Combined Near-field and Far-field Models to predict Mixing Processes of Complex Cooling Water System

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Abstract

The aim of this paper is to improve the predictive capability of the mixing processes of complex cooling water system where several discharge sources may interact with large pollutant loadings in a critical layout like the Nile River. An approach to link validated near-field model predictions to hydrodynamic far-field simulations was developed. In this strategy, environmental conditions from the near-field model were used to produce boundary conditions for execution of a suite of far-field simulations. This is to allow more detailed presentation of the mixing processes. Also, it was found that one type of hydrodynamic models used to predict the mixing processes delivered highly conservative plume dilution predictions in and around the outfall site. In this study, a linking approach between the near-field model "CORMIX" and a far-field model "DELFT 3D" was employed. The results of "CORMIX" model was used as boundary conditions in the simulation process of "DELFT 3D" model. As a case study to apply this methodology, the impact of the discharge of heated effluents from diffuser outfall of the South Helwan Power Plant (planned to be built) into Nile River on the temperature distribution of the Nile water in the vicinity of the intake structures of El-kureimat Power Plant which is located 7.5 km downstream of the South Helwan Power Plant was investigated. The model results show that the thermal plume transport from the outfall of the South Helwan Power Plant will cause a temperature rise in the vicinity of the intakes of El-kureimat Power Plant of 0.7 ^{o}C in the summer time and an average rise of 1.67 ^{o}C in the winter time. Also, the produced mixing zone sizes in the vicinity of the two power plants are within the limitations stated by the aquatic environmental laws.

Keywords: Near-field, Far-field, CORMIX, DELFT 3D, Mixing Process, Power Plants, Outfalls, Intakes, Environmental Protection.

1. INTRODUCTION

The hydrodynamics of an effluent continuously discharging into a receiving water body can be conceptualized as a mixing process occurring in two separate regions. The first region which is close to the outfall structure is called the near-field region. In this region, the initial jet characteristics of momentum flux, buoyancy flux (due to density differences), and outfall geometry influence the effluent trajectory and degree of mixing [10]. The second region, which is the far-field region, the turbulent plume travels further away from the source. Ambient environmental conditions will control trajectory and dilution of the turbulent plume through buoyant spreading motions, passive diffusion due to ambient turbulence, and passive advection by the often time-varying, non-uniform, ambient velocity field. An extensive survey of these processes has been given by [4, 7, 9, 12 and 15]. The physical process for the flow discharge in water bodies environment can be seen in Figure (1).

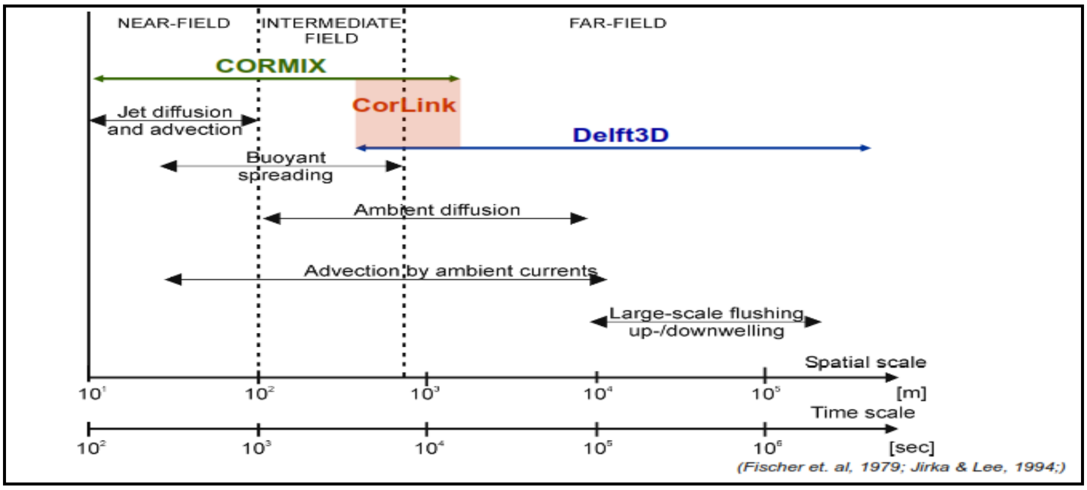

Figure 1: The Physical Processes of Flow Discharge in Water Bodies' environments [7]

There are several diagnostic and predictive methodologies for testing the mixing of different point sources and checking its compliance with environmental quality standards [2]. It was found that deploying typically adopted 'direct insertion' techniques to simulate the brine discharge within the hydrodynamic model was problematic. Specifically, it was found that, the direct insertion technique delivered highly conservative brine dilution predictions in and around the outfall site, and these were grid and time-step dependent [3]. To improve the predictive capability, a strategy to link validated near-field model predictions to hydrodynamic far-field simulations was devised. In this strategy, environmental conditions from the near-field model were used to produce boundary conditions for execution of a suite of far-field simulations [8, 13].

In this research, a linking approach of a near-field model with the far-field model is implemented. A case study of South Helwan and El-Kureimat power plants discharging their heated effluents from several outfalls into the Nile River was chosen to demonstrate the linking approach especially with complex systems where several discharge sources may interact with large pollutant loadings in a critical layout like the Nile. The Nile water is not only used for the agricultural purposes but also for domestic, navigational and recreational purposes as well.

2. OBJECTIVES

The main objective of this research is to deploy a technique that is capable of describing all important spatial and temporal scales of the mixing processes especially with complex systems where several discharge sources may interact with large pollutant loadings in a critical layout like Nile River which serves as the main source for water supply to agriculture, domestic purposes, navigational and recreational uses in Egypt. This is to verify that the mixing process from point sources complies with environmental quality standards.

3. CASE STUDY

To achieve the aim of this research, the following activities were carried out:

- Two adjacent thermal power plants separated by 7.5 kilometers; namely South Helwan and El-Kureimat Power Plants discharging heated effluents from several outfalls into Nile River were chosen as a representation of complex systems in a critical layout.
- Apply a new technique that combines near-field and far-field models to describe with good resolution the details of physical mixing processes (mass advection and diffusion).
- Checking the compliance of the mixing process results with the environmental quality standards.

4. DESCRIPTION OF THE COOLING SYSYTEMS OF THE POWER PLANTS

4.1. Cooling System of El- Kureimat Thermal Power Plant

EL-Kureimat Power Plant is located on the East Bank of the Nile River, approximately 95 kilometers south of Cairo. It comprises two 628 MW gas/oil fired units and two combined cycle (I and II) with power generation capacity of 750 MW each. Each module of these is composed of two gas turbines 2 x 250 MW at site conditions, and one steam turbine of capacity 250 MW. The cooling system is operated according to the once-through cooling water cycle. It consists of intake structures and outlet structures. The intake structures are attached to the right bank of the Nile River in front of a small sand bar, while the discharge structure of the combined cycle unit II is located on the west side of the sand bar. All other discharge structures are located on the East Bank of the Nile River downstream the intake structures. Figure (2) shows the arrangements of both the intake and outfall structures of EL-Kureimat Power Plant cooling system with respect to the Nile River. Also, Tables 1 and 2 present the characteristics of the intake and outfall structures respectively. The cooling system discharge varies according to the operational conditions of the power plant. While, the river flow conditions at the cooling system vicinity vary along the year. The flow and the flow depth values fluctuate between the low winter flow conditions and the maximum summer flow conditions.

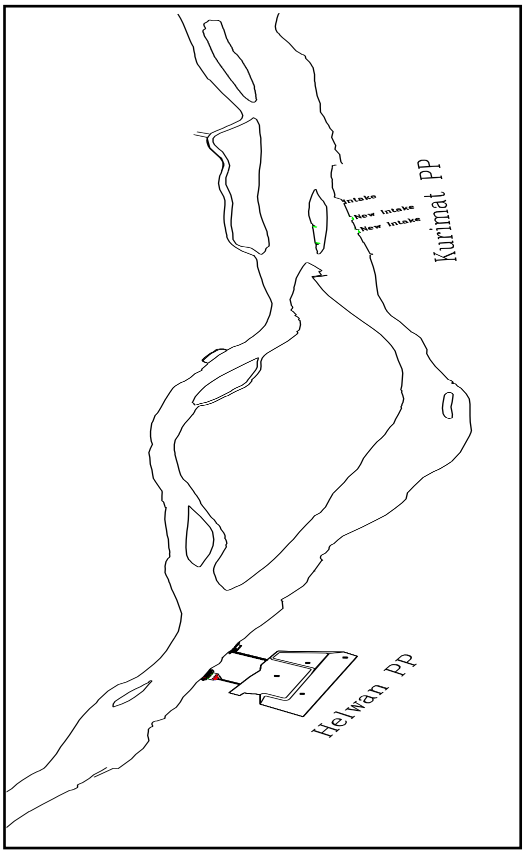

Figure 2: The Layout of El-kureimat Power Plant and South Helwan Power Plant

Table 1: Characteristics of Intake Structures of El Kureimat Power Plant

Type	Units	Power/unit (MW)	Q_{total} (m^3/s)	Width (m)	Sill Level (m) +MSL
Steam	2	628	40.28	27	(17.50)
Combined	1	750	13.6	37.6	(18.50)
Combined	1	750	13.6	37.6	(18.50)

Table 2: Characteristics of Outfall Structures of El Kureimat Power Plant

Type	Units	Power/unit (MW)	Δt (°C)	Q_{total} (m^3/s)	Width (m)
Steam	2	628	10	40.28	17
Combined	1	750	8	13.6	8
Combined	1	750	8	13.6	8

4.2. Cooling System of the South Helwan Thermal Power Plant (SHTPP)

A new power plant; South Helwan Thermal Power Plant (SHTPP) is planned to be built. The capacity of the plant is 3×650 MW and will be located about 7.5 km upstream of El-Kureimat Power Plant at the right bank of the Nile River. The plant will use the Nile River water for its once-through cooling system of the steam turbine generator. Water for cooling will be abstracted from the river through the plant intake. The effluents will be discharged back to the river through the outfall structure. The cooling system of the power plant consists of the intake and the outfall structure. The outfall structure of the plant is designed as a diffuser discharge with 75 ports of 0.7 m diameter each. The total effluent discharge is 75 m^3/s with excess water temperature of 8º C above the ambient water.

4.3. The Flow Condition of the Nile River in the Vicinity of the Power Plants

The Nile River flow rate fluctuates between 2245 m^3/s and 550 m^3/s in the summer and winter periods respectively. Also, the ambient water temperature is 28^o C and 15^o C in the summer and winter periods respectively.

5. EFFLUENT DISCHARGE MODELS

Regions with multiple current regimes (inertial or buoyancy driven) and with large pollutant loadings, especially where several sources may interact and additional diffuse sources may exist; near-field models must be supplemented by larger-scale (far-field) transport and water quality models. The latter are capable of prediction over greater distances in the water body of the concentration distributions for different pollutants. They do not, however, have the high spatial resolution that is required to predict near-field mixing processes which necessitates the approach of combined modeling to be utilized

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5.1. Near-Field Model

The near-field focused expert-system CORMIX [1, 11 and 14] was chosen because it addresses the full range of discharge geometries and ambient conditions, and predicts flow configurations ranging from internally trapped plumes, buoyant plumes in uniform density layers with or without shallow water instabilities. Boundary interaction, upstream intrusion, buoyant spreading and passive diffusion in the intermediate field are also considered.

5.2. Far-Field Model

The velocity field and the pollutant concentration field may be obtained using a number of public domain or commercial codes that are available at present to aid in the prediction and engineering design of effluent discharge schemes. In this study DELFT3D model, which is developed by Deltares [5 and 6] was chosen as a modeling tool for the following reasons:

- Hydrostatic pressure assumption: The water depth is assumed to be much smaller than the characteristic horizontal length scale. Thus, the shallow water depth assumption is valid and the vertical momentum equation is reduced to the hydrostatic pressure equation.
- Boussinesq approximation: Density changes are neglected except when the density is multiplied by gravitational acceleration, thus retaining the important stratification (i.e. buoyancy) effects.
- The equations are formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates on the globe.
- The following effects are included in the Delft 3D model: tidal forcing, Coriolis force, density driven flow, advection–diffusion solver, wind and atmospheric pressure, advanced turbulence models to account for the vertical turbulent viscosity and diffusivity.

6. COMBINING NEAR- AND FAR-FIELD MODELS

The recommended procedure to incorporate the near- field model with the far- field model is based on a simple approach which consists of the following steps: calibration has to be done using existing field-data, near-field mixing and transport modeling, intermingle both the far-field and the near-field models and far-field transport modeling with Delft 3D. The following approach was recommended by [8] based on the following linking algorithm.

- Set up the field measurements (velocity and temperature fields) as input for the near-field model.
- Near-field modeling with CORMIX.
- Analyze and prepare the near-field model results as input for the far-field model.
- Far-field modeling with DELFT 3D.

7. NEAR-FIELD MODELING OF SHTPP'S OUTFALL WITH CORMIX

CORMIX is a mixing zone model for the assessment of near field dilution and mixing zones resulting from continuous point source discharges such as the diffuser outfall. In this research, CORMIX is employed using the baseline time-series as input files. The proposed outfall is parallel to the river bank with a 150 m diffuser that has 75 evenly spaced ports. The ports are arranged in a staged diffuser configuration, staggered at an angle of 40° with the center line to allow for maximum dispersion of the effluent. Figure (3) shows the configuration of the intake and outfall structures of the South Helwan Thermal Power Plant. Furthermore, effluent data and the diffuser geometry have to be specified. The parameters used in CORMIX model are listed below (case of summer flow):

- Average depth of diffuser 6 m
- Average depth in Area downstream 7 m
- Ambient current velocity1.123 m/s
- Wind speed 0 m/s (calm condition)
- Bottom friction Manning's N 0.028
- Ambient water temperature 28 °C
- Diffuser distance offshore 5 m (parallel to the right bank)
- Port diameter 0.70 m
- Riser height 1.0 m
- Staged diffuser configuration, Gamma = 0, Theta = 0, beta = 45, and perpendicular to current Sigma = 45
- Number of ports 75
- Port spacing 2.03 m (150 m length / 75)

- Total effluent flow 75 m^3/s
- Effluent Temperature +8 °C

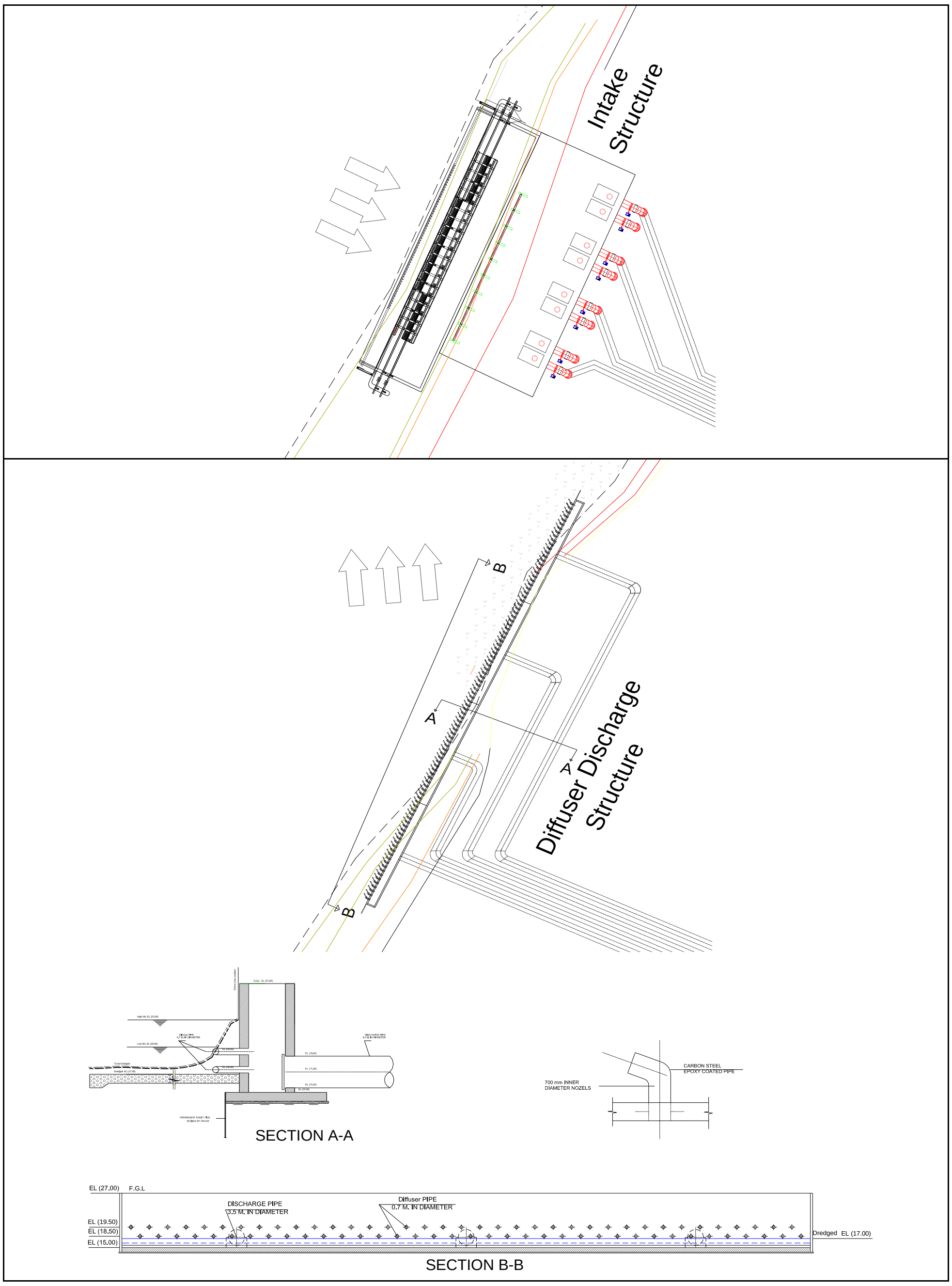


Figure 3: The configuration of the intake and outfall options of South SHTPP

The short travel time of the effluent in the near-field region allows running CORMIX without decay processes. Two simulations were carried out using the mixing zone model CORMIX with the above input parameters to find the concentrations and dilutions of the effluent discharge just getting out of the diffuser ports. These simulations include the summer flow conditions and the winter flow conditions. CORMIX results are plume trajectories and concentrations or dilutions. These are classified into two classes: surfacing plume and internally trapped plume. For each class time series files are computed containing plume geometries (horizontal and vertical extent with respect to the centerline), plume centerline orientation and vertical location (with respect to the diffuser and its midpoint), volume flux and mass flux at the coupling position defined as a distance from the diffuser midpoint. Figures (4) and (5) show the concentration of the temperature plume with the distance starting from the outfall centerline in case of summer and winter flow conditions. The temperature plume concentration above the ambient water temperature obtained from the CORMIX was accurately interpreted into DELFT3D model through X, Y, and Z coordinates and the excess temperature values.

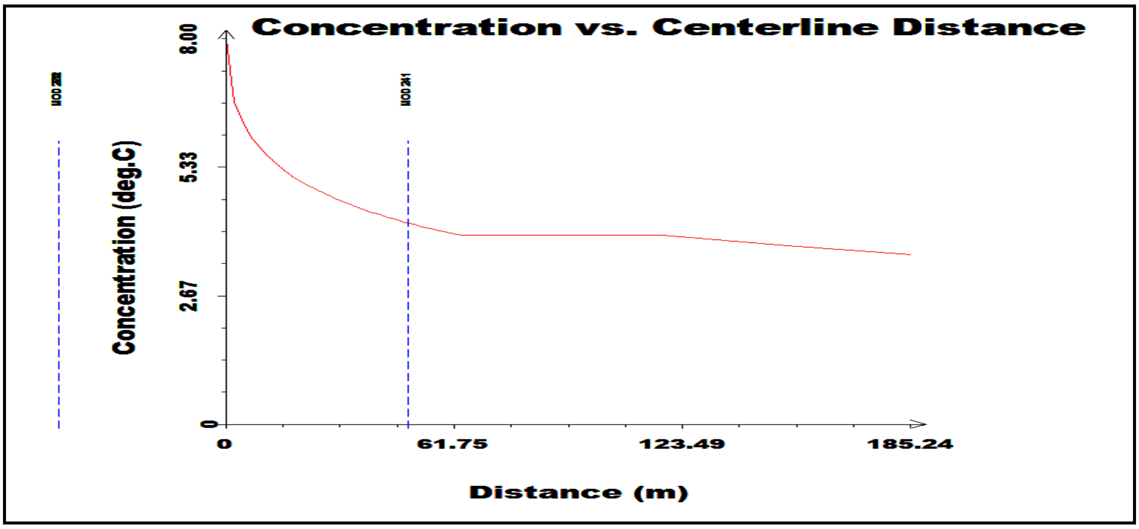


Figure 4: The Concentration of the Plume Temperature along a Distance Measured from the Outfall Centerline (Summer Case of Maximum River Flow)

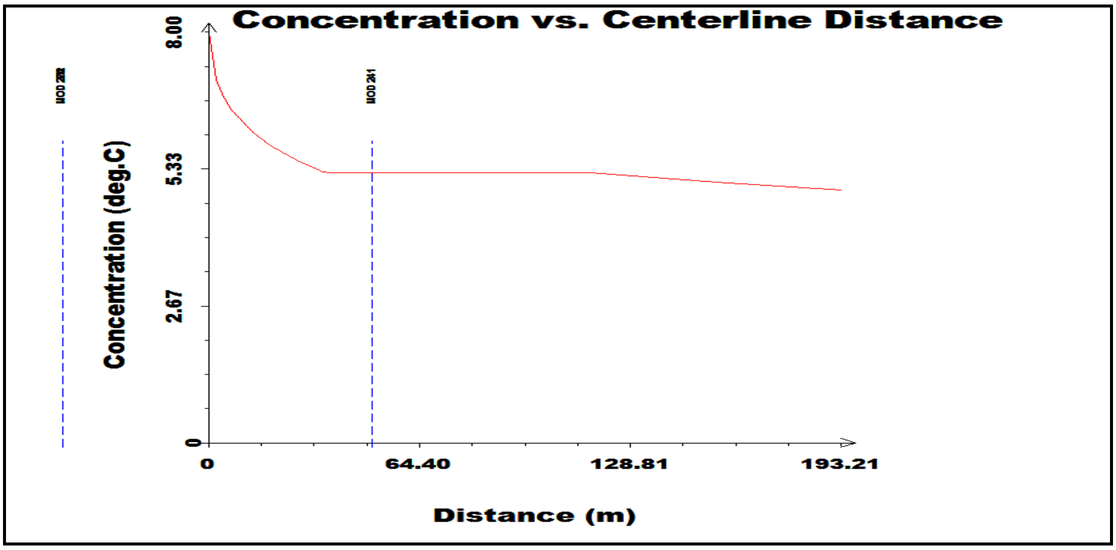


Figure 5: The Concentration of the Plume Temperature along a Distance Measured from the Outfall Centerline (Winter Case of Minimum River Flow)

8. FAR-FIELD MODELING WITH DELFT 3D.

A three dimensional far-field hydrodynamic numerical flow model was developed to simulate the flow pattern in the vicinity of the study area including the intakes/outfalls of both South Helwan and El-Kureimat Power Plants. The model covers a length of about 13.0 km along the Nile River (3.5 km upstream of the South Helwan Power Plant and extended 2 km. in the downstream of El-Kureimat Power Plant). The model is about 0.50 km. wide and has a high resolution near the plants. The model is used to study the thermal plume effluent from the outfall of South Helwan Power Plant and its effect on water temperature in its vicinity and at the intakes of El-Kureimat Power Plant. The model was calibrated and validated using the existing field measurements data as described in [9]. The flow pattern in the cooling system vicinity of the SHTPP as modeled by Delft 3D is shown in Figure (6).

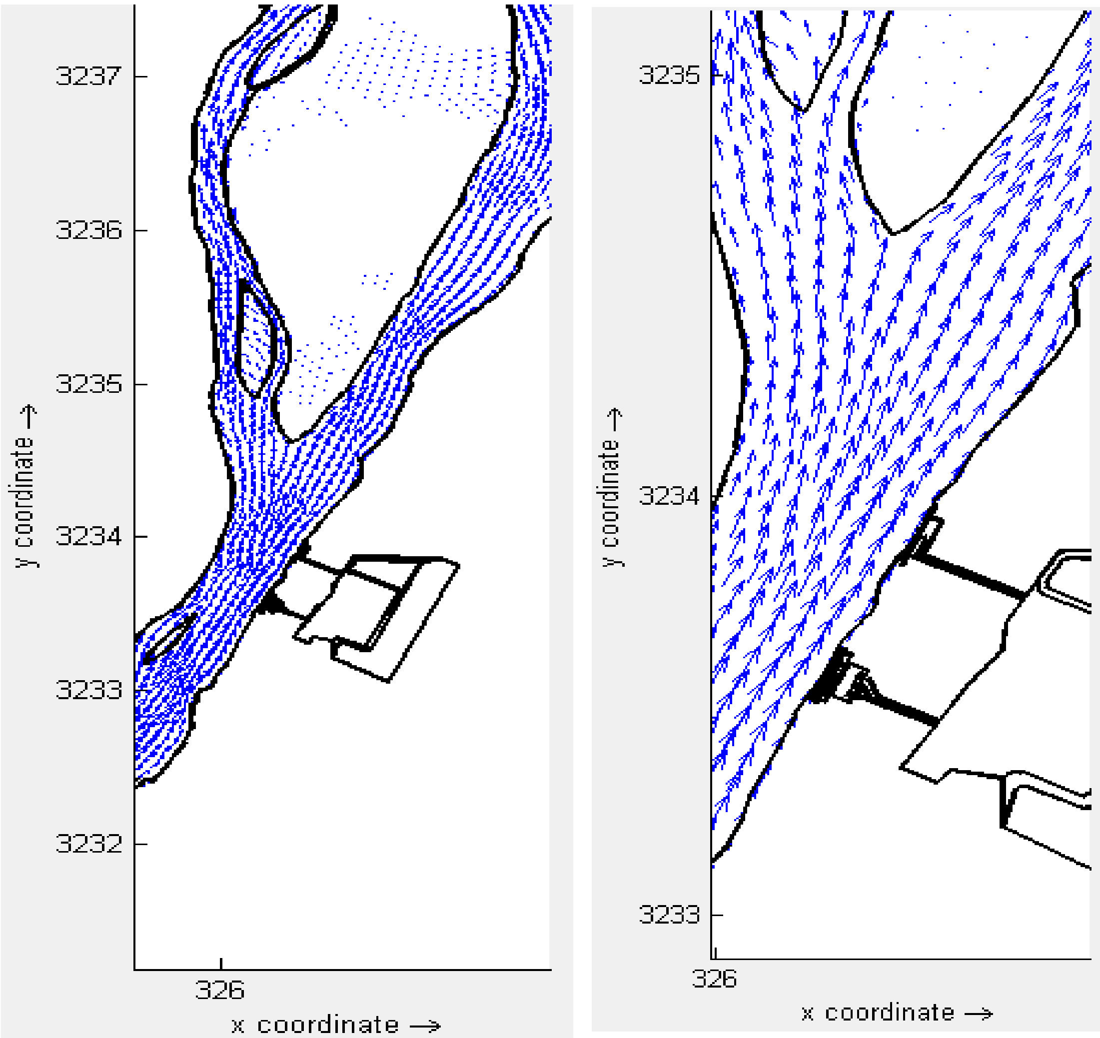


Figure 6: The Flow Pattern in the Cooling System Vicinity of the SHTPP

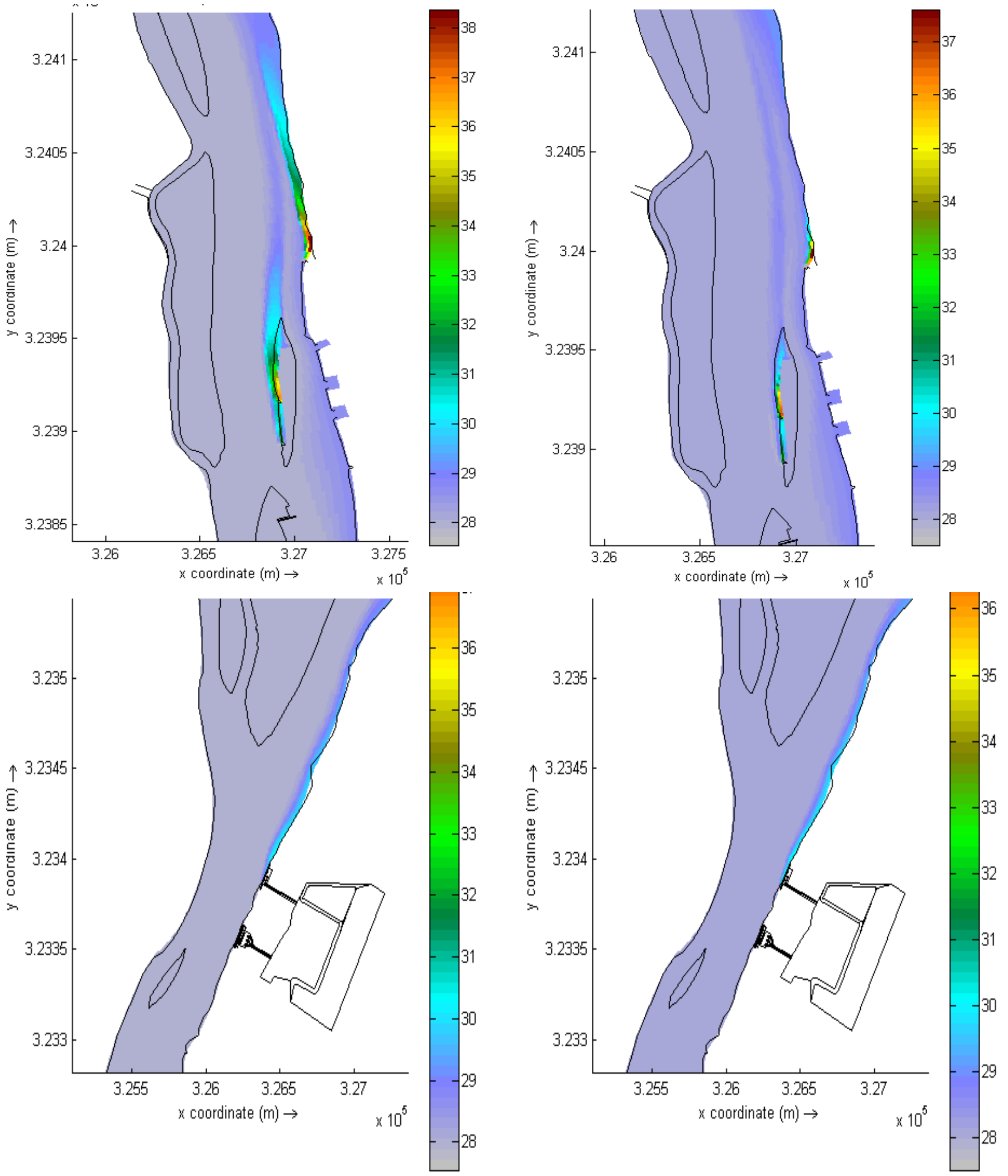
9. RESULTS AND ANALYSIS

From the application of the far-field model after linking it with the results of the near-field model, the followings could be depicted:

- There is no stratification in the temperature in the vicinity of the South Helwan and El Kureimat power plants all the year around.
- There is no recirculation of the heated effluent from the outfall of the South Helwan Power Plant to its intake in the winter and the summer time as well.
- The transport of the thermal plume from the outfall of the South Helwan power plant further downstream will cause a temperature rise in the vicinity of the intakes of El-Kureimat Power Plant as shown in Table 3:
- It is clear from Table 3 that the mixing process in the summer will cause more dilution than in the winter. This is because the water depth and the flow velocity in the summer are much higher than in the winter and this will cause more dilution.
- The mixing zone size for both plants complies with the aquatic protection laws, Law No. 48, 1982 and Law No. 4, 1994 in Egypt.
- Figures (7) and (8) show the temperature distribution in the vicinity of the power plants in the top and bottom layers in the summer and winter periods respectively.

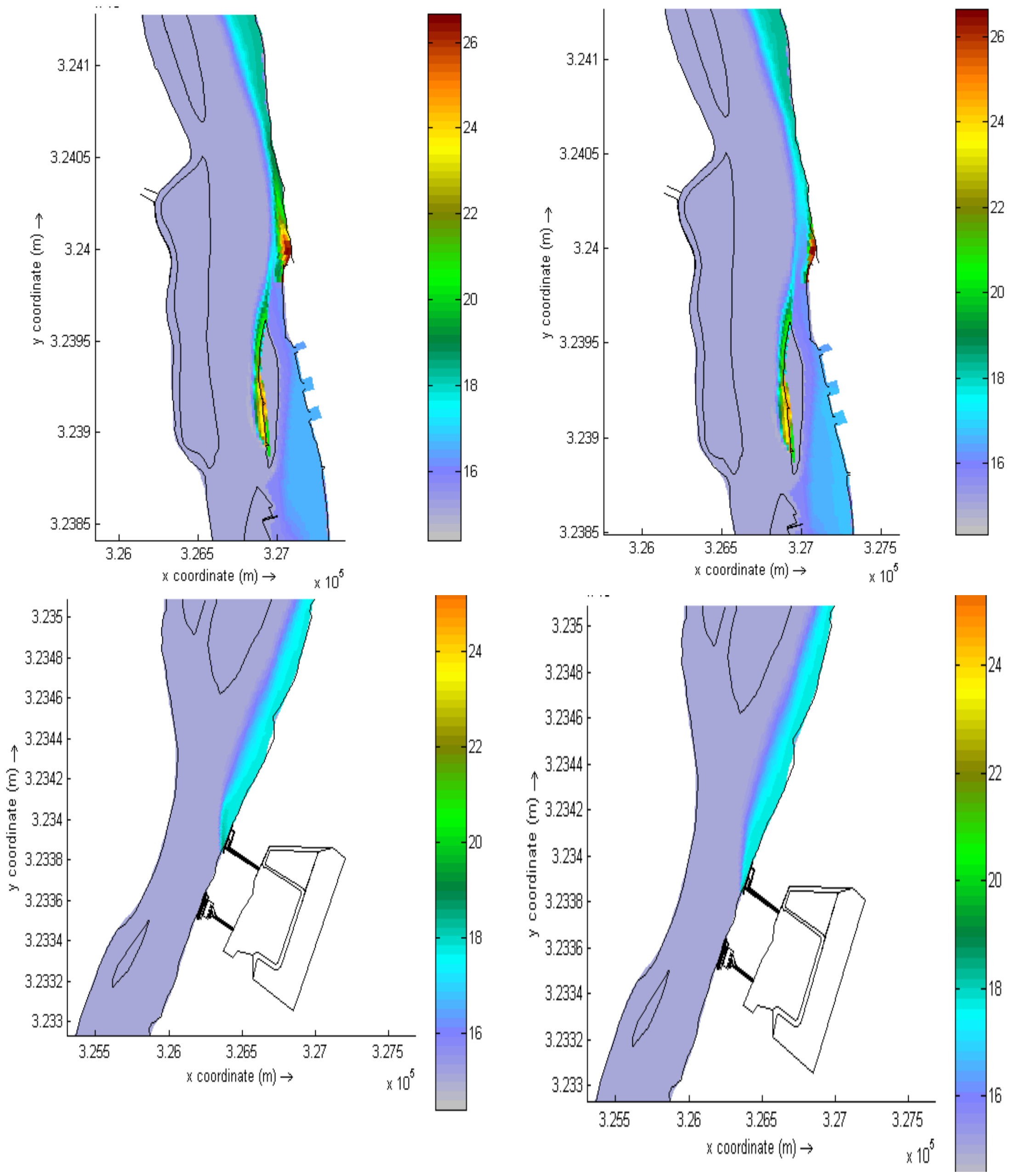
Table 3: Temperature Rise at El-Kureimat Intakes after operating SHTPP

Time	Temperature Rise (ΔT°C) above Ambient Water Temperature		
	Intake I	Intake II	Intake III
Summer	0.7	0.7	0.7
Winter	1.5	1.75	1.75



Temperature distribution in the top layer   Temperature distribution in the bottom layer

Figure 7: Temperature Distributions in the Summer Period



Temperature distribution in the top layer Temperature distribution in the bottom layer

Figure 8: Temperature Distributions in the Winter Period

10. CONCLUTIONS

From the study results and analysis, the following could be concluded:

- The predication of pollutant concentrations due to the discharge of wastewater effluents in water bodies' environments is essential for water quality control.
- There is no general model that is capable to simulate solely all important spatial and temporal scales of the mixing process, especially with complex systems where several discharge sources may interact with large pollutant loadings in a critical water body.
- The linking of mixing zone models (near-field) and general water quality models (far filed) became the most important tool as scientific approaches and techniques for predicting environmental impacts for large regions and long time periods.

- A simple approach that combines the results of the near-field model (CORMIX) with the far-field model (DELFT 3D) was applied.
- The impact of the discharge of the heated effluent from the outfall of the South Helwan Thermal Power Plant, which is located upstream of the El-kureimat Thermal Power Plant, on the temperature rise of the ambient water in the vicinity of the intakes of El-kureimat Thermal Power Plant was studied using the linking approach between the near-field and the far-field models.
- The model results show that the thermal plume transport from the outfall of the South Helwan Thermal Power Plant will cause a temperature rise in the vicinity of the intakes of El-kureimat Thermal Power Plant of 0.7 ^{o}C in the summer time and an average rise of 1.67 ^{o}C in the winter time.
- The produced mixing zone sizes in the vicinity of the power plants are within the limitations stated by the aquatic environmental laws.

11. ABBREVIATIONS

^{o}C	Degrees Celsius
m	Meters
MSL	Mean Sea Level
N	Manning Bottom Friction
MW	Megawatt
SHTPP	South Helwan Thermal Power Plant
X	Coordinate in the X-Direction
Y	Coordinate in the Y-Direction
Z	Coordinate in the Z-Direction

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