# Investigation of pollutants dispersion from power stations

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# SHORT COMMUNICATION

# Investigation of pollutants dispersion from power stations

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## SUMMARY

Theoretical investigations were conducted of pollutants dispersion, $NO_x$, $SO_2$ and Particulate Matter (PM), from stacks of arbitrary four power plants in Libya, e.g. North Benghazi, South Tripoli, Zweitina, Khoms. The first four stations are gas power plants, while the last one is gas and steam station. Gaussian plume model has been used to identify ground-level $NO_x$ concentrations profile downwind and crosswind of the chimneys through urban regions and also the location of maximum pollutant concentrations. The study is based on the worst-case emission conditions of Pasquill stability categories (class D). Results indicate that maximum ground-level $NO_x$ impacts for all plants locate at a distance of approximately 1.0–2.5 km from stacks. The site most critical to ambient air $NO_x$ impact is Zweitina, where the plant site is in direct vicinity to residential areas. Khoms electric station exhibits the maximum emitted $NO_x$, $SO_2$, and PM intensity, about 305, 48, and 0.7 $\mu g/m^3$, respectively, that is lower than allowable concentrations recommended by World Health Organization. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: pollutants; dispersion; ground-level concentration; power plants; Libya

## 1. INTRODUCTION

Industrial air pollution has been known to be a problem since early in the industrial revolution. Towns and cities suffered noxious and sometimes deadly smog and poor quality air. In the 1960s, scientists began to realize that the effects of air pollution were global, not just local. Emissions from industries, automobiles, and other sources could have negative effects many thousands of miles away. This, scientists found out, was the reason why many lakes and forests, far removed from population centres, were dying. Thus, it is vital that we determine accurately

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pollution concentrations in the atmosphere since the quality of the air around us becomes of increasing concern.

Finardi *et al.* (2001), used three-dimensional modelling system, made by a mass-consistent wind field model and by a Lagrangian particle model, which applied to a Mediterranean complex coastal site to describe the atmospheric dispersion of pollutants emitted by thermal power plants. Egan *et al.* (2002), simulate the air quality implications of sources affected by sea breeze flows by coupling of a fine grid version of MM5, meteorological model, to drive dispersion models capable of accommodating spatially and time varying meteorological fields. Ulas Im and Yenigun (2005), describe the application of the CALMET meteorological model and CALPUFF plume dispersion model to the Yatagan district to study the impact of Yatagan Power Plant emissions on the $SO_2$ levels. Davis and Jesse (2006) had concluded that air dispersion modelling, ADM, used as an alternative or in conjunction with monitoring, is a valuable tool. ADM is not limited by physical location, and may simulate any specified meteorological conditions, making it ideal for theoretical analysis and forecasting. ADM has also been shown by Gareth, to be valuable for culpability analysis, stack design and evaluation of pollution control devices.

The aim of the present work is to study theoretically the dispersion of pollutants using Gaussian plume model, through areas surrounding 5 electrical thermal power stations in Libya. The analysis is based on actual data taken from plants site. The locations of maximum ground level pollutant concentrations in urban sites are determined as well. Libyan electrical generations are based on 17 steam and gas power plant stations, which are sited in the coast at Mediterranean Sea. The total energy produced at the end of 2002 is 4608 MW with the contribution of the steam stations of 42% while, 58% for gas plants (Libyan General Electric Company, 2002). Figure 1 shows the increase of electric power production rate through 32 years. It is due to progressive increase in the demand for electricity, which is subsequently due to exponential growth of population and industrial expansions. The energy produced from Libyan stations comes from combustion of heavy oil, light oil, and natural gas. The combustion process of fuel is accompanied by emission to the atmosphere of huge amount of exhaust gases as pollutants, such as, $NO_x$, $SO_2$, CO, dust, and $CO_2$ with increasing rate annually corresponding to that of conventional electric energy produced.

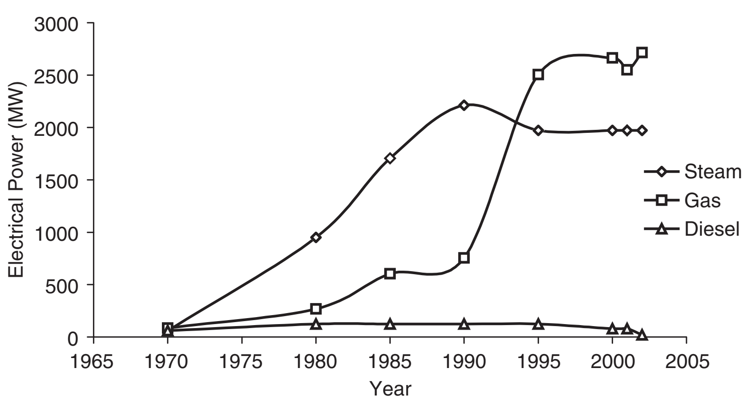


Figure 1. Growth of electric power generations in Libya (Libyan General Electric Company, 2002).



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## 2. THEORETICAL APPROACH

### 2.1. Gaussian plume model

A control volume is defined in the plume. Bulk motion and diffusion (or dispersion) transport pollutants into the upwind side of the volume and outwind side as shown in Figure 2 with the assumptions as follows:

- Steady state conditions.
- Transport by bulk motion in the $x$-direction exceeds effective diffusion in the same direction.
- Wind speed in the $x$-direction does not vary with $x$. The plume species do not react

A mass balance for the elementary volume yields

$$U\frac{\partial c}{\partial x} = D_y\frac{\partial^2 c}{\partial y^2} + D_z\frac{\partial^2 c}{\partial z^2} \tag{1}$$

The above is solved subject to the following boundary conditions:

- $c \to \infty$ as $x \to 0$;
- $c \to 0$ as $x$, $y$, $z \to \infty$;
- $D_z\, \partial c/\partial z \to 0$ as $z \to 0$;
- $\int_0^\infty \int_{-\infty}^\infty Uc(c, y, z)\, \mathrm{d}y\, \mathrm{d}z = \dot{m}_{i,s}$ at $x \geqslant 0$.

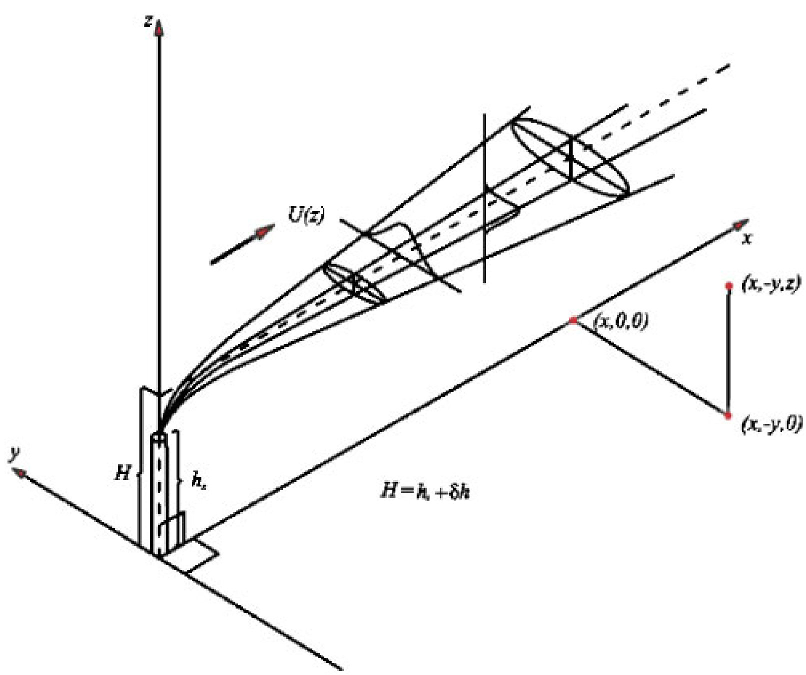


Figure 2. Pollutant dispersion from a stack.

Equation (1) is called Gauss's equation. It is used to describe the behaviour of plumes, the resulting analytical description is called Gaussian plume model (Heinsohn and Kabel, 1999). The solution to Equation (1) is

$$C_i(x,y,z) = \left(\frac{\dot{m}_{i,s}}{2\pi x(D_y D_z)^{1/2}}\right)\exp\left(\frac{U}{4x}\right)\left(\frac{y^2}{D_y}+\frac{z^2}{D_z}\right) \tag{2}$$

it is convenient to rearrange as below

$$C_i(x,y,z) = \left(\frac{\dot{m}_{i,s}}{\pi U\sigma_y\sigma_z}\right)\exp\left[\left(-\frac{1}{2}\right)\left(\frac{y}{\sigma_y}\right)^2 - \frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right] \tag{3}$$

### 2.2. *Dispersion coefficients*

Briggs presented a series of dispersion coefficients equations for the urban region depending on atmospheric stability class with the averaging time of 1 h (Griffiths, 1994). The U.S. EPA adopted these equations. For D stability in urban region,

$$\sigma_y = 0.16x(1+0.0004x)^{-1/2} \tag{4}$$

$$\sigma_z = 0.14x(1+0.0003x)^{-1/2} \tag{5}$$

### 2.3. *$NO_x$ and $SO_2$ pollutants ground-level concentrations*

Pollutant has poor solubility in soil, water, vegetation, and so on. Hence, it is assumed to be accumulated along the ground. A mathematical model accounting for the accumulation is performed (Wark and Warer, 1981), which depends on the superposition of the plume and its mirror image located a distance ($z=-H$) below the ground. The model is

$$C(x,y,z) = \frac{\dot{m}_{i,s}}{2\pi U\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]\right\} \tag{6}$$

At any downwind distance $x$, the largest ground-level $NO_x$ concentration is shown in Figure 3 and expressed as follows:

$$C_{i,\mathrm{GL}}(x,0,0) = \frac{\dot{m}_{i,s}}{\pi U\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{7}$$

### 2.4. *Particulate matter ground-level concentration*

Large particles in plumes fall to earth with a velocity $v_t$ called the settling velocity as well as being carried downwind at the wind speed $U$. Thus, for plume containing particles (Heinsohn and Kabel, 1999), the dispersion expression

$$C(x,y,z) = \frac{\dot{m}_p}{2\pi U\sigma_y\sigma_z}\exp\left\{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2 - \frac{1}{2}\left[\frac{z-(H-v_t x/U)}{\sigma_z}\right]^2\right\} \tag{8}$$

the largest ground- level PM concentration is expressed as follows:

$$C(x,0,0) = \frac{\dot{m}_p}{2\pi U\sigma_y\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{H-v_t x/U}{\sigma_z}\right)^2\right] \tag{9}$$



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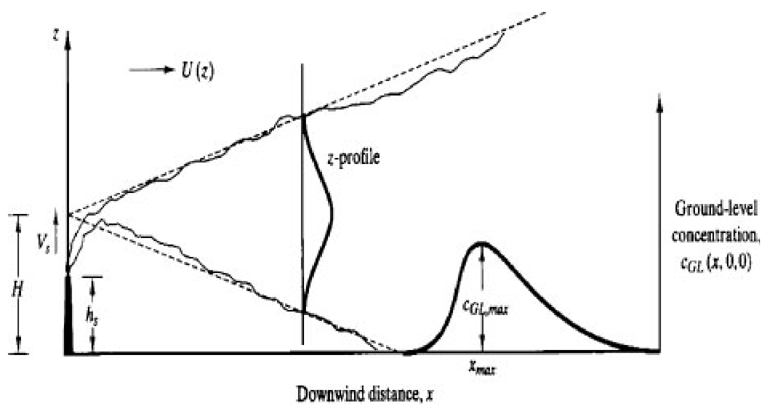


Figure 3. Ground-level pollutant concentration profile.

### 2.5. *Modified Briggs plume rise formula*

The plume rise is the maximum height achieved by the plume after leaving the stack. The height to which the plume rises must be estimated to calculate the effective stack height. Hence

$$H = h_s + \Delta h \tag{10}$$

For buoyancy-dominated plumes, unstable or neutral conditions, A, B, C, and D, the plume rise is calculated (Karl *et al.*, 2000), as follows:

$$\Delta h = \frac{1.6 f_b^{1/3} (3.5x^*)^{2/3}}{U} \tag{11}$$

$$x^* = 34 F_{\mathrm{b}}^{2/5}, \quad F_{\mathrm{b}} \geqslant 55 \tag{12}$$

$$x^* = 14 F_{\mathrm{b}}^{5/8}, \quad F_{\mathrm{b}} < 55 \tag{13}$$

where

$$F_{\mathrm{b}} = g V_{\mathrm{s}} \frac{d_{\mathrm{s}}^2}{4} \left(1 - \frac{T_a}{T_{\mathrm{s}}}\right) \tag{14}$$

### 2.6. *Wind speed*

The wind speed at stack exit is required in the analysis. The expression (Hanna *et al.*, 1982), used is

$$U(z) = U_{10} \left(\frac{z}{10}\right) \quad \text{for } z < 200\,\mathrm{m} \tag{15}$$

The value of $P$ is 0.25 for stability class D in urban areas.

## 3. DISCUSSION OF RESULTS

The results are based on the actual characteristics of four thermal power stations in Libya (e.g. North Benghazi, South Tripoli, Zweitina, Khoms. These characteristics are station type (e.g. steam or gas), kind of fuel used (e.g. heavy oil, light oil, or natural gas), fuel consumption rate, Pollutant emission rate, exit gas velocity and temperature, stacks height and diameter, and metrological data. The following hints are considered through the analysis:

- Power plants works at 100% load.
- Receptor height ($z$) is taken to be 8 m. Its position is fixed at the centreline of the mid-stack for some stations and at the centreline of stack of high emission for others.
- Super position criteria are used to analyse total emission from multiple stacks.
- Downwind and crosswind dispersions of pollutant are considered.
- The Khoms gas and steam plants are considered as one station, since the stacks of both plants are close to each other.
- Predominant wind direction at plants sites is concerned in the analysis.
- For plants using two types of fuel, one that gives rise to more amount of pollutant is used.
- Surrounded plants area is proposed to be simple terrain.
- Background of $NO_x$ and $SO_2$ concentrations are zero.
- Number of stacks for the station is of the range 3–10.
- No stacks and buildings downwash conditions, that is $V_s > 1.5\,U$. The significant adverse aerodynamic effects are avoided as well.
- Chemical reactions are not taken into account during dispersion of the pollutants.

Figure 4 illustrates the arrangement of the stacks of both khoms gas and steam power plants. Figures 5 and 6 relate $NO_x$, $SO_2$, and PM ground level concentrations in $\mu g/m^3$ emitted from Libyan power stations with downwind distance. Pollutant emission concentrations increase exponentially downstream of the stacks to a certain location where maximum ground-level value is reached, after that the gas intensity at the ground reduces. The location of the peak ground level concentration is pointed out in the range 1.0–2.5 km. Khoms power station points out maximum $NO_x$, $SO_2$, and PM intensity, about 305, 48, and 0.7 $\mu g/m^3$, respectively. This is due to the large electric generation that means of much fuel consumption rate. Both gas and

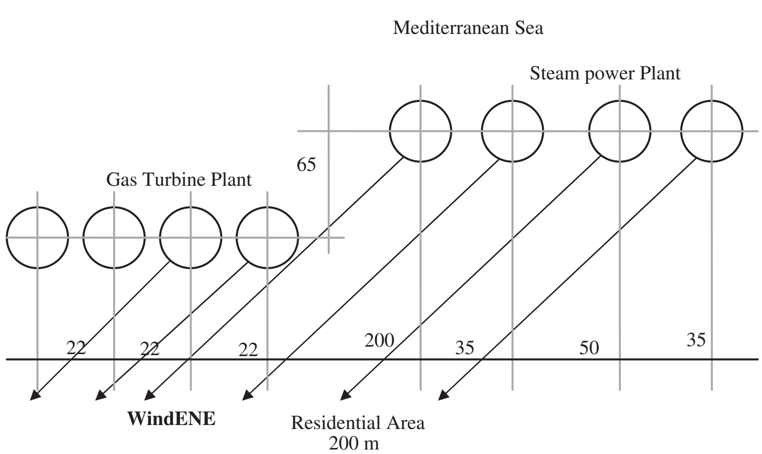


Figure 4. Layout of the stacks of Khoms plant.



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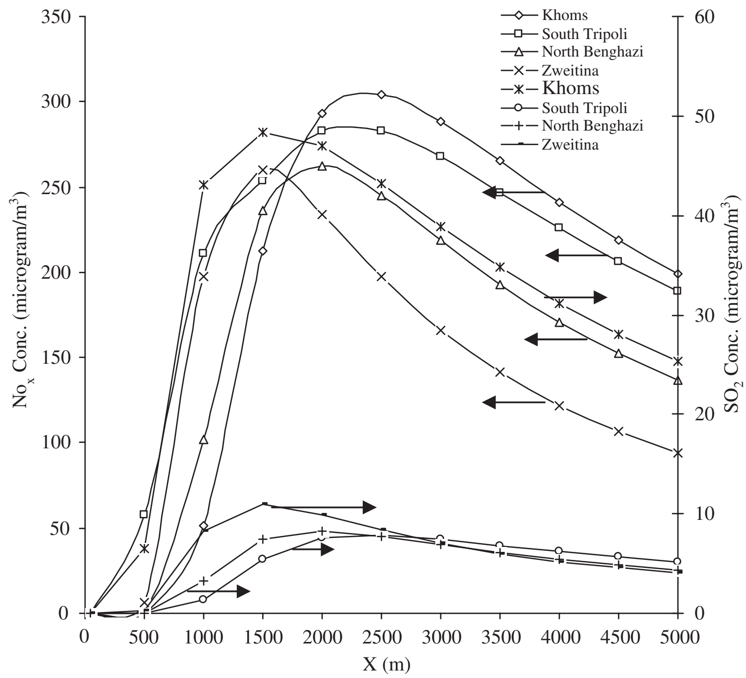


Figure 5. Ground-level $NO_x$ and $SO_2$ concentrations downwind of plants stacks.

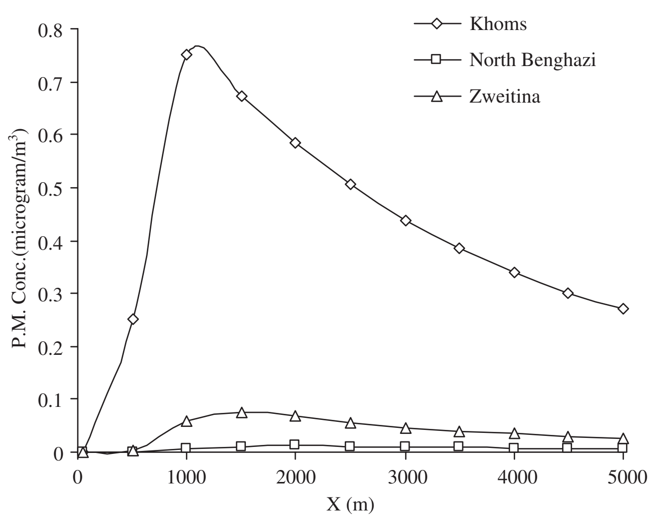


Figure 6. Ground-level PM concentrations downwind of plants stacks.

steam Khoms station is treated as one plant. The site most critical to ambient air $NO_2$ impact is Zweitina, where the plant site is close to residential areas. Crosswind $NO_x$ dispersion has also been studied as shown in Figures 7–10. The contours represent pollutant intensity, which is

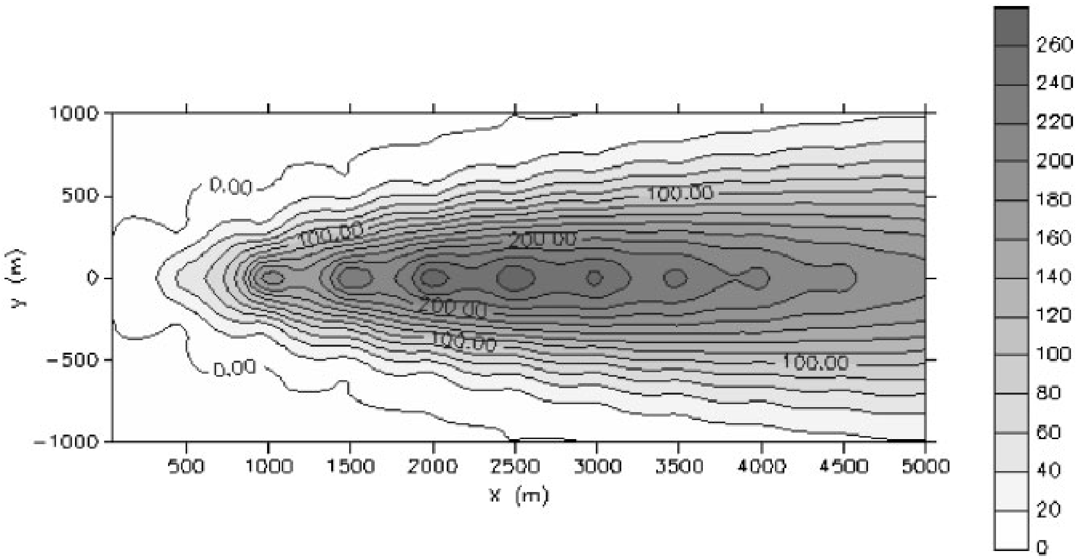


Figure 7. Ground-level $NO_x$ concentrations crosswind of Khoms plant stacks.

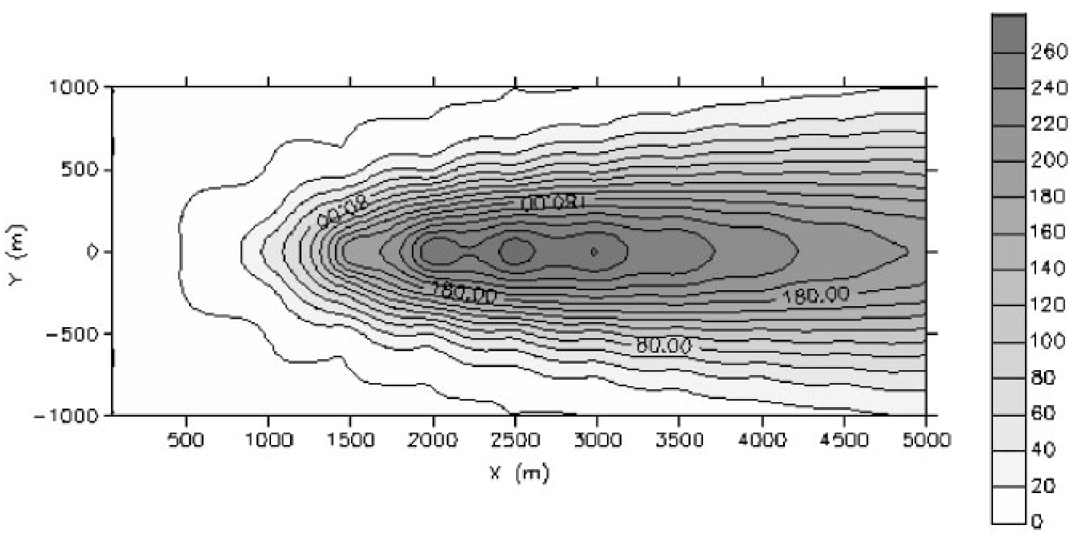


Figure 8. Ground-level $NO_x$ concentrations crosswind of South Tripoli plant stacks.

explained at right-hand scale. The color intensity increases with pollutant concentration. However, maximum ground level Pollutants concentration from studied power stations is in compliance with air pollution regulations recommended by WHO. The recommended concentration is 400, 350, and 188 $\mu g/m^3$ for $NO_x$, $SO_2$, and PM, respectively.

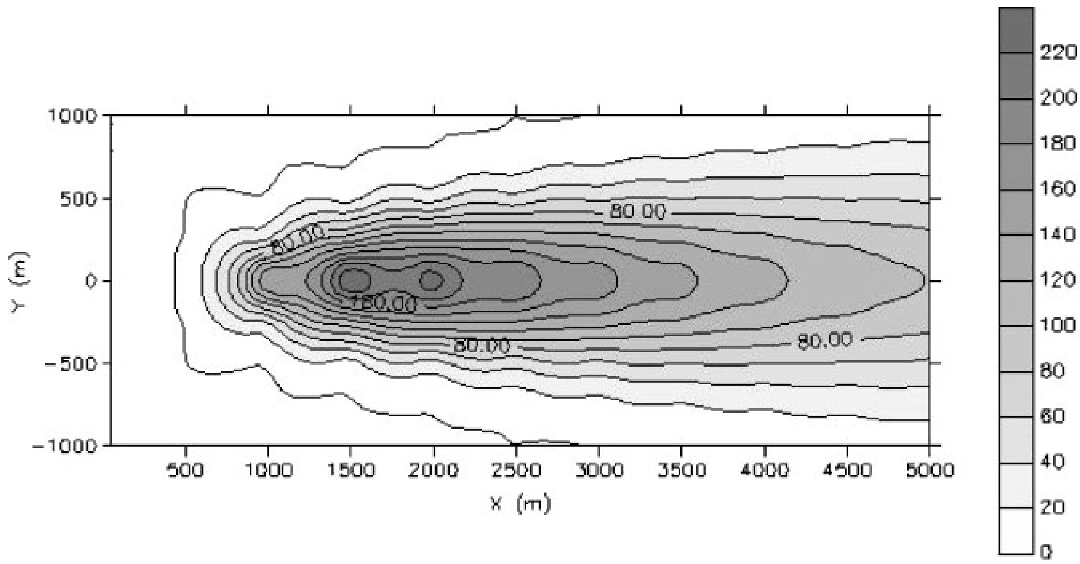


Figure 9. Ground-level $NO_x$ concentrations crosswind of Zweitina plant stacks.

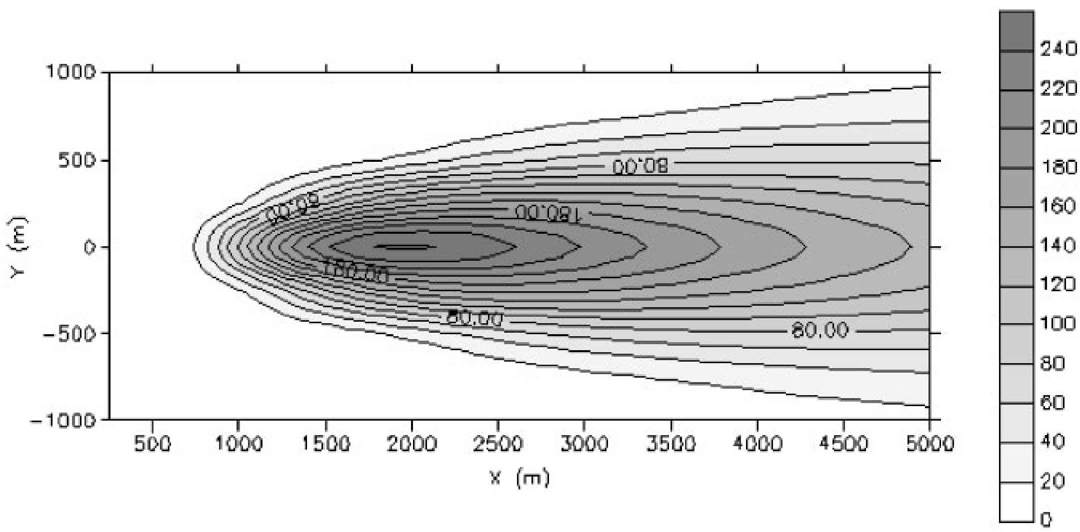


Figure 10. Ground-level $NO_x$ concentrations crosswind of North Benghazi plant stacks.

## 4. CONCLUSIONS

Analytical method based on Gaussian plume model is performed to predict $NO_x$, $SO_2$ and PM concentrations at 8 m above ground-level and the location of maximum values for Libyan electric power plants. The location of maximum $NO_x$ concentration is found to be 1.0–2.5 km. Zweitina plant site is in direct vicinity to residential areas. Thus, this site is expected to be most critical to ambient $NO_x$ impact. Khoms electric station exhibits the peak intensity of $NO_x$, $SO_2$, and PM intensity, about 305, 48, and 0.7 μg/m$^3$ respectively. However, pollutants emitted from Libyan power plants are in compliance with air pollution regulations recommended by World Health Organization. Air dispersion modeling, used in conjunction with representative practical monitoring of pollutants hourly, daily or annually is essential at different locations surrounding power plants to insure that populated areas are safe.

## NOMENCLATURE

| | |
|---|---|
| $C$ | = species concentration (μg/m$^3$) |
| $d_s$ | = stack diameter (m) |
| $D$ | = diffusivity (m$^2$/s) |
| $F_b$ | = buoyancy flux parameter (m$^4$/s$^3$) |
| $h_s$ | = stack height (m) |
| $H$ | = effective stack height (m) |
| $\delta h$ | = plume rise(m) |
| $\dot{m}_{i,s}$ | = pollutant emission rate from stack (μg/s) |
| $\dot{m}_p$ | = particulate emission rate from stack (μg/s) |
| $P$ | = power in Equation (15) |
| $T$ | = temperature (K) |
| $U$ | = wind speed (m/s) |
| $V_s$ | = exit gas velocity (m/s) |
| $V_t$ | = particle settling velocity (m/s) |
| $x$ | = downwind direction (m) |
| $x^*$ | = distance to final plume rise (m) |
| $y$ | = crosswind direction (m) |
| $z$ | = vertical direction (m) |

*Subscript*

| | |
|---|---|
| $a$ | = atmosphere |
| $i$ | = species |
| GL | = ground level |
| $s$ | = stack |
| $x$ | = $x$-direction |
| $y$ | = $y$-direction |

*Greek symbols*

| | |
|---|---|
| $\Delta$ | = difference |
| $\sigma$ | = dispersion coefficient (m) |

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