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PARTICULATE MATTER AND HEALTH	• *exposure to particulate matter* • *health aspects of atmospheric particulate matter* • *full chain approach*
PARTICULATE MATTER AND REGULATORY ISSUES	• *issues related to monitoring of particulate matter* • *legislative aspects* • *abatement strategies*

6.2. MODELING OF PM_{10} DISPERSION FROM COAL THERMAL POWER PLANTS KOSTOLAC A AND B

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ABSTRACT

Serbian electricity production is predominantly based on coal power plants, which produce large sources of particle matter emissions. Modeling of PM_{10} dispersion from the combustion process of thermal power plants Kostolac A and B (TEKO A and TEKO B) is performed in order to examine the impact of the newly built TEKO B's Flue Gas Desulphurization (FGD) units, and the results are presented in this paper. Two scenarios are discussed within this study, "without FGD" and "with FGD". The AERMOD dispersion model, with hourly meteorological data (five years in row) from a representative measuring station, is used as modeling tool. Despite the large reduction in emission values of TEKO B after installation of the FGD system, the results achieved indicate that the FGD has had no significant impact on air quality in the observed domain, due to dominant influence of TEKO A and characteristics of TEKO B stack/s.

INTRODUCTION

Serbian electricity production is predominantly based on coal power plants, which produce large sources of particle matter emissions. All thermal power plants (TPP) are equipped with electrostatic precipitators (ESP), as a technique to reduce particulate emissions. Total emissions of PM in 2016 from all coal power plants in Serbia were 12.501,978 t (PE EPS, 2016), while TPP Kostolac A and B, with a current total installed capacity of 1000 MWe, had total emissions of 3.197,000 t (PE EPS, 2016). TPP Kostolac A consists of two units A1 (100 MWe) and A2 (210 MWe), while TPP Kostolac B has two equal units B1 and B2 (2x350 MWe). Despite high SO_2 emissions, these TPPs, as well all other TPPs in Serbia, have operated from the very beginning of their operational time without Flue Gas Desulphurization (FGD) systems. According to environmental standards and prescribed domestic and EU legislation, the installation of FGD systems in Serbian TPPs has started, and the first FGD system has been installed at Kostolac B. The term Flue Gas Desulphurization (FGD) system has traditionally referred to wet scrubbers that remove SO_2 emissions from large electric utility boilers. The FGD systems emerged in the industrial field of the coal-fired power plants and in some industrial processes in the early 1970s in the United States (US) and Japan, and expanded rapidly in the 1980s into Europe (Córdoba, 2015). The installed FGD system at TPP Kostolac B is a wet scrubber, limestone-gypsum process (Figure 1.).

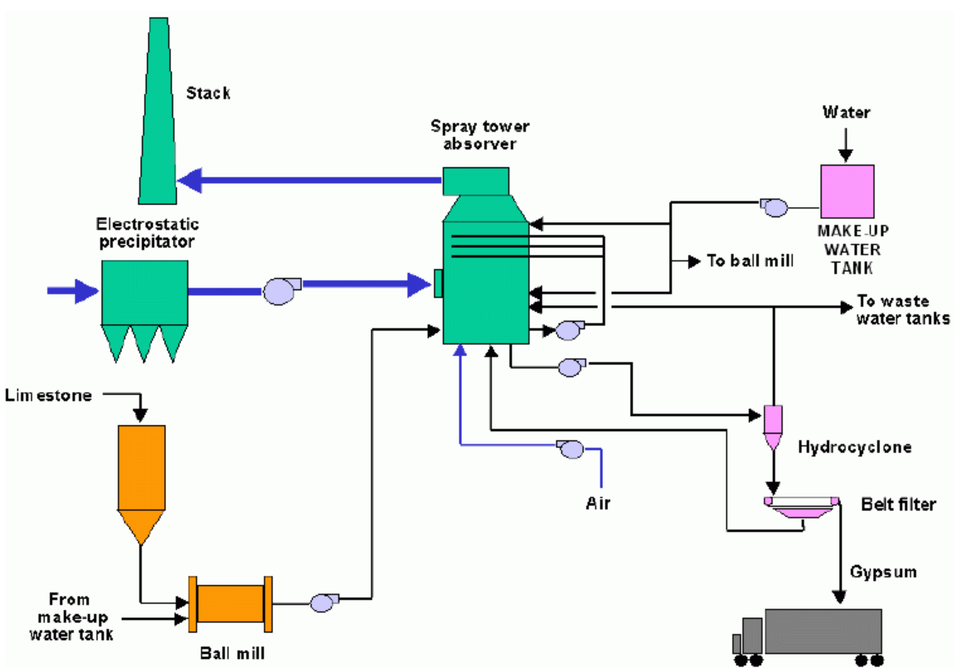

Figure 1. *Schematic flow diagram of a lime/limestone wet scrubber FGD process (BREFs, 2016)*

Wet scrubbers, especially the limestone-gypsum process, are the leading FGD technologies. They have about 80% of the market share and are used in large utility boilers (BREFs, 2016). Despite the high efficiency of electrostatic precipitators (>90%), a small fraction of fly ash escapes and goes into the FGD system. Once in the FGD, fly ash components may be dissolved in the aqueous phase of the absorbent slurry or retained in the solid fraction (gypsum sludge). Fly ash not dissolved in the aqueous phase of the absorbent slurry may be retained in the solid fraction (gypsum sludge) and subsequently extracted from the system by the FGD-gypsum, and/or may firstly be retained in the solid fraction and subsequently entrained with the outgoing flue gas FGD (OUT-FGD) as PM (Córdoba, 2015). After a wet FGD, about 40% of the particulate loadings in the flue gases consist of fly ash, 10% of gypsum particles, while 50% originate from dissolved compounds left over after droplets are evaporated (Meij, 1994). In Europe, experiences with wet FGDs have indicated collection efficiencies of PM by wet FGDs 90%. In the Netherlands, after 1990, wet FGD systems were introduced as a result of which the particulate loads (PLs) were further reduced to <10 mg/m^3 (Córdoba, 2015).

Besides the installed FGD, the old 280 m height common stack for B1 and B2 units is replaced with two 180 m "wet stacks"[1]. Those plant modifications could influence air quality in a closer or wider area and should be examined with adequate tools. Dispersion modelling is a mathematical simulation of emissions as they are transported throughout the atmosphere. Dispersion models replicate atmospheric conditions, (which includes wind speed and direction, air temperature and mixing height), and provide an estimate of the concentration of pollutants as they travel away from an emission source.

In order to analyse the influence of modifications of TPP Kostolac B, the standard model of EPA (US Environmental Protection Agency) AERMOD is used, and modelling results are presented in this study.

METHODOLOGY

AERMOD, which is based on the Gaussian model, includes a wide range of possibilities for modelling the effects of released pollutants on ambient air quality. This model includes modeling of multiple sources of pollution including point, line, area and volume sources. The model contains algorithms for analyzing the aerodynamic flow in the vicinity of, and around, buildings (building downwash) (EPA, 2004). The Gaussian plume model uses a realistic description of dispersion, where it represents an analytical solution to the diffusion equation for idealized circumstances. The model assumes that the atmospheric turbulence is both stationary and homogeneous. In reality, none of these conditions is fully satisfied,however, the Gaussian plume model has been successfully used for rural configurations (Abdel-Rahman, 2008).

The Diffusion Equation and the Gaussian Plume Model

According to (Macdonald, 2003), by performing a mass balance on a small control volume, a simplified diffusion equation, which describes a continuous cloud of material dispersing in a turbulent flow, can be written as:

$$\frac{dC}{dt} + U\frac{dC}{dx} = \frac{d}{dy}\left(K_y \frac{dC}{dy}\right) + \frac{d}{dz}\left(K_z \frac{dC}{dz}\right) + S \qquad (1)$$

where:
x = along-wind coordinate measured in wind direction from the source,
y = crosswind coordinate direction,
z = vertical coordinate measured from the ground,
C (x, y, z) = mean concentration of diffusing substance at a point (x, y, z) [kg/m^3],
K_y, K_z = eddy diffusivities in the direction of the y- and z- axes [m^2/s],
U = mean wind velocity along the x-axis [m/s],
S = source/sink term [kg/m^3-s].

Equation (1) is grossly simplified, since several assumptions are made in its derivation. The Gaussian plume model, which is at the core of almost all regulatory dispersion models, is obtained from the analytical solution to Equation

[1] "Wet stack" implies special construction of the stack used in wet FGD systems, which allows that saturated gases exiting the system's absorber could be directly sent to the stack without reheating and drying.

(1). For a continuous point source released at the origin in a uniform (homogeneous) turbulent flow the solution to Equation (1), for an elevated plume released at z = H_p is:

$$C(\mathrm{x,y,z}) = \frac{Q}{2\pi U_p \sigma_y \sigma_z} \exp\left(\frac{-y^2}{\sigma_y}\right)\left[\exp\left(-\frac{\left(z-H_p\right)^2}{2\sigma_z^{\ 2}}\right)+\exp\left(-\frac{\left(z+H_p\right)^2}{2\sigma_z^{\ 2}}\right)\right] \qquad (2)$$

Schematic representation of the principle of dispersion of pollutants based on the Gaussian model is given in Figure 2.

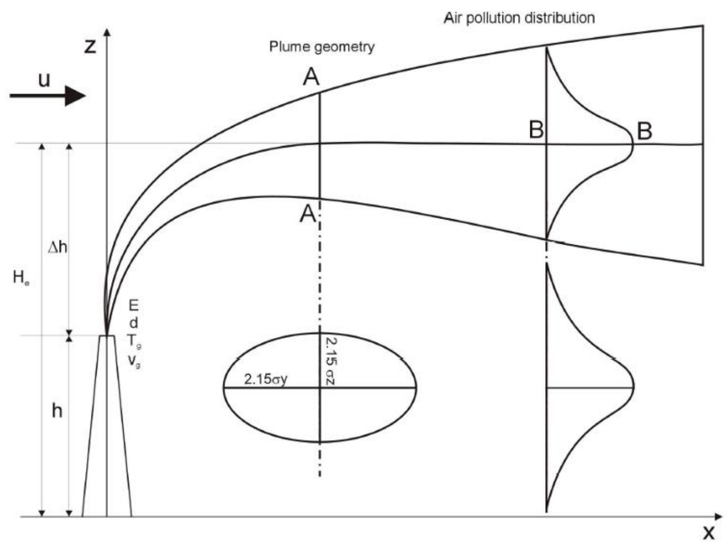

Figure 2. *A scheme of a Gaussian plume model (Markiewicz, 2006)*

Modeling approach

The results presented in this paper were obtained using a model which included the emissions of PM_{10} from the all units of TPP Kostolac A and B. The model included only the stacks of the mentioned units, while neither other sources of emissions, nor background concentrations were included. The focus of modeling presented in this paper is not to evaluate the overall air quality in the project area, but rather to present a representative assessment of the impact of FGD at TPP Kostolac B on air quality in the model domain.

The modeling procedure included the following steps: 1. Preparation of the facility plan, including sources and facilities; 2. Defining the modeling domain and the receptors' locations; 3. Developing source inventories and categorization of all considered sources; 4. Processing of required meteorological data; 5. Terrain data processing; 6. Modeling runs and analysis of the results. Based on the input parameters for all sources, emissions and meteorological data, modeling resulted in the spatial distribution of ground level concentrations of selected pollutants over the selected averaging periods of 24 hours and one-year averages.

Terrain data

A modeling domain of 50 km x 50 km (2500 km^2), with TPPs Kostolac in its centre was selected for this study. A Cartesian coordinate system with the distance of 400 m between adjacent points (receptors) is used, which implies that the models processed 15876 points (receptors). To obtain necessary terrain data, SRTM1 - Shuttle Radar Topography Mission data (resolution: ~ 30m, 1 arc-sec) was used (Figure 3).

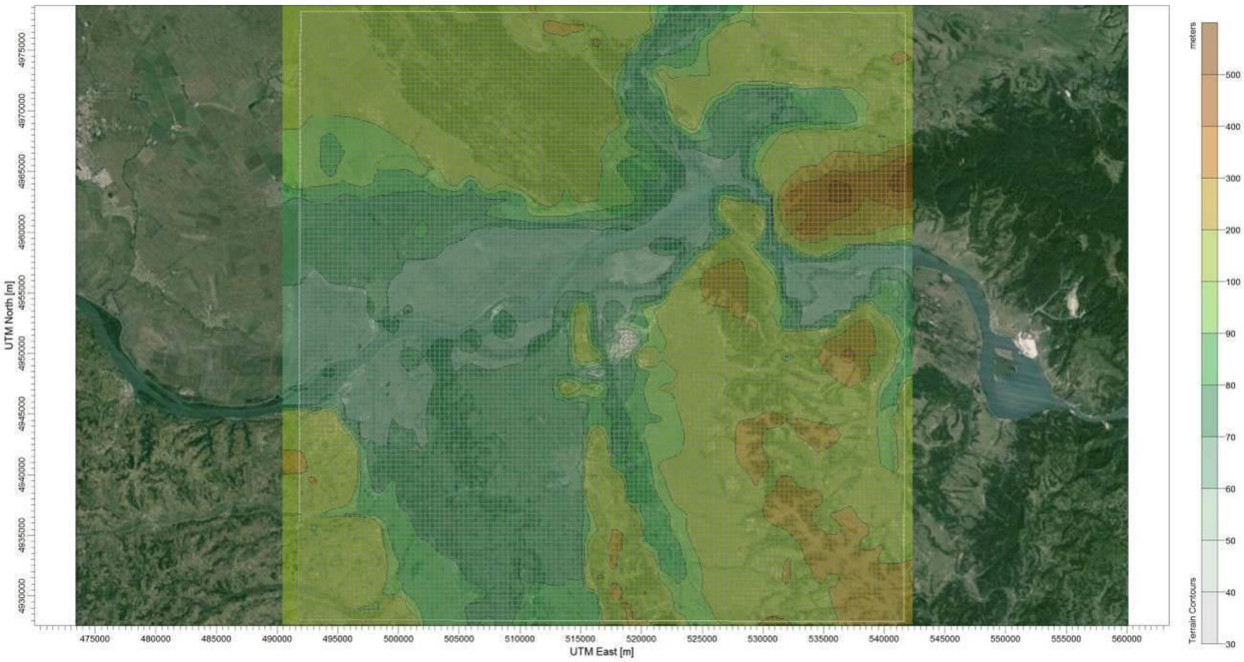

Figure 3. *Processed terrain elevation and Cartesian receptor grid at model domain*

Meteorology data

AERMET, a meteorological preprocessor, prepares hourly surface data and upper air data for use in AERMOD. The surface data are hourly observations of surface level parameters such as wind speed and direction, ambient temperature, and cloud cover that are used by AERMET to generate a surface file for use in AERMOD. The upper air data file provides information on the vertical profiles of atmospheric parameters. This includes the altitude, pressure, dry bulb temperature, and relative humidity (EPA, 2004). Meteorological data that are used for the preparation of model included hourly values of:

wind speed,

wind direction,

ambient temperature,

relative humidity,

atmospheric pressure,

cloud cover - opaque.

Since upper air data were not available, AERMET Upper Air Estimator is used. Hourly meteorological data for the period of 2010-2014 were obtained from the Republic Hydrometeorological Service of Serbia (RHMZ). The closest meteorological station to the power plants was *Veliko Gradište*, and the data from this station were used. Figure 4 demonstrates the wind rose (blowing from) and frequency analysis, based on meteorological data for the period of 2010-2014.

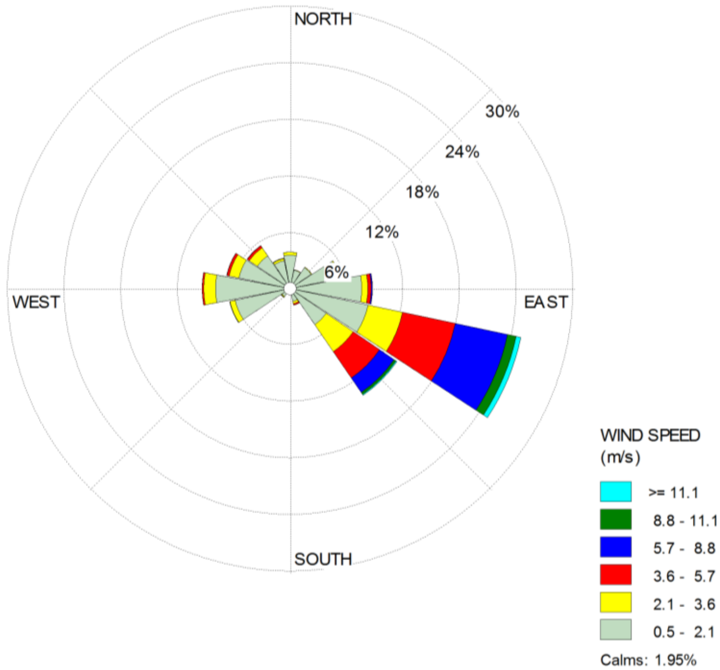

Figure 4*. Wind rose and frequency analysis 2010-2014*

Based on the presented wind statistics (wind roses), it could be concluded that none of the observed years has shown significant differences and that the prevailing wind direction is from east-southeast followed by the southeast direction. This implies that most of the time, released pollutants will be dispersed towards the west-north-west and north-west from the source.

Sources characteristics

For the modeling process the following parameters have to be obtained either by measurements or by calculations so as to accurately characterize each of the emission sources:

• the type of pollutants,
• physical stack height,
• geographic coordinates of stack,
• diameter of the stack,
• the flow rate of flue gases through the stack,
• the temperature of flue gases exiting the stack,
• pollutant concentrations.

All sources characteristics presented in this paper are calculated.

Scenarios 1 and 2

Scenario 1 considers the current state of TPPs Kostolac A and B. In Scenario 2, work conditions at TPP Kostolac A remain the same as in Scenario 1, while TPP Kostolac B employs FGD and units B1 and B2 are connected to the double inner tube "wet stack" 180 m high, instead of one common 280 m height stack as is the case in Scenario 1. All modelling input data of TPPs Kostolac A and B units within the discussed Scenario 1 and Scenario 2 are presented in the tables below (Table 1 and Table 2).

Table 1. *Scenario 1 (without FGD) - Work parameters of units*

Parameter	Unit A1	Unit A2	Unit B1-B2	Unit
Chimney Height	**105**	**110**	**250**	**[m]**
Chimney Diameter	**6.5**	**6.5**	**9.9**	**[m]**
Flue Gas Temp. at exit	**186.5**	**182.9**	**178.4**	**[°C]**
Flue Gas Flow (at work condition)	**1,391,690**	**2,079,056**	**6,270,480**	**[m^3/h]**
Mass Flow PM_{10}	**10.07**	**46.2**	**74.7**	**[g/s]**

Table 2. Scenario 2 (with FGD) - Work parameters of units

Parameter	Unit A1	Unit A2	Unit B1	Unit B2	Unit
Chimney Height	**105**	**110**	**180**	**180**	**[m]**
Chimney Diameter	**6.5**	**6.5**	**6.7**	**6.7**	**[m]**
Flue Gas Temp. at exit	**186.5**	**182.9**	**66.22**	**66.22**	**[℃]**
Flue Gas Flow (at work condition)	**1,391,690**	**2,079,056**	**2,509,640**	**2,509,640**	**[m^3/h]**
Mass Flow PM_{10}	**10.07**	**46.2**	**10.4**	**10.4**	**[g/s]**

As buildings could radically influence the dispersion of pollutants there is a need for building downwash analysis. Figures 5, 6 and 7, present 3D models, designed using AERMOD, with point sources (red stacks) of TPP Kostolac A and B. Beside point sources, 3D model includes possible significant buildings from the downwash effect perspective.

Figure 5. *3D model of TPP Kostolac A*

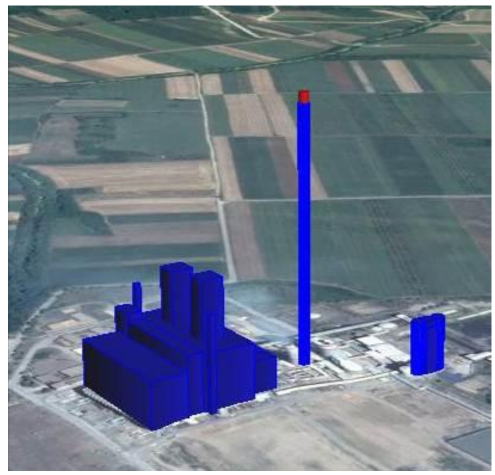

Figure 6. *3D model of TPP Kostolac B (Scenario 1)*

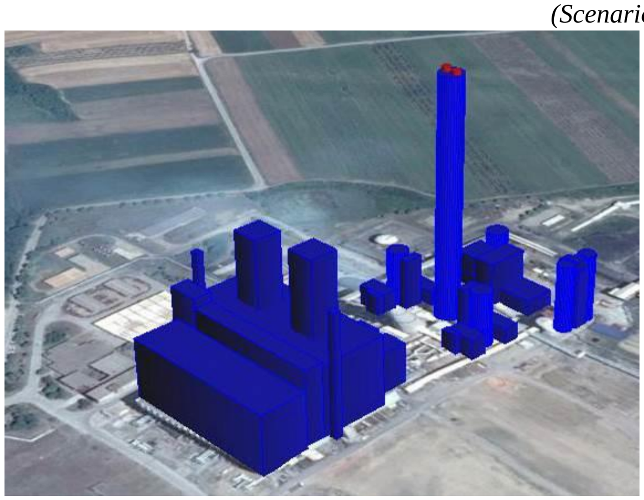

Figure 7. *3D model of TPP Kostolac B* (Scenario 2)

RESULTS AND DISCUSSION

Modeling prepared for this research, did not taken into account background pollution, so presented results (plots) do not represent air quality (PM_{10} concentration) in the model domain, but the contribution of the power plants Kostolac A and B, as a dominate stationary source of PM_{10}, to overall PM concentration at model domain. As well, modeling ha s not taken into consideration emissions of area sources of PM_{10} (ash dump). It is very important to note that these models represent “the worst case” scenarios, by considering that all pollutant sources emit their maximum emission rate *24 hours* a *day, 365 days a year, which is certainly not the case.*

Besides decreased emissions caused by FGD installations, stack design could be very important for ground level concentration. Namely, stack height (H_s), top inside stack diameter (D), flue gas temperature (Ts), ambient temperature (Ta) and stack exit velocity (vs) define buoyancy flux (Equation (3)):

$$F = g v_s D^2 \frac{T_s - T_a}{4T_s} \ , \qquad (3)$$

which directly influence plume rise (Δh) and effective stack height (H) (Equation (4)). So it is very important to set realistic stack and flue gas parameters as much as possible.

$$H = H_s + \Delta h \ . \qquad (4)$$

As a result of modelling scenarios, the model provides textual and graphical plots, which include maximum and mean concentrations of PM_{10}, as presented in Figures 8-13. Apart from daily maxima, in accordance with National Air Quality Objectives, PM_{10} concentrations are presented as 90.40th of maximum concentrations for daily means and annual mean concentrations.

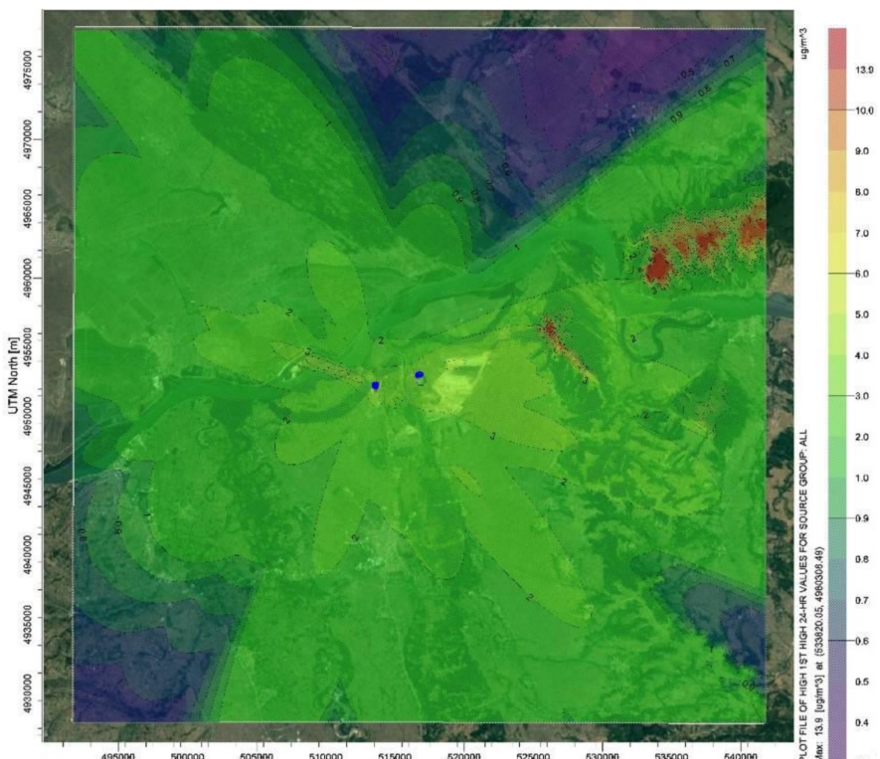

Figure 8. *Scenario 1 - Daily maximum concentration [g m*$^{-3}$*]*

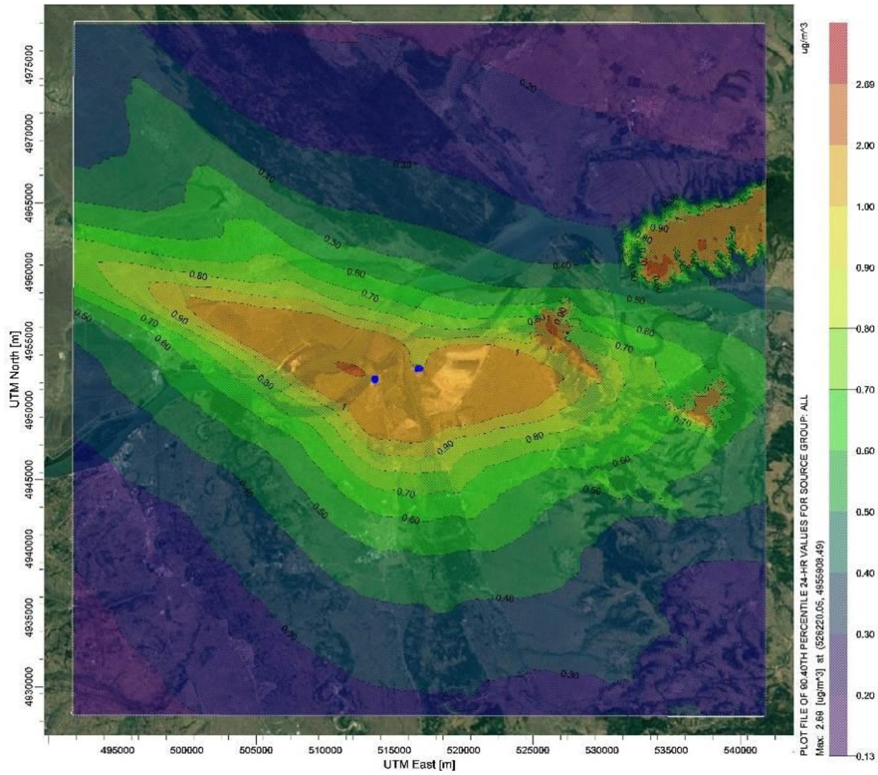

Figure 9. *Scenario 1 - 90.40^th^ percentile of daily mean concentration [g m^-3^]*

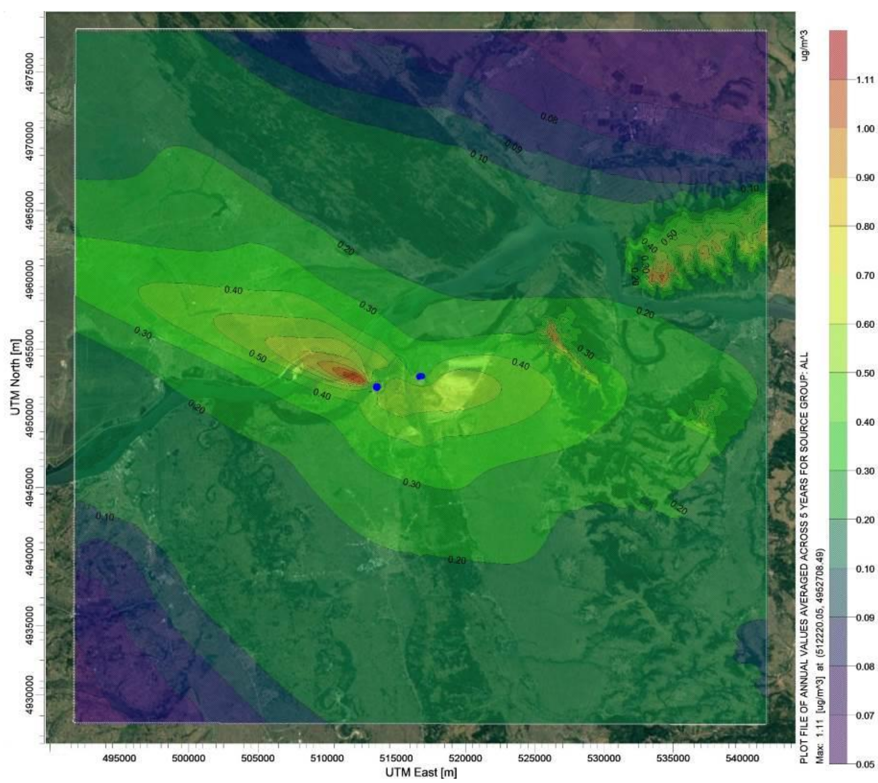

Figure 10. *Scenario 1 - Annual mean concentration [g m^-3^]*

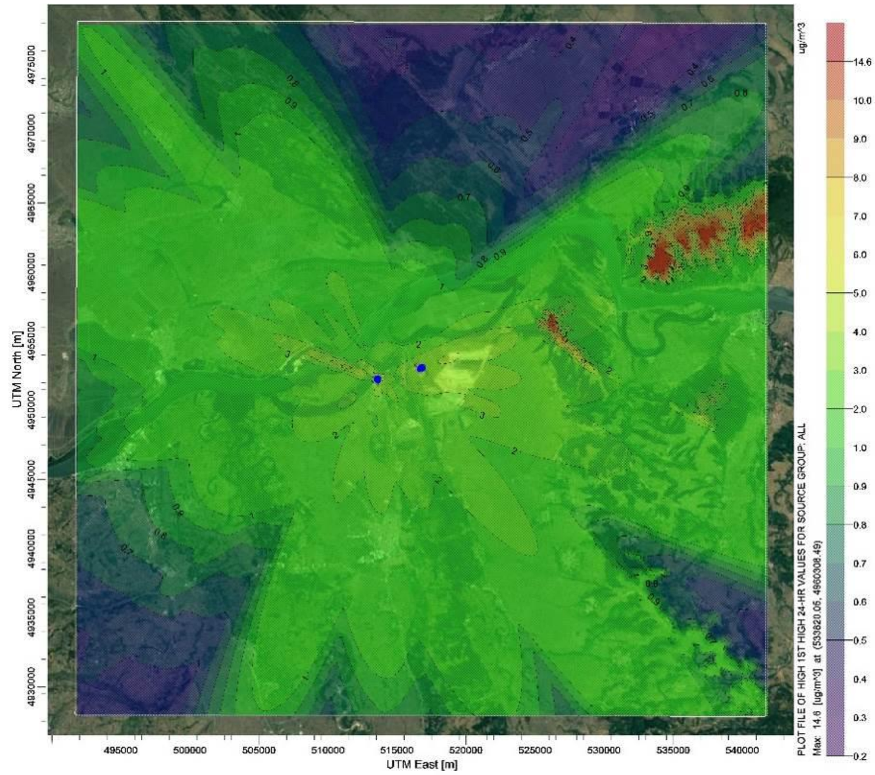

Figure 11. *Scenario 2 - Daily maximum concentration [g m^{-3}]*

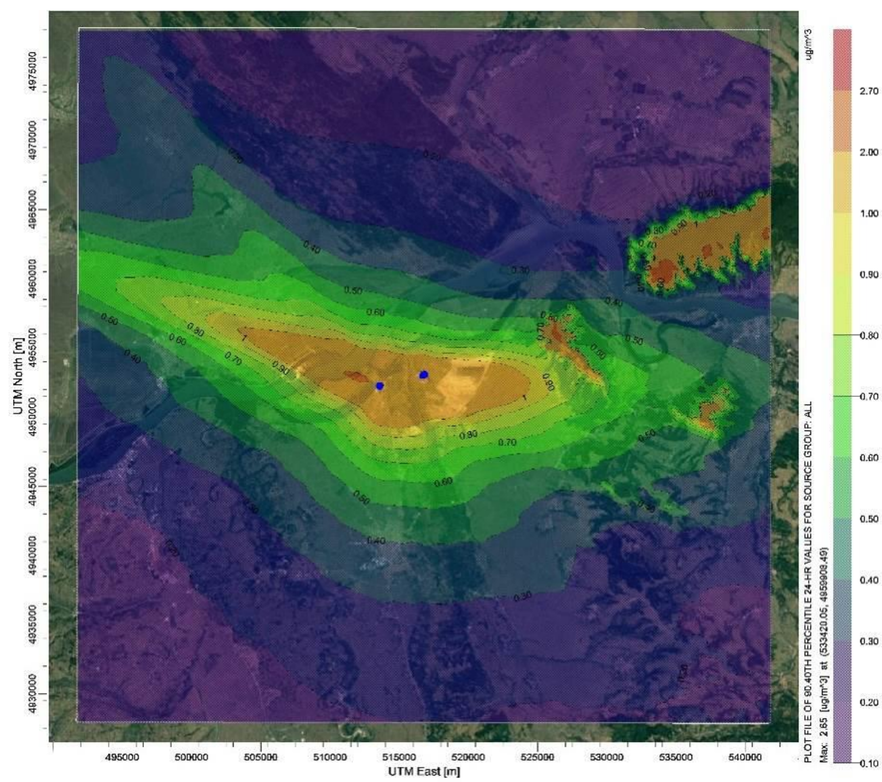

Figure 12. *Scenario 2 - 90.40th percentile of daily mean concentration [g m^{-3}]*

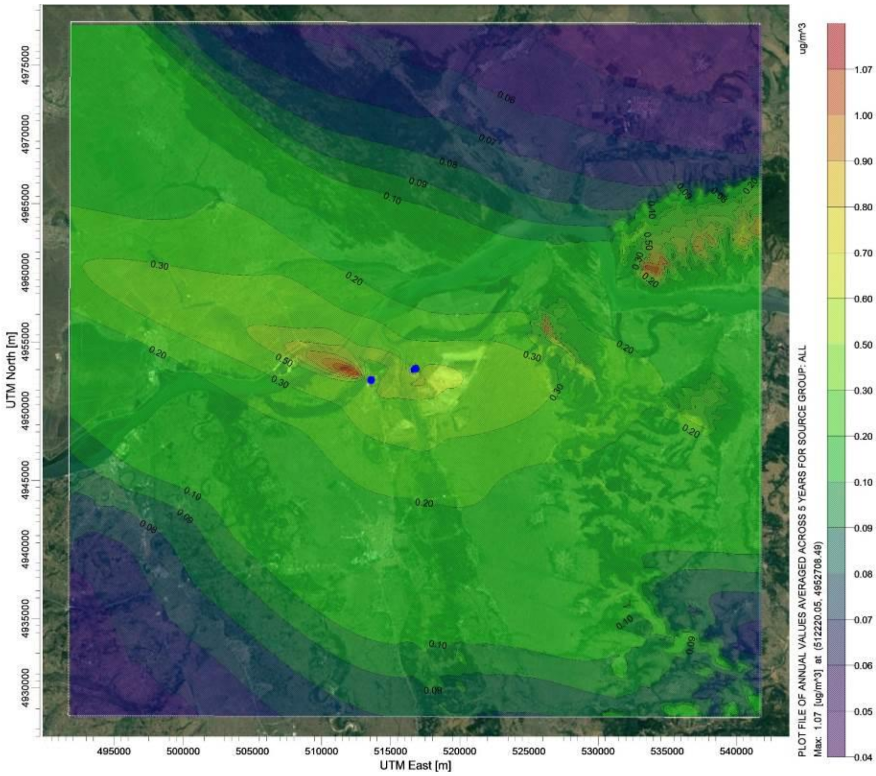

Figure 13. *Scenario 1 - Annual mean concentration [g m*$^{-3}$*]*

Modeling results indicate generally 3 locations where the highest concentrations of PM_{10} could be expected. Maximum concentrations at given plots for daily maximum and 90.40th percentile are located at the north-east of model domain. In addition to the source characteristics presented in Table 1 and 2, relief has dominant influence on ground level concentrations at the afore mentioned locations. Deposition of PM_{10} occurs since plume, which is influenced by meteorology conditions, is not able to overcome the complex terrain that is on its path. While annual concentrations are mainly influenced by meteorology (mainly wind direction) and certainly with source characteristics of TPP Kostolac A. Maximum ground level concentrations for both scenarios are presented in table 3.

Table 3. *Maximum ground level concentrations*

Max. concentrations	**Scenario 1 µg/m³**	**Scenario 2 µg/m³**
24h max	**13.91**	**14.61**
24h (90.40th percentile)	**2.69**	**2.64**
Annual mean	**1.11**	**1.07**

It is very important to note that maximum concentrations are observed at same locations for both scenarios. Based on the results presented on plots and given in Table 3 for both scenarios, it could be concluded that there is no significant influence of FGD on spatial dispersion of PM_{10}, neither on the expected maximum concentrations. It may indicate that TPP Kostolac A, which has the same characteristics for both scenarios, has a dominant influence on PM_{10} ground level concentration. In order to investigate that assumption, additional modeling is done only for TPP Kostolac A and the results are presented in *Figures 14-16.*

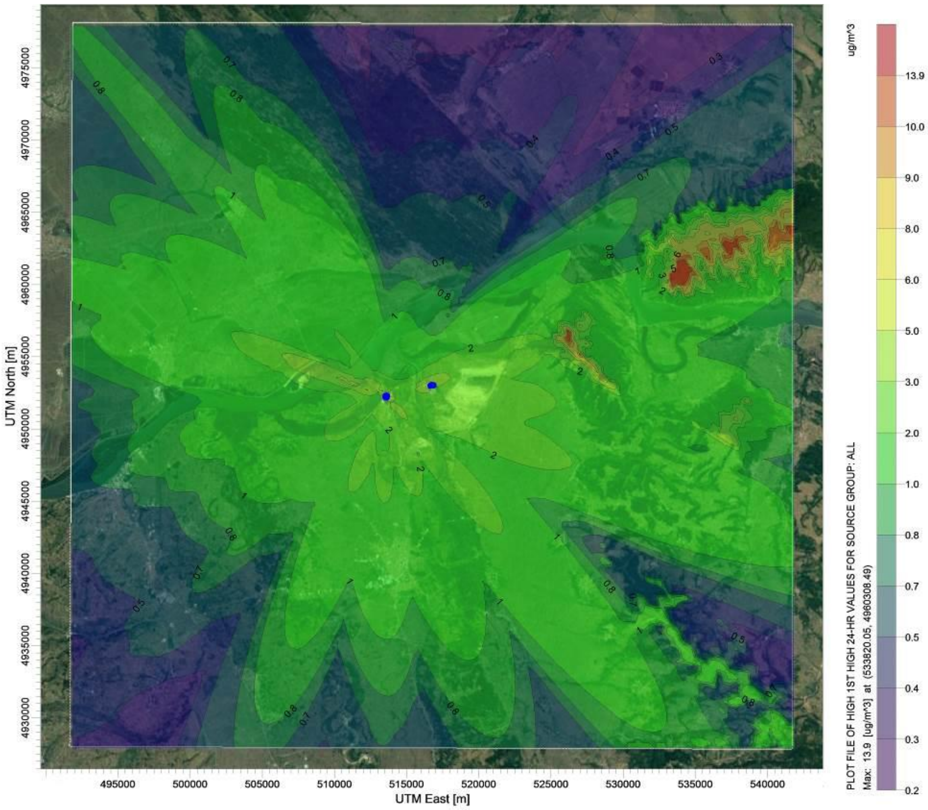

Figure 14. *TPP Kostolac A - Daily maximum concentration [g m^{-3}]*

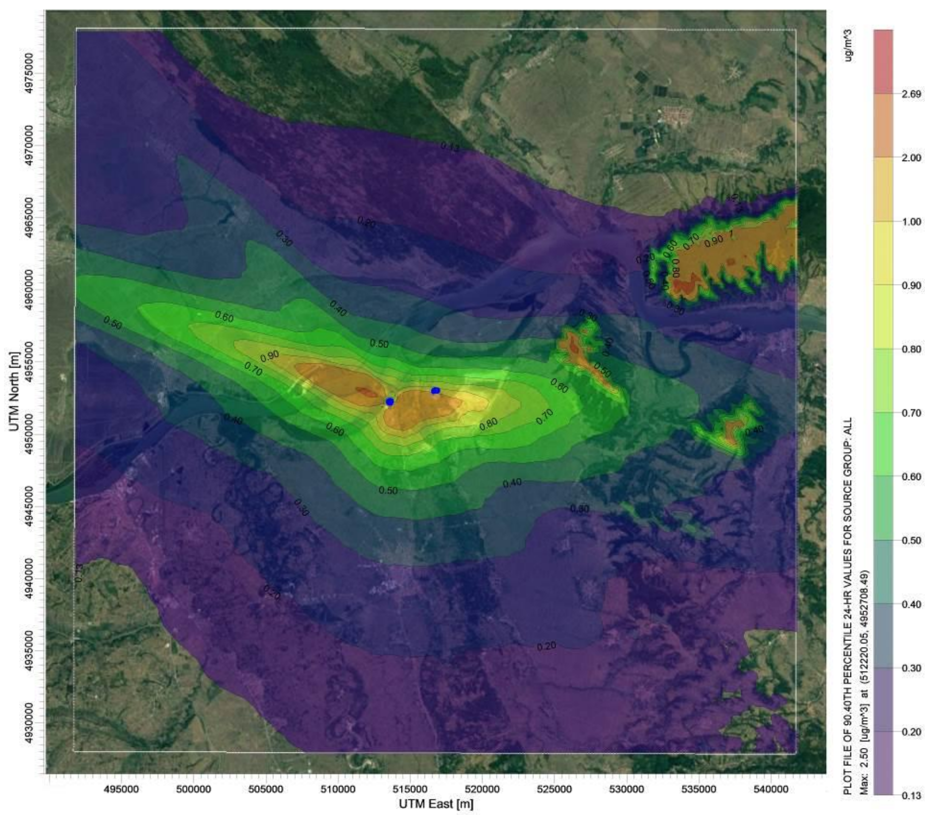

Figure 15. *TPP Kostolac A - 90.40th percentile of daily mean concentration [g m^{-3}]*

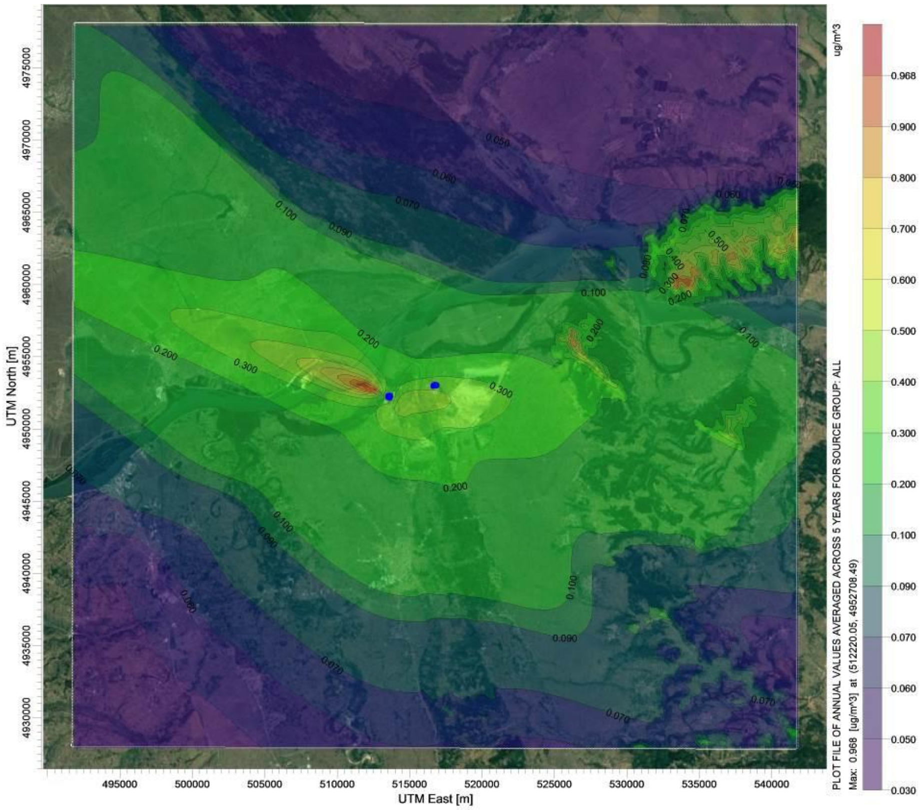

Figure 16. *TPP Kostolac A - Annual mean concentration [g m^{-3}]*

The results for TPP Kostolac A confirm the assumption that TPP Kostolac A has had a dominant influence on PM_{10} ground level concentration at model domain. Bearing in mind that meteorological and relief data are same for all scenarios, this result is directly connected to the height of TPP Kostolac A's stacks (105 m for Unit A1 and 110 m for Unit A2), respectively effective heights of TPP Kostolac A's stacks. While in the same manner it could be concluded that the effective heights of TPP Kostolac B's stacks provide an almost negligible influence of TPP Kostolac B on PM_{10} ground level concentration at model domain.

The effective heights of TPP Kostolac B's stacks are responsible for slightly higher concentration comparing Scenario 1 and Scenario 2 for daily maximum concentration (Table 3). Namely, the flue gas flow and mass flow of PM_{10} are significantly reduced for Scenario 2 as compared to Scenario 1, *stack height is reduced from 250 m to 180 m and flue gas temperature is decreased from 178,4* ℃ to 66,2 ℃, which leads to a decreased effective height of TPP Kostolac B's stacks.

CONCLUSION

In order to investigate the influence of the newly built FGD system at TPP Kostolac B on ground level concentration of PM_{10}, this paper discussed 3 different modelling scenarios: modelingThe AERMOD dispersion model was used. Hourly meteorological data (5 years in row), from a representative measuring station, SRTM1 terrain data and deatiled source parameters were the primary inputs. Considering that these models' runs did not take into consideration background pollution, the results obtained by this modeling do not represent overall ambient air quality in the models' area, but only considered the contribution of TPP Kostolac A and B, as major PM_{10} source, to overall air quality, which gives the opportunity to make conclusions of FGD influence. Firstly, according to the presented results and based on the National Air Quality Objectives, ambient concentrations obtained as a result of all scenarios are below the prescribed regulatory limits. Maximum results in both scenarios are 14.61 g m^{-3} and 2.69 g m^{-3} for daily maximum concentration and 90.40th percentile of daily mean concentration, and 1.11 g m^{-3} for annual mean concentration, while National Air Quality Objectives gives 50 g m^{-3} for 90.40th percentile of daily mean concentration and 40 g m^{-3} for annual mean concentration. Further, based on additional modeling scenario, it is concluded that TPP Kostolac A has a dominant influence on PM_{10} ground-level concentration in the model domain, due to effective heights of the stacks (105 m and 110 m are *physical stacks' height*), while TPP Kostolac B has negligible influence for both scenarios. In Scenario 1 common stack of 250 m height and other sources characteristics give favorable conditions from an air dispersion point of view, while within Scenario 2 apart from a reduced physical stack height to 180 m and other changed source parameters, it kept same insignificant influence on model domain.

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