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Environmental and hydraulic design of thermal power plants outfalls "Case study: Banha Thermal Power Plant, Egypt"

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Abstract A physical model study was conducted for designing the intake/outfall combination to comply with the Egyptian environmental laws. Based on the dominant flow patterns, and temperature measurements, two alternatives were examined. The first alternative of outfall structure consists of surface open channel. The output of this design did not comply with the environmental laws and has negative impacts on the water quality and ecological life. It was proposed to widen the outfall with 24 nozzles (multi port diffuser) arranged in two rows and separate the outfall into many jets. This new alternative for the outfall hydraulic design succeeded to improve the mixing process and complies with the Egyptian environmental laws.

1. Introduction

The discharge of thermal effluent from thermal power plants into water bodies would result in harmful impacts on the ecological life. The higher forms of aquatic life require oxygen for survival. The high temperature decreases the concentration of oxygen in water. So, it is important to dilute the thermal concentration into water bodies and confine it into small areas to maintain the allowable limits of oxygen needed for the aquatic life. A case study of thermal power plant was selected and studied to deduce the optimal plant outlet which can help for improving the mixing process to comply with the environmental Egyptian laws and to increase the Saturated dissolved oxygen (DO) levels in the water bodies. For this purpose, Banha Thermal Power Plant was taken as a case study in this research. It will be located at El-Rayah El-Tawfiki and will abstract water from it through the intake for its once through cooling system. The effluent discharge will increase the water temperature above the ambient by 10 °C which will cause negative impacts to the environment. El-Rayah El-Tawfiki has an Average Water Quality Index, AWQI of about 70% which is characterized as fair for human activities.

The Egyptian Electricity Holding Company, EEHC is planning to construct a new thermal power plant at El-Rayah El-Tawfiki, which is Banha Power Plant. The plant power capacity is 750 MW. It will abstract its cooling water from El-Rayah El-Tawfiki through its intake for its once-through cooling system and will be discharged back to El-Rayah El-Tawfiki through the plant outfall. The effluent discharge is characterized by its increased water temperature above the ambient

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Nomenclature

AWQI	average water quality index	MOE	ministry of environment
DO	dissolved oxygen	pH	hydrogen-ion activity
BOD	Biochemical Oxygen Demand	n_q	discharge scale ratio
COD	Chemical Oxygen Demand	n_t	time scale ratio
Tp	Total-Phosphates	n_v	velocity scale ratio
NH_3	Ammonia	n_l	length ratio
NO_3	Nitrates	Fr	froude number
TDS	Total Dissolved Solids	Frd	densimetric froude number
TA	Total Alkalinity	V	velocity (m/s)
TC	Total Coliform	g	gravitational acceleration (m/s^2)
As	Arsenic	h	water depth (m)
Cd	Cadmium	ρ	density (kg/m^3)
Cr	Chromium	$\Delta\rho$	density difference (kg/m^3)
Cu	Copper	Δt	specified temperature excess
Fe	Iron	Δt_0	initial temperature excess
Zn	Zinc	q_r	river discharge
EEHC	Egyptian Electricity Holding Company	q_0	outlet discharge
HRI	Hydraulics Research Institute	x	centerline plume length
MWRI	ministry of water resources and irrigation	b	width of outlet

water by 10 °C. The Hydraulics Research Institute, HRI was assigned by the EEHC to carry out the hydraulic model study for the proposed once-through cooling system and the optimum design of the intake/outfall of the plant from the hydraulic point of view. El-Rayah El-Tawfiki is considered as one of the most ancient canals in Egypt, it was constructed in 1889. It runs over a length of 192 km and irrigates 970,000 feddans. It is feeded directly from the upstream of the Delta Barrages and estuaries at the Midetrenian Sea. It crosses Qalyoubia, Dakahlia and Damietta Governorates [1]. Its water is used for different purposes such as irrigation, drinking, industry and fishing. Fifteen water quality pollutants were selected as indicators, these are dissolved oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total-Phosphates (Tp), Ammonia (NH_3), Nitrates (NO_3), Total Dissolved Solids (TDSs), Total Alkalinity (TA), Total Coliform (TC), Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Iron (Fe), and Zinc (Zn). These indicators are used to calculate the Average Water Quality Index, AWQI for the collected samples [2]. It was found that, the AWQI at El-Rayah El-Tawfiki is about 70% which is characterized as fair. Fig. 1, shows AWQI for some irrigation canals and Rayahs in Egypt, [3–5]. Throughout the present paper, the physical model was conducted to design the intake/outfall combination to comply with the Egyptian environmental law with the classification of AWQI.

2. Bathymetric survey and field measurements

Regarding the bathymetric survey, it covered reaches of 4 km length at El-rayah El-Tawfeky upstream Gamgara regulator two kilometers upstream its intake and the two kilometers downstream the outfall out of Banha Power plant. As for the field measurements, they were carried out by HRI in August 2009 to collect the data required for the physical scale models. The data consisted of bathymetric survey and flow measurements.

Bathymetric data was acquired by a high precision echo sounder operating at 200 kHz. The echo sounder was operated and calibrated in both analogue and digital mode. The cross section was executed every 50 m with very high accuracy. The bathymetric data was used to obtain the contour map which is used to build the physical scale model with contour interval 0.5 m. all the details are shown in [6].

The flow measurements were carried out at three cross-sections covering the surveyed reach using calibrated current meters. The locations of the flow cross sections are shown in Fig. 2. The measured discharges and water levels at the measuring cross sections were used for the physical model calibration. A Van Veen grab sampler was used to collect the bed material samples. Analysis of samples was included grain size distribution and specific weight, Fig. 2, shows the schematic diagram of EL-Rayah EL-Tawfiki surveyed area.

3. Hydraulic physical model

The scaled physical model was constructed with fixed bed had an undistorted scale of 1:50 in the horizontal and the vertical direction represents four kilometers of EL-Rayah EL-Tawfiki in the vicinity of the Banha Thermal Power Plant intake/outfall. Model similarity, construction, calibration and measuring devices were reported in details in HRI [7].

For the important hydraulic and thermal phenomena in a hydraulic scale model, a number of requirements must be fulfilled when determining the model scales which are geometric kinematics and dynamic similarity as the follow:

3.1. Geometric similarity

Geometric similarity of a model is achieved if all geometric dimensions of length, width, and depth in prototype, exhibit a constant ratio to the corresponding dimensions in the model:

$$\text{Length ratio} = n_l, \quad \text{Area ratio} = (n_l)^2, \quad \text{Volume ratio} = (n_l)^3$$

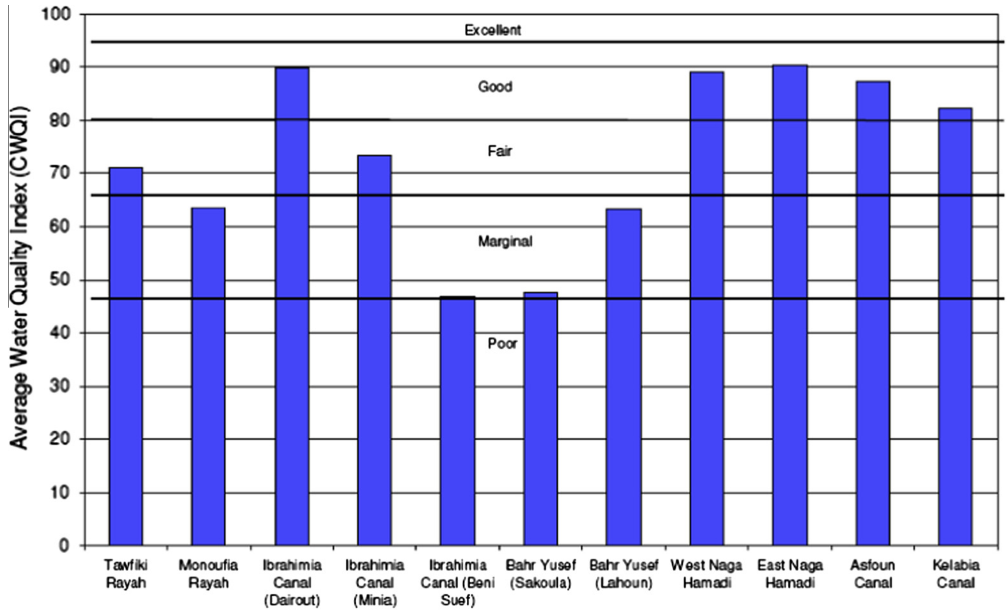

Figure 1 AWQI for the different irrigation canals and rayahs, after NRI 2004.

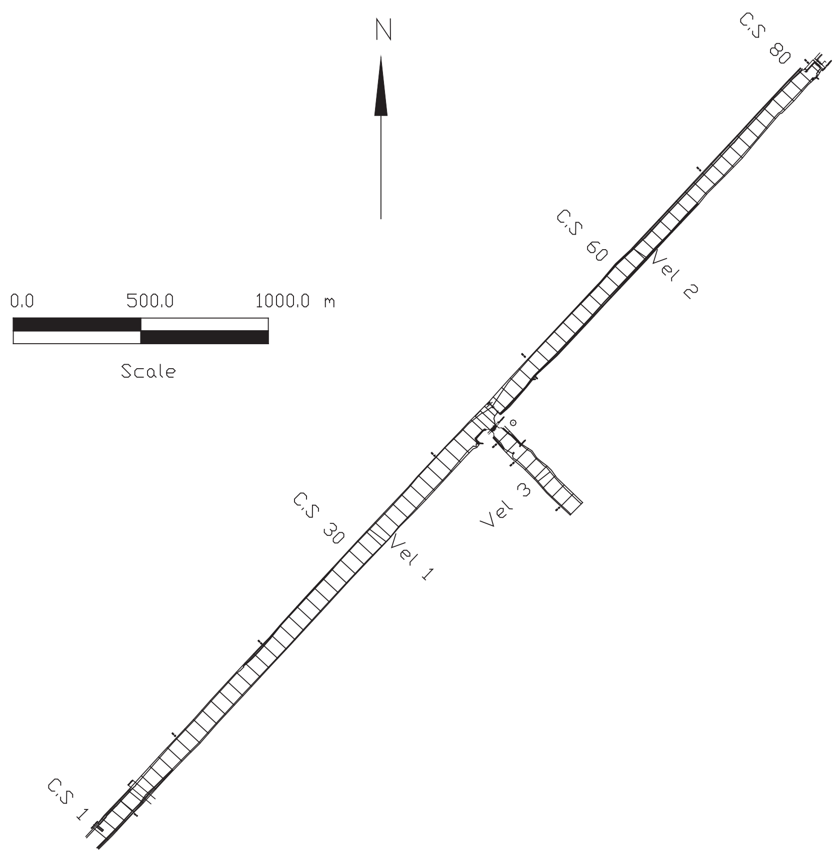

Figure 2 Schematic diagram of EL-Rayah EL-Tawfiki surveyed cross section and velocities sections measurements.

3.2. Kinematics similarity

Kinematics similarity between the prototype and the model requires that time-dependent events proceeded in the model and prototype is the same in a way, such that corresponding time intervals in prototype and the model would show a constant ratio

$$n_t = n_l/n_v$$

where n_t is the time scale ratio and n_v is the velocity scale ratio.

3.3. Dynamic similarity

Dynamic similarity implies that corresponding forces in prototype and model must show a constant ratio. These ratios can be derived from the relations between the acting forces in the flow field. The relevant forces in case of free surface flow with density difference are inertia, gravitational, buoyancy, and viscous forces. The force ratios are:

Froude number (Fr)

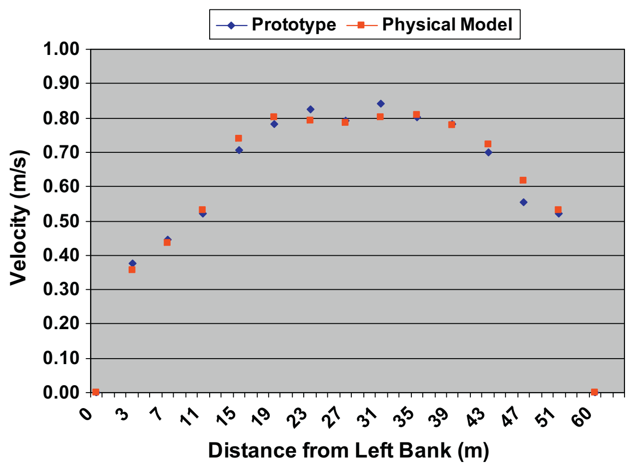

Figure 3 Comparison between the measured and computed flow velocities at the third measuring cross sections.

Froude Number is the ratio of inertia to gravitation forces:

$$Fr = \frac{V}{\sqrt{gh}}$$

Densimetric Froude Number is the ratio of buoyancy to gravitation forces:

$$Frd = \frac{V}{\sqrt{(\Delta\rho/\rho)gh}}$$

In which V is the velocity (m/s) g the gravitational acceleration (m/s^2), h the water depth (m), ρ the density (kg/m^3), $\Delta\rho$ the density difference (kg/m^3)

Based on the condition that Froude Number in both prototype and model is equal, the velocity, discharge and the time scale ratio can be determined as follows:

- Velocity scale ratio $= n_v = (n_h)^{0.5}$
- Discharge scale ratio $= n_q = n_l n_h n_v = n_l\,(n_h)^{1.5}$
- Time scale ratio $= n_t = n_l/n_v = n_l/(n_h)^{0.5}$

The model scale which is 1:50 in the horizontal and vertical directions (undistorted scale model) was selected based on the available space in HRI and also to fulfill the Densimetric Froude Number. They are most important criterion to be validated in the model.

3.4. Model construction and calibration

The model has fixed bed made of mortar. According to the bathymetric and topographic survey, which were carried out

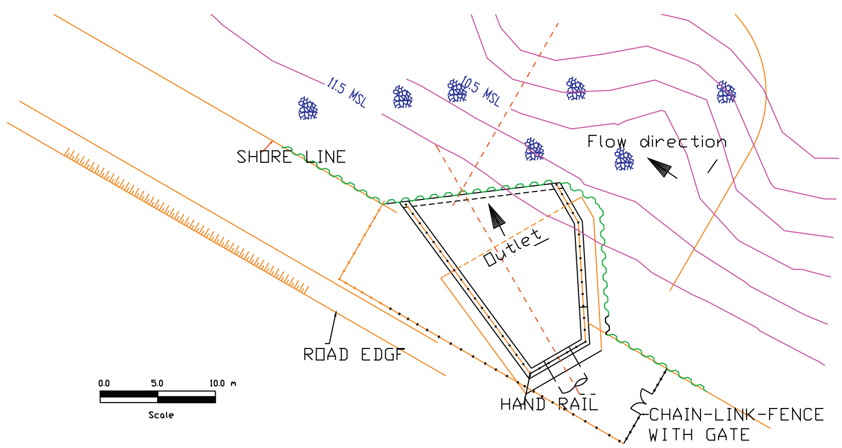

Figure 4 Schematic diagram of the surface outfall.

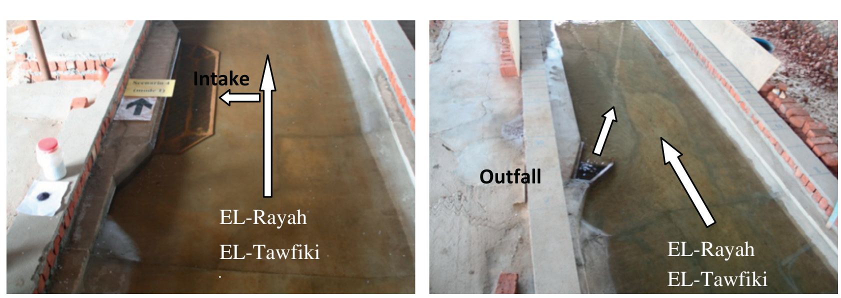

Figure 5 New Banha Thermal Power Plant intake and outfall.

by HRI, the horizontal coordinates of the measured cross sections and the bed levels along these sections were obtained. These cross sections were then scaled down to the model dimensions (1:50 in horizontal and vertical directions) and positioned at their proper coordinates in the model area.

In order to ensure that both the model and prototype are geometrically, kinematically, and dynamically similar, the model was calibrated with respect to water surface slope along

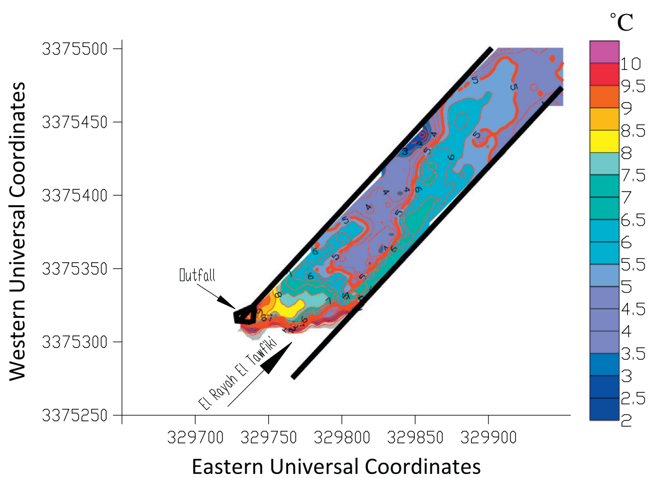

Figure 6 Thermal contours (the excess water temperature above the ambient water) at dominant flow of El-Rayah El-Tawfiki.

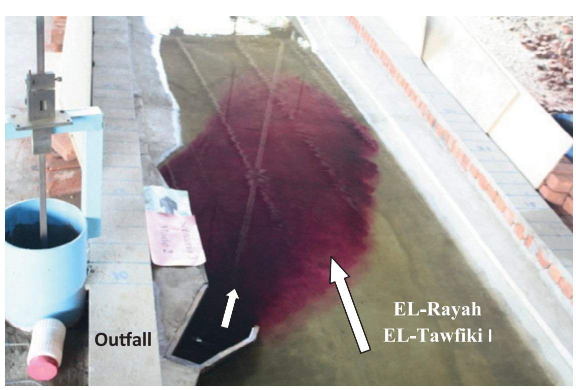

Figure 7 Dye diffusion at the dominant flow of El-Rayah El-Tawfiki.

the modeled reach and water velocity distribution at a specified cross sections.

The model was calibrated by measuring the velocity distribution for three cross-sections and the results were compared with their equivalent velocities in the prototype. Fig. 3 shows the location of the three velocity cross sections. Fig. 3 shows the comparison between the measured and computed flow velocities at the third measuring cross sections as an example. The figure shows that there is a good agreement between the model and the measurements.

Dominant discharge of EL-Rayah EL-Tawfiki at the location of Banha Thermal Power Plant is about 46 m^3/s. The corresponding relevant water level of 12.30 m + MSL was provided from the historical data, the ambient temperature is 25 °C, intake/outfall flow is 9.13 m^3/s and the excess temperature at the outfall is 10 °C above the ambient. The average velocity of EL-Rayah EL-Tawfiki at this location is 0.6 m/s, the dominant water depth is about 3 m and the dominant bed width is 26 m. The schematic diagram of the surface outlet is shown in Fig. 4. The intake/outfall structure configurations are presented in Fig 5. The outfall structure consists of surface open channel that discharges the effluents from the plant to EL-Rayah EL-Tawfiki. The outfall inclined with an angle of 30° with the main flow direction.

The thermal measurements that extended from the proposed intake structure to the downstream outfall structure were presented as thermal contours of the excess water temperature above the ambient water and shown in Figs. 6 and 7 show dye diffusion at the dominant flow case. The mixing zone is defined within about 1/3 of the width of the cross section of El-Rayah El-Tawfiki, [7]. The excess temperature outside the mixing zone is more than 5 °C above the ambient temperature. The contour line of 6 °C has reached the right bank of El-Rayah El-Tawfiki and extended to the Gamgara Regulator.

4. Thermal effect on El-Rayah El-Tawfiki

The main effect of temperature on chemical reactions is that, high temperature may inhibit reversibility. Commonly, increasing of water temperature by an amount of 10 °C might lead to double the rate of the chemical reaction [8]. The AWQI of El-Rayah El-Tawfiki is found to be about 70% which means fair. The construction of the New Banha Thermal Power Plant at El-Rayah El-Tawfiki might cause the following impacts:

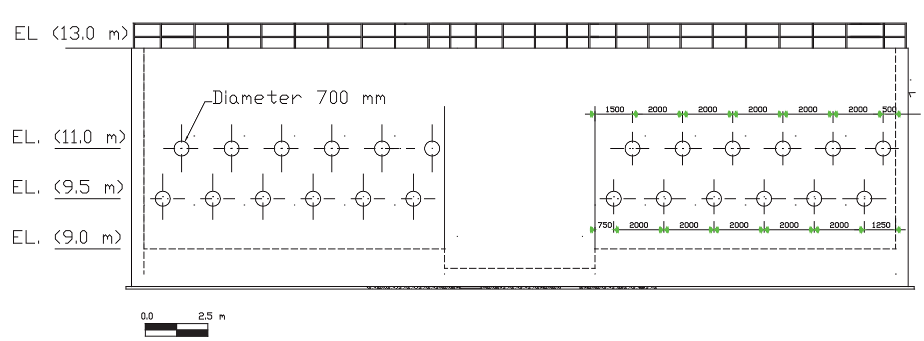

Figure 8 Detailed elevation of diffuser outfall.

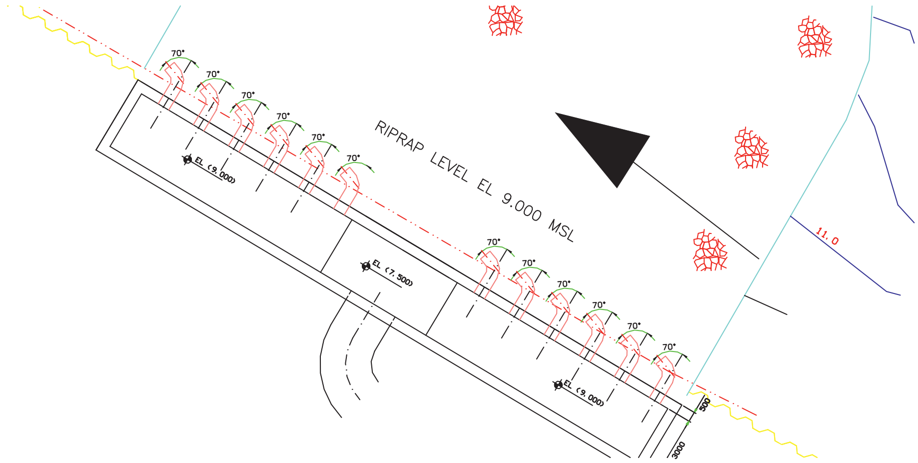

Figure 9 Plan of the diffuser outfall.

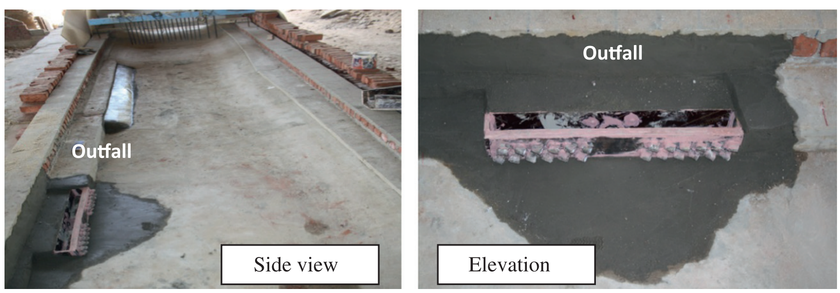

Figure 10 Side view and elevation of the modeled diffuser outfall.

- Main properties of water quality

Higher temperatures decrease pH and DO values. Higher temperatures increase electrical conductance and ion concentration.

- Main constituents of water quality

The increased solubility is attained as water temperature rises. As an example, increasing the water temperature will increase the solubility of silica, calcium and sodium.

- Main standards of water quality

The chemical composition of the water supply and water temperature affects the amount and severity degree of salt-disposal problems in irrigated areas. Standards quality and temperature are required for industries processes such as the manufacture of high-grade paper or pharmaceuticals, where impurities and water temperature would seriously affect the quality of the product [8].

- Ecological life

Discharging thermal effluent into water bodies would result harmful impacts on the ecological life [8] as, sudden fish kill near the outlet, change the reproduction mechanism and population of organisms, change in growth rate and preventing fish immigration due to thermal barrier. The higher forms of aquatic life require oxygen for survival, and the DO determination is used widely in evaluations of the biochemistry of streams and lakes. The effect of DO generally is biological which means a suitable growth period is required for the organism involved. The equilibrium concentration of DO in water in contact with air is a function of temperature and pressure. Values for DO in water in equilibrium with water-saturated air at (1 atmosphere) at temperatures from 0 °C to 50 °C are given in [9]. The temperature (from 10 °C to 40 °C) affects to dissolve oxygen magnitude (from 10.9 mg/L to 6.6 mg/L) respectively.

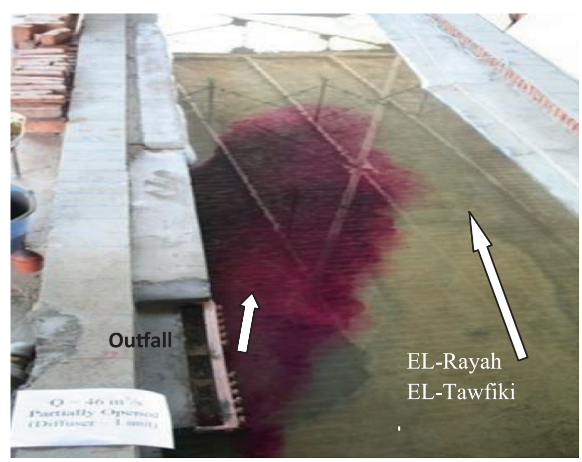

Figure 11 Dye diffusion at dominant flow of El-Rayah El-Tawfiki for the proposed new outfall structure.

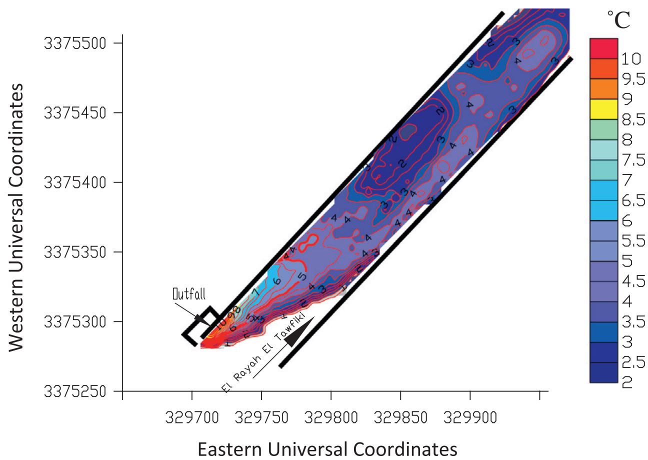

Figure 12 Thermal contours (the excess water temperature above the ambient water) at dominant flow of El-Rayah El-Tawfiki for the proposed new outfall structure.

5. Design criteria

The design of the once through cooling system should meet some criteria in order to fulfill the environmental laws that control the discharge of heated water to open channels [10,11], the MWRI Law state that:

- The maximum absolute water temperature due to the effluent discharge is 35 °C.
- The water temperature outside the mixing zone does not exceed 5° C above the ambient water temperature.

These criteria are common for all types of canals, and since the AWQI of El-Rayah El-Tawfiki was found to be about 70%, i.e. fair, it should be satisfied MWRI Law. The thermal mixing formulae that derived by [12], is shown as follow:

$$\frac{\Delta t}{\Delta t_0} = c_1\left(\frac{q_r}{q_0}\right)m\left(\frac{X}{b}\right)^n$$

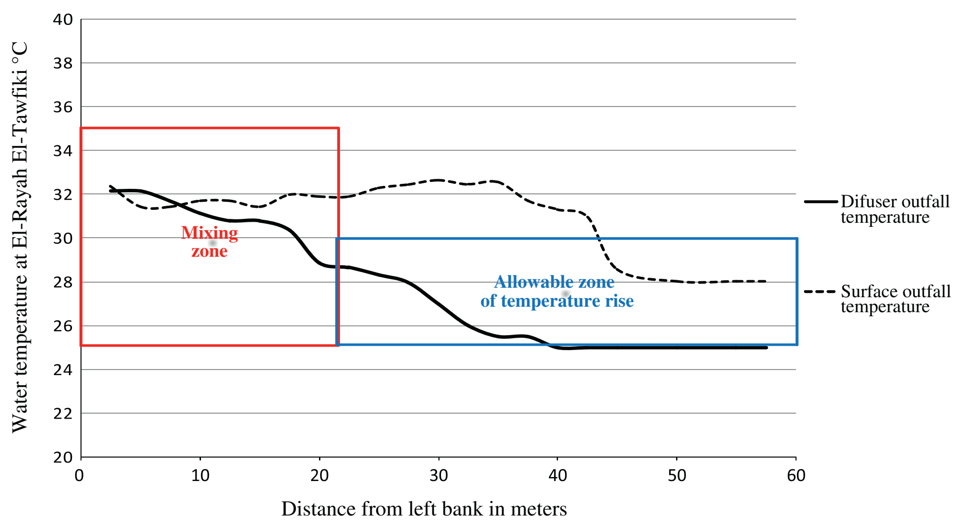

Figure 13 Measured temperatures for a cross section at El-Rayah El-Tawfiki, downstream the outfall by 25 m.

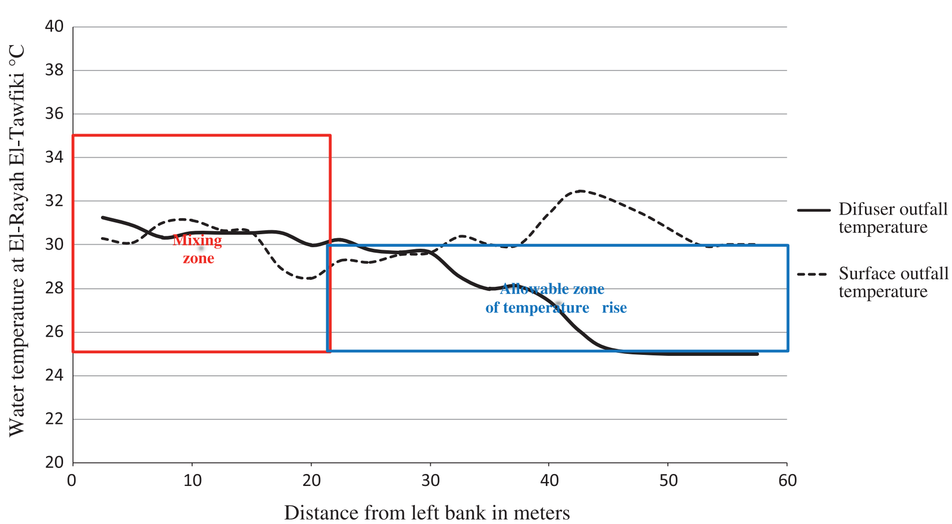

Figure 14 Measured temperatures for a cross section at El-Rayah El-Tawfiki, downstream the outfall by 50 m.

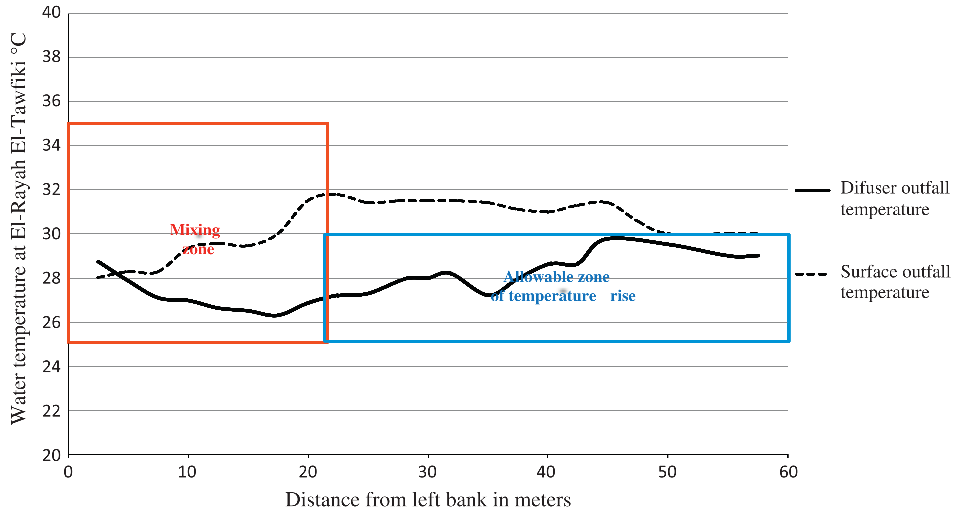

Figure 15 Measured temperatures for a cross section at El-Rayah El-Tawfiki, downstream the outfall by 135 m.

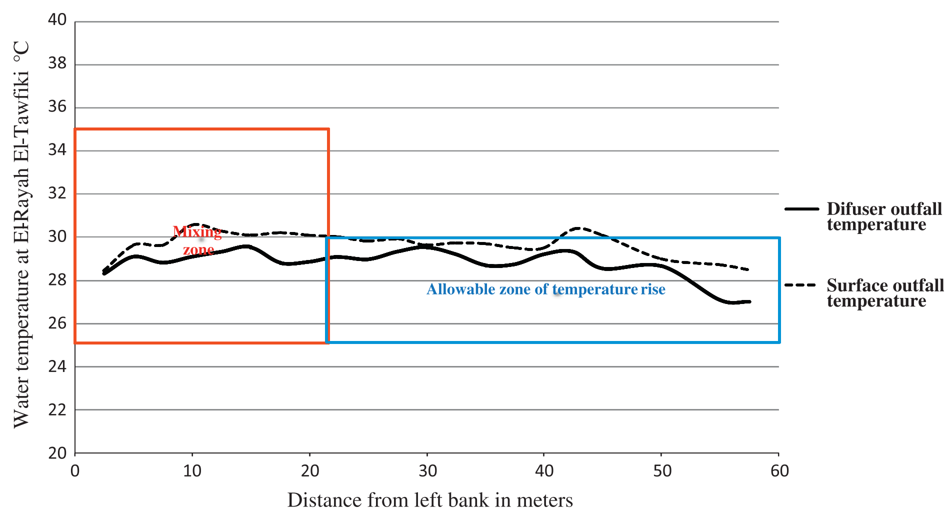

Figure 16 Measured temperatures for a cross section at El-Rayah El-Tawfiki downstream the outfall by 225 m.

where Δt is the specified temperature excess (°), Δt_0 the initial temperature excess (°) q_r the river discharge (L^3/T) q_0 the outlet discharge (L^3/T) x the center line plume length (L), b the width of outlet (L).

m, n, $c1$ coefficients are determinate from the measured field data (the coefficients are variable according to river nature), [12].

As the dominant flow pattern for El-Rayah El-Tawfiki is fixed and the Banha Power Plant intake/outfall flow ratio $\frac{q_r}{q_0}$ also is fixed, so, to minimize the mixing zone, the width of the outlet should be wider to increase mixing process and divide the outfall area to many jets.

6. Proposed new outfall structure

After performing the theoretical and experimental hydraulic calculations, it is proposed to design the outfall with 24 nozzles arranged in two rows, the internal diameter of each nozzle is 700 mm and the distance between the nozzles is 2000 mm as shown in Figs. 8–11 presents dye diffusion at the dominant flow for the proposed new outfall structure and Fig. 12 presents the thermal contours (the excess water temperature above the ambient water) at dominant flow for the proposed new outfall structure. The excess temperature above the ambient did not exceed 4 °C just upstream Gamgara Regulator, outside the mixing zone, which was less than 5 °C. This complies with the Egyptian environmental water quality standards and laws.

Table 1 Effect of Temperature on dissolved oxygen.

Saturated dissolved oxygen (DOX) levels		
Temperature (°C)	Saturated level of DOX (mg/L)	
	Freshwater	Sea water
10	10.9	9.0
20	8.8	7.4
30	7.5	6.1
40	6.6	5.0

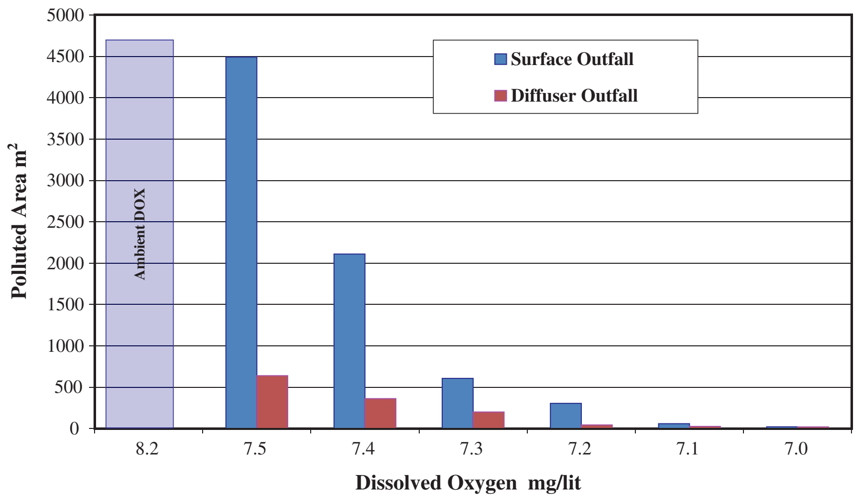

Figure 17 Predicted dissolved oxygen surface area downstream the outfall at El-Rayah El-Tawfiki.

7. Comparison between surface and diffuser outfall

Figs. 13–16, show the comparison between using surface outfall and diffuser outfall with temperature measurements cross section at El-Rayah El-Tawfiki, downstream the outfall by 25, 50, 135 and 225 m. Apparently, using diffusers outfall improve the mixing process and reduce the thermal pollution to the allowable limits according to MWRI environmental laws. According to Table 1 [9], Fig. 17 shows the predicted dissolved oxygen surface area downstream the outfall at El-Rayah El-Tawfiki. A comparison between using surface outfall and diffuser outfall show the effect of temperature reduction to vital aquatic parameters like dissolved oxygen.

8. Conclusion

The discharge of thermal effluent from thermal power plants into water bodies would result in harmful impacts on the ecological life. The higher forms of aquatic life require oxygen for survival and the high temperature decreases its concentration in the water. This phenomenon was found that it will be critical in El-Rayah El-Tawfiki especially with the construction of Banhaa Power Plant which will abstract water from it for its cooling system. El-Rayah El-Tawfiki has an Average Water Quality Index, AWQI of about 70% which is characterized as fair for human activities. So, with the construction of the power plant, the water in El-rayah El-Tawfiki will have high temperature which will decrease the dissolved oxygen in the water.

For solving this problem, a physical model study was conducted for designing the intake/outfall combination to comply with the Egyptian environmental laws. Based on the dominant flow patterns, and temperature measurements, two alternatives for intake/outfall configuration were tested. The first design of outfall structure consisted of surface open channel. The thermal plume area which has temperature rise more than 5 °C above the ambient was 4500 m^2. This means that this area will have dissolved oxygen value less than 7 mg/L which is considered a critical value and can affect on the water quality and ecological life in this region and consequently not comply with the environmental laws. Upon these results, it was proposed to widen the outfall with 24 nozzles (multi port diffuser) arranged in two rows and separate the outfall into many jets. This new alternative for the outfall hydraulic design succeeded to improve the mixing process and decreased the area of temperature rise to be more than 5 °C to 600 m^2 instead of 4500 m^2 which is considered a small area and has minor affect on the aquatic live in this region.

9. Recommendation for future studies

Based on the study results and conclusions, it was recommended for future researches to:

- Inter-relate of the environmental laws with the classification of AWQI for each canal.
- Design according to the environmental aspects and the AWQI.
- The hydraulic methodology should increase the the mixing process and minimize the mixing zone area. The width of the outlet should be widened as possible.

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