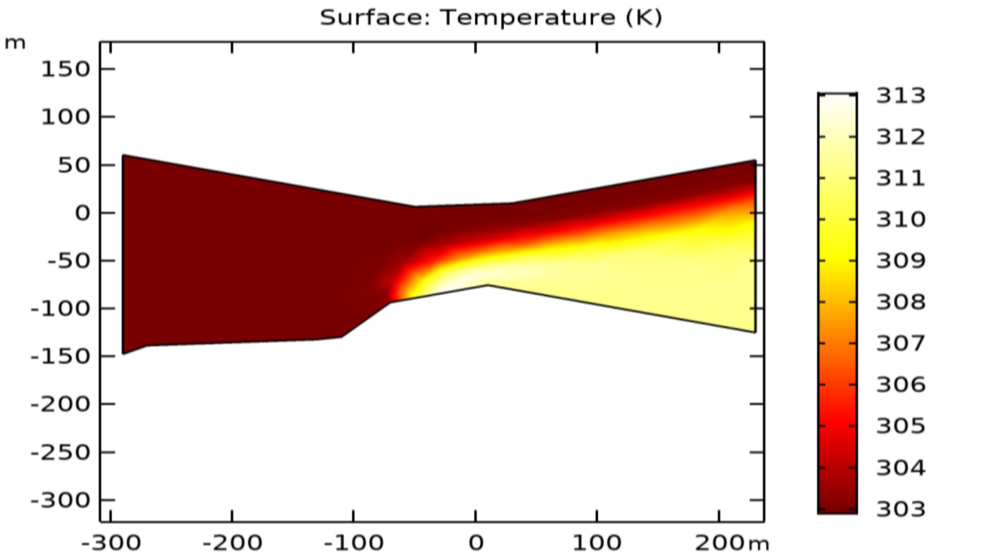

Figure 6. Simulation of Temperature distribution in Tigris River stretch due to hot water disposed from the AL Dora power plant in summer with a discharge of 576 m^3/s.

3.1 The scenarios

The first scenario includes the simulation by the COMSOL model using a value of 1m/s for the velocity of disposed hot water from the Al- Dora power plant to the Tigris River. The discharge of hot water was not changed, but the width of discharging channel was increased so that the hot water velocity became 1m/s. For the above conditions, the results of thermal mixing in Tigris River obtained from the simulation model for summer are shown in **Fig. 7**. The second scenario included reducing the hot water velocity to 0.5 m/s. The simulation based on this change in velocity is shown in **Fig. 8**. The reduction in velocity had a clear impact on the thermal mixing in Tigris River at the AL Dora power plant location. Comparing **Fig. 7** and **Fig. 8**, the improvement in thermal mixing is noticeable. The actual or measured hot water velocity from the outfall was found to be 1.6 m/s, and when the velocity of the disposed hot water was reduced in the simulation scenario to 0.5 m/s, the improvement in the thermal mixing in the Tigris River showed a reduction in temperature up to 4 ^oC. **Fig. 7** and **Fig. 8** show the improvement in the thermal mixing in the Tigris River. Finally, the application of different scenarios shows how the impact of thermal pollution can be reduced by controlling the velocity of the disposed hot water from the Al-Dora power plant to the Tigris River .

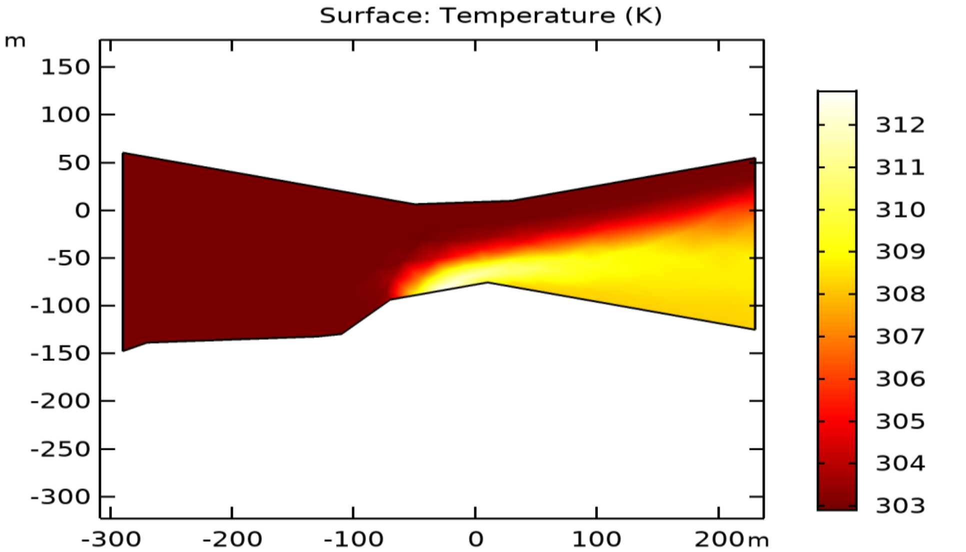

Figure 7. Simulation of thermal mixing in Tigris River by COMSOL for the first scenario (hot water velocity of 1 m/s) in summer

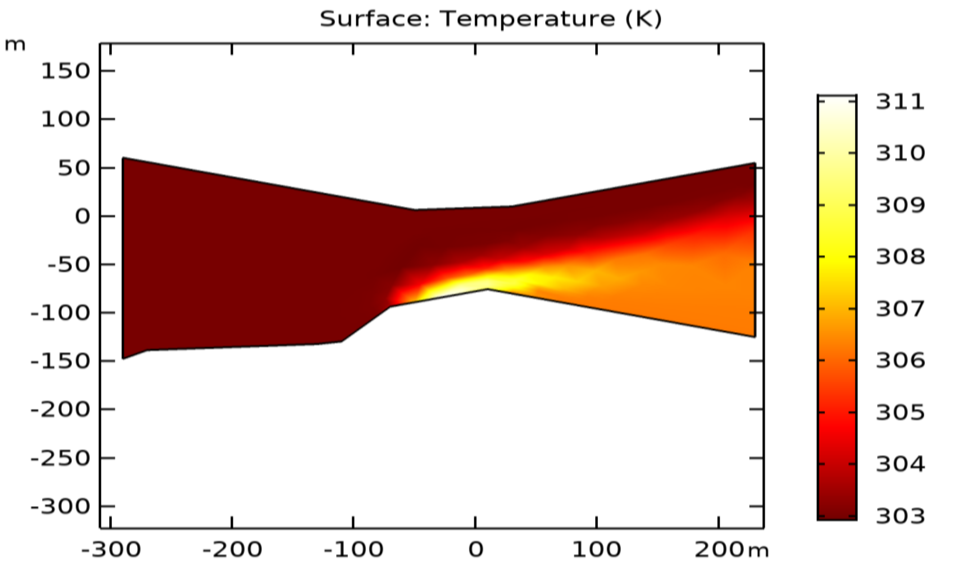

Figure 8. Simulation of thermal mixing in Tigris River by COMSOL for the second scenario (hot water velocity of 0.5 m/s) in summer

The river has gradually reduced the mixing distance the impact of this thermoregulatory pollution area so that the reduced velocity of the disposed of hot water decreases the mixing distance in all the seasons (winter, spring, and summer). When the disposed hot water velocity was 1.6 m/s, the mixing length was about 200 m. A significant effect was obtained when the hot water velocity was reduced to 0.5 m/s. **Fig. 9** shows that the minimum mixing lengths were approximately 75, 64, and 55 m in the summer, spring, and winter seasons. These results were obtained from the COMSOL model for the disposed hot water velocity of 0.5 m/s .

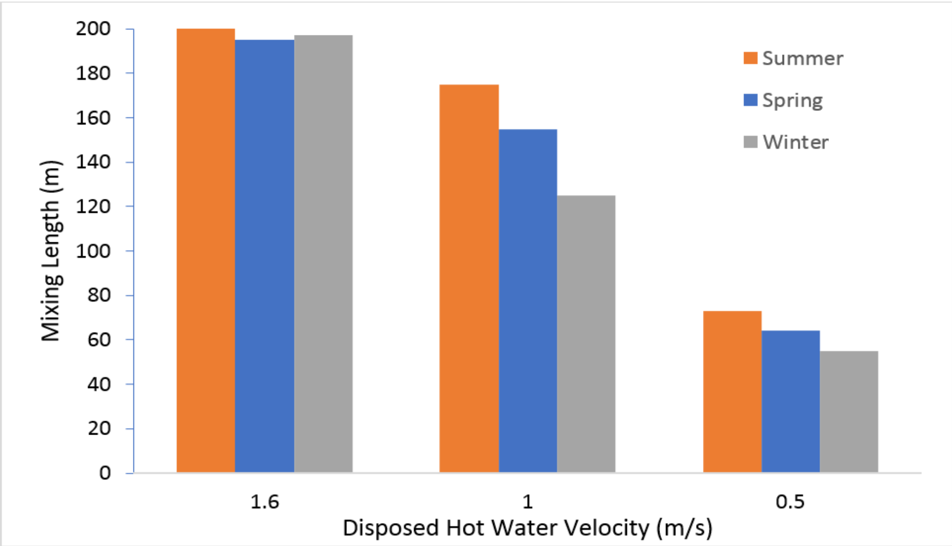

Figure 9. Effect of hot water velocity on mixing length in Tigris River

3.2 Model verification

After the disposal of hot water from the Al Dora power plant, temperatures in the Tigris River were measured in three seasons (winter, spring, and summer). The COMSOL model calibration and verification were carried out by comparing the measured and predicted temperatures. The results show good agreement and a significant positive relationship between measured and predicted values, with maximum errors of 5.69%, 9%, and 13.3% in winter, spring, and summer, respectively. However, the confidence level was less than 5% ($p < 0.05$) for the winter, spring, and summer predictions. **Figus 10, 11, and 12** show the predicted and measured values along the selected stretch of Tigris River.

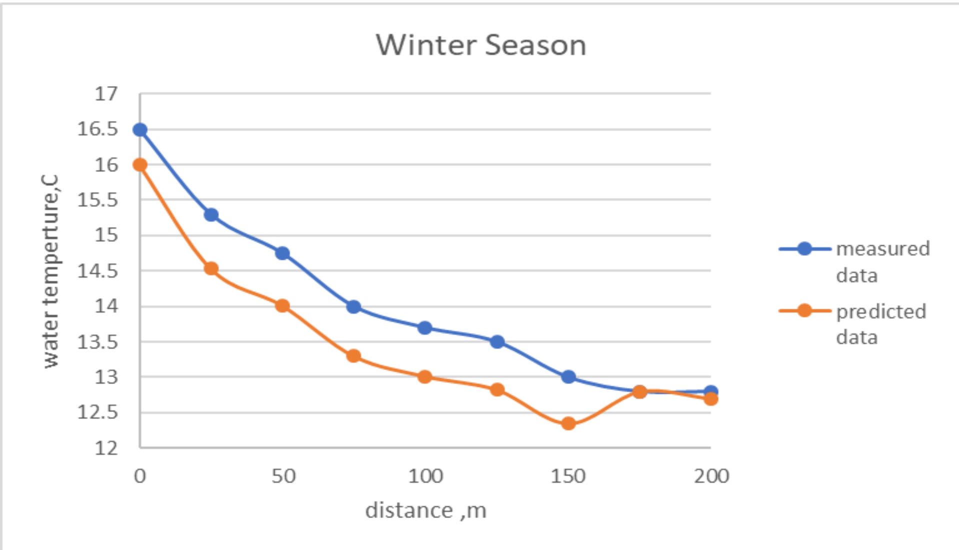

Figure 10. Measured and predicted temperatures along the studied stretch of the Tigris River in winter

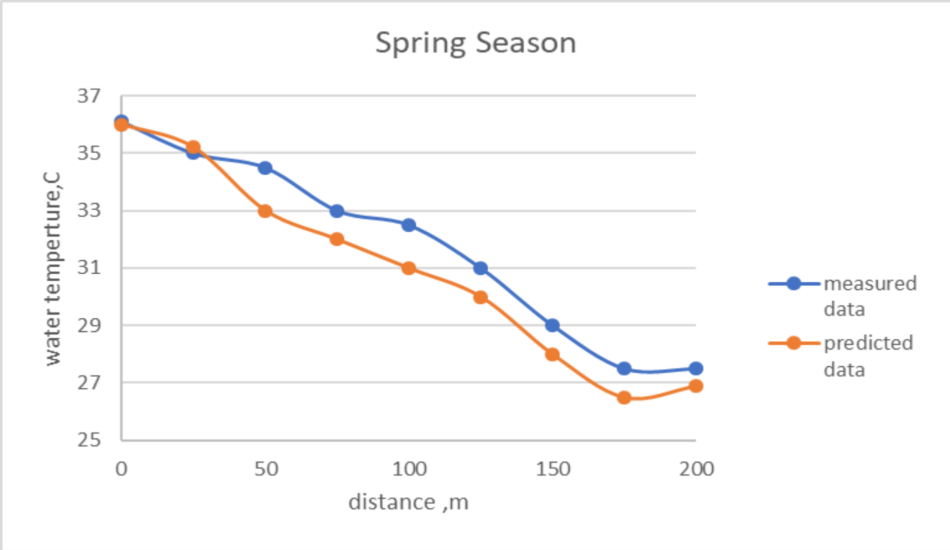

Figure 11. Measured and predicted temperatures along the studied stretch of the Tigris River in spring

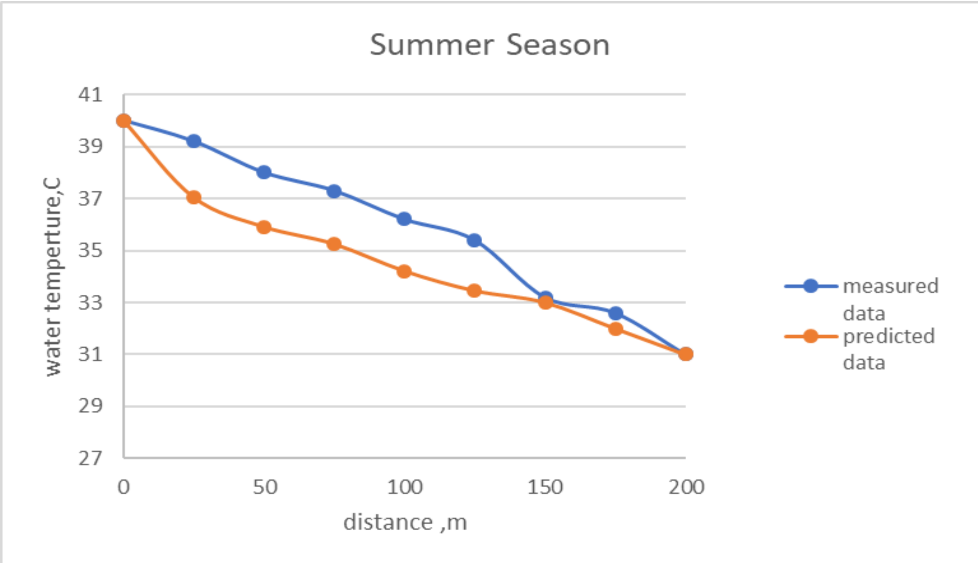

Figure 12. Measured and predicted temperatures along the studied stretch of the Tigris River in summer

3.3 Estimation of Water Temperature Recovery Distance

Eq. (1) was used to estimate the water temperature recovery distance in Tigris River due to the hot water disposal from the AL- Dora power plant.

$$X = \frac{\rho w C w\ h\ u}{Ke}\ ln\left[\frac{20}{3}(T_O - T_b)\right] \tag{1}$$

where, X in meters, is the water temperature recovery distance which is the distance until the river water temperature returns to the original temperature, T_b in °C is the water temperature at the upstream, T_o in °C is the water temperature after the discharge becomes fully mixed with the river water, Ke in W/m^2 °C) is the surface heat exchange coefficient, ρw is the water density (998.2 kg/m^3). Cw is the specific heat of water (4186 J/kg °C), h in meters is the mean river depth, and u in m/s is the water velocity. The limit condition at the heat flow discharge entry point is $T = T_o$, where To is the temperature after the river water is mixed with effluent water. Values are shown in **Table 3**. Had been used to estimate the temperature recovery distance in the river for three seasons. For water temperature, depth, and flow velocity, the average values for each season were utilized. The minimal value for each season was used for flow rate and surface heat exchange.

Table 3. Input data for the water temperature recovery distance

Season	U/S River Temperature,°C	River Flow m^3/s	Heat exchange coefficient Ke, W/m^2 °C
Winter	12.9	624	16.35
Spring	27.5	608	19.47
Summer	30.5	576	20.03

The difference in temperature between the power plant and the Tigris River was set to be 10.5, 8.6, and 5.1°C during winter, spring, and summer, respectively. The effluent thermal flow rate of 40 000 m^3/hr was discharged into the Tigris River, and complete mixing may occur in case there are no other weather or environmental changes. In addition, the depth of the water, the flow velocity, and the wind speed were calculated. The weighted average value of the river flow and discharge was used to set the mixed water temperature immediately after entering the Tigris River. The temperature of the river, the discharge water temperature, the mixed water temperature immediately after entering, and the calculated water temperature recovery distance are all shown in **Table 4.**

Table 4. Thermal mixing length obtained from Eq. (1)

Season	U/S River Temperature, °C	Disposed Hot water Temperature, °C	Mixed Water Temperature Immediately after the hot water, °C	Estimated Water Temperature Recovery Distance Eq. (1), m
Winter	12.9	18	13.05	1608
Spring	27.5	36.1	27.75	2116
Summer	30.5	41	30.85	3403

Field measurements found that the impact of the mixing length extends to 1500 m in winter, 1810 m in spring, and 2450 m in summer. The difference between measured and calculated recovery distance by **Eq. (1)** is shown in **Fig. 13**. Measurements in winter, spring and summer seasons were less than that calculated using **Eq. (1)**, while **Fig. 14** shows the recovery distance along the river that is affected by the disposal of hot water of the power plant in winter, spring, summer respectively.

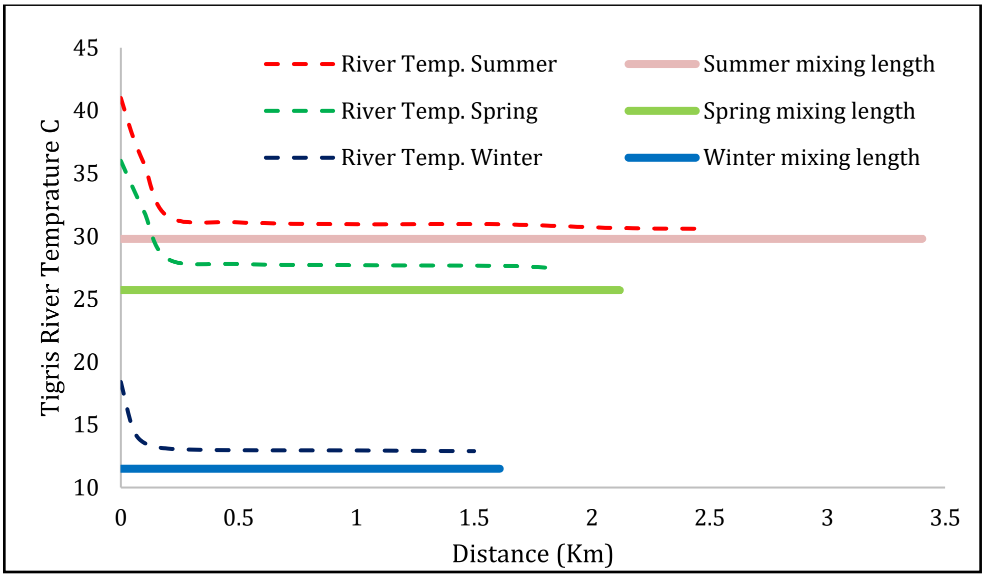

Figure 13. Measured and predicted recovery length in winter, spring, and summer

3.4 Prediction of Dissolved Oxygen Concentrations

After measuring the temperature in the Tigris River, it is required to determine the effect of the increase in temperature on aquatic life. This can be done by determining the dissolved oxygen concentrations in the studied stretch of the Tigris River affected by the disposal of hot water from the Al-Dora power plant. The dissolved oxygen as a function of temperature is represented using a model for river water as given by **(Nasir et al., 2013)**.

$$DO(mg/l) = 14.6 - 0.3943T + 0.007741T^2 - 0.0000646T^3 \qquad (2)$$

Where DO is the dissolved oxygen concentration, and T is the temperature.

The temperature range observed in the three seasons was between 12.9 and 41^{o}C. The dissolved oxygen distribution ranges in Tigris River obtained from **Eq. (2)** were found from 9.6 to 10.7 mg/l in winter, (7.4-8.3) mg/l in spring, and (6.9-7.9) mg/l in summer. **Fig. 15** shows the estimated dissolved oxygen concentrations in Tigris River using **Eq. (2)** in winter, spring and summer. For optimal fish health, a DO concentration of 5 mg/l is required (**Dodds and Whiles, 2010; Al-Suhili, et al., 2012**). Although sensitivity to low dissolved oxygen levels varies by species, most fish species become anxious when DO falls below 2-4 mg/l. The change in DO affects the movement of the fish. With decreasing DO concentrations, most fish may travel vertically and laterally to escape locations. In the River, fish growth rate and benthic invertebrate concentrations diminish in places suffering occasional low dissolved oxygen concentrations, resulting in a lower fish growing rate that is restricted to these locations. Fish and invertebrates that remain incapable of fleeing may die because of rapid reductions in DO concentrations**.**

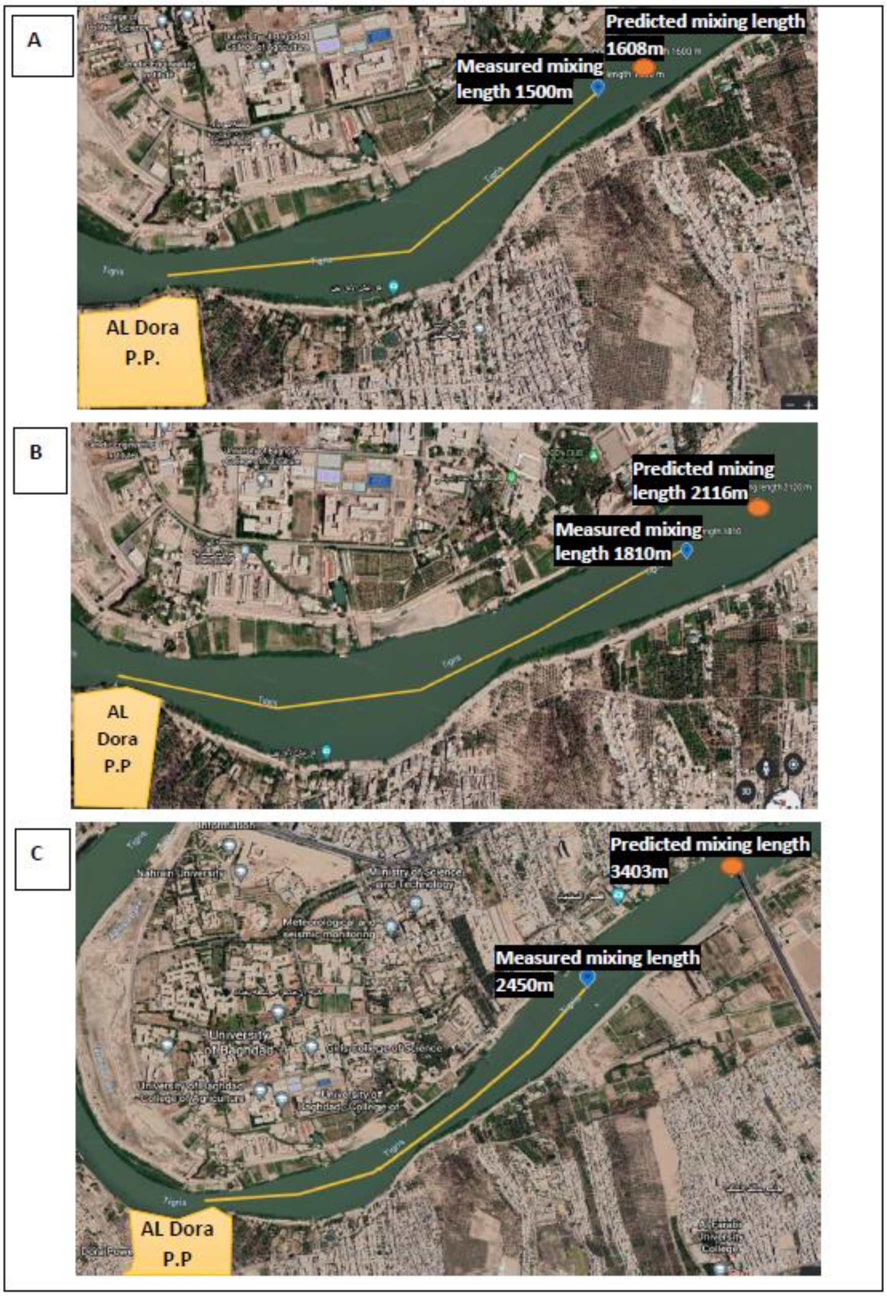

Figure 14. Measured recovery length in winter, spring, and summer

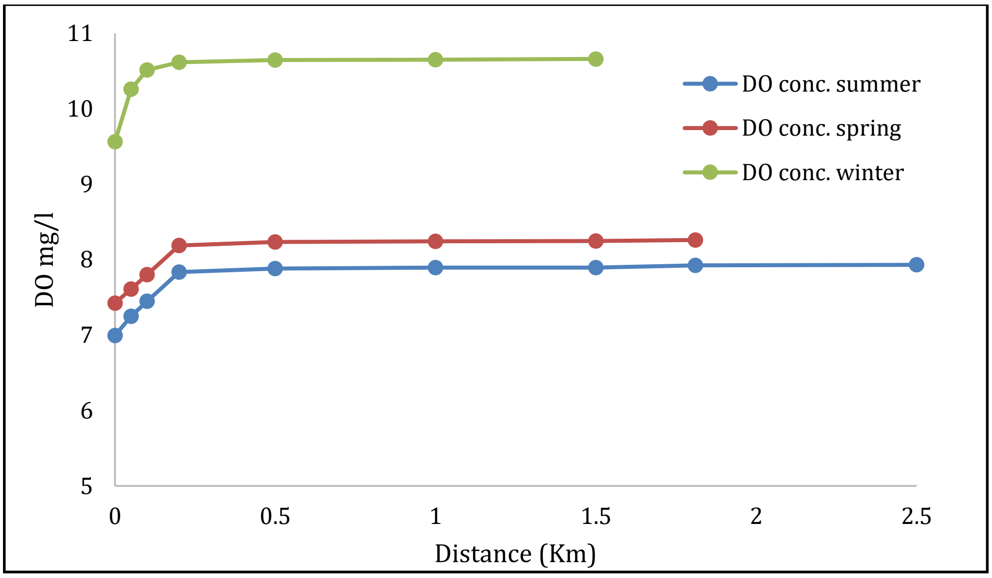

Figure 15. Effect of river temperature on dissolved oxygen

4. CONCLUSIONS

In this study, the impact of hot water disposal from the Al-Dora power plant on the Tigris River stretch located near the plant was assessed based on field measurements in winter, spring, and summer and numerical simulation by the COMSOL model. The simulation included two main scenarios in which the hot water velocity from the Al-Dora power plant was reduced to 1 m/s and then 0.5 m/s. From the conducted methodology, the following conclusions can be drawn**:**

- Field measurements showed the water temperature of the Tigris River stretch is affected by the hot water disposal from the Al-Dora power plant. The increase in temperatures was 5.1°C, 8.6°C, and 10.5°C in winter, spring, and summer, respectively. However, a temperature difference greater than 5 C° is affected the aquatic life in the Tigris River **.**
- The numerical simulation by the COMSOL model showed that the change in velocity of hot water disposal from the Al-Dora power plant from 1.6 m/s to 1 m/s and to 0.5 m/s highly affected the temperature distribution and the mixing length. The reductions in temperature were 1.2, 2.3, and 4°C in winter, spring, and summer, respectively, while the mixing lengths were reduced to 75, 64, and 55 m in summer, spring, and winter, respectively**.**
- The measured water temperature recovery distance was found to be 1500 m, 1810 m, and 2450m in the winter, spring, and summer seasons, respectively. However, the estimated water temperature recovery distance by using **Eq. (1)** was found to be 1608, 2116, and 3403 m in winter, spring, and summer, respectively **.**
- Based on the measured temperature, the dissolved oxygen concentrations were estimated by using **Eq. (2)**. The ranges of dissolved oxygen concentrations were found to be (9.6–10.7) mg/l, (7.4-8.3) mg/l, and (6.9-7.9) mg/l in winter, spring and summer respectively. However, these ranges are more than 5mg/l, which is the maximum needed for the fish population to survive **.**

Using thermal water as a heat source in electricity production offers several advantages for industry, including lower costs and money-saving. However, this also comes at the expense of the environment. When the temperature is elevated, warping or boiling water in power plants can harm marine life because of the increased aerobic decomposition. The content of nutrients is lowered when organic matter is added to water. To minimize the effect of thermal pollution caused by the discharge of cooling water from the Al Dora power plant, the results showed that reducing the velocity of water flowing from the plant to 0.5 m/s results in lowering the temperature and, thus, conditions suitable for aquatic life inside the river**.**

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Conflict of Interest

The authors confirm that there is no conflict of interest in publishing the present research work

NOMENCLATURE

Cw = specific heat of water, J/kg °C
h = mean river depth, m
Ke = surface heat exchange coefficient, W/m^2 ^{o}C
u = water velocity, m/s
X= water temperature recovery distance, which is the distance until the river water temperature returns to the original temperature, m
T_b = water temperature at the upstream, °C
T_o = water temperature after the discharge becomes fully mixed with the river water, °C
ρw = water density, kg/m^3

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