Assessment of the AERMOD dispersion model in complex terrain with different types of digital elevation data

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Abstract. The AERMET/AERMOD (American Meteorological Society (AMS)/EPA Regulatory Model) dispersion modeling system constitutes a tool recommended by the United States Environmental Protection Agency (U.S. EPA) both for flat and complex terrain in a local scale with a distance of 50 km. This model requires several input data for pollutant prediction. As part of the research, the effectiveness evaluation of the AERMOD model was conducted based on two of the model evaluation databases (Martin’s Creek and Lovett) depending on different available DEM sources. The analysis involved comparison of different modeling results obtained with the application of different DEM datasets, i.e. NED (National Elevation Dataset), ASTER (Aster Global Digital Elevation Model), SRTM (Shuttle Radar Topography Mission) and USDEM (US GeoData Digital Elevation Models). Achieved outcomes indicated, that the use of different elevation datasets did not influence the evaluation results of the AERMOD model in a local scale and complex terrain significantly. Regardless of the field experiment and DEM dataset, for each case the values of \(FB\) and \(FB_{RHC}\) fell within the range of \(±0.33\). The highest values of the model performance measures reached 0.89 – 0.91 for IOA and 0.78 – 0.81 for COE in the case using the NED dataset. Slightly worse model performance was observed for the SRTM data with \(IOA\) equal to 0.82 – 0.91 and \(COE\) reaching 0.64 – 0.83.

1. Introduction

Air pollution dispersion models are one of the important tool of the air quality management system [1,2]. Their applications include, among others, the air quality impact assessments of the emission sources to obtain permission for the release of gases and dust into the air. Dispersion models are used for the air quality assessments, determination of the emissions shares from different sources in the total air pollution or identification of the main directions of actions aimed at the reduction of emission [3–8]. Numerous development studies, whose key objective is the sensitivity analysis of the applied input data in order to improve the outcomes of the air pollutants concentration predictions, are also undertaken [9–12].

The AERMET/AERMOD air pollutant dispersion modeling system is one of the most recognizable and popular models applied for the air quality impact assessment in a local scale (< 50 km). AERMOD was developed through collaboration of the American Meteorological Society (AMS) and the United States Environmental Protection Agency (U.S. EPA). In 1991, they initiated cooperation in order to implement conceptions of the planetary boundary layer (PBL) in the air pollutant dispersion models, especially under unstable atmospheric conditions. First formulation of the AERMOD model was presented in 1996 [13,14]. Developmental assessment was conducted using five dispersion model evaluation databases [14,15]. In 2000, the U.S. EPA proposed AERMOD model as replacement for the ISC3 model, and in 2005 the AERMOD officially replaced the earlier ISC3 [16]. Currently, the AERMOD model is continuously developed and supported, and its evaluation is carried out based on...
17 experimental datasets [17,18]. According to the latest update of the air quality modeling guidelines, the AERMOD model is recommended for the regulatory purposes in a local scale both in flat and complex terrain [19]. In 2017, the “Memorandum: EPA white papers on planned updates to AERMOD modeling system” was released, which included the most important directions of the model development [20]. Core issues addressed in the white book of the AERMOD model are as follows [20]: model’s tendency to overpredict under low wind conditions, treatment of moist plumes, downwash algorithms, NO$_2$ modeling techniques, mobile source modeling and overwater modeling.

One of the basic characteristics of the air pollution dispersion models is the need to provide time series input data. Uncertainty of the input data may determine the accuracy of yielded modeling outcomes (parametric uncertainty of the model). Therefore, it is necessary to carry out studies aimed at determination of the uncertainty for selected air pollutants dispersion models using different input data. One of the most important input datasets processed by the air quality models in case of the complex terrain applications is the digital elevation model (DEM). Over the past several years, an intensive development of the land data acquisition through remote sensing techniques has been observed. In effect, numerous digital terrain model datasets were produced, i.e. NED, ASTER, SRTM, USDEM, which may be adopted into air pollutants dispersion models. Consequently, as part of this study, the authors decided to verify how using different DEM datasets influence accuracy of the AERMOD model. Issue connected to the comparison of different DEM datasets using AERMOD model was previously discussed in case of dispersion modeling for the open pit source in Israel [21]. Theoretic discussion concerning the use of digital elevation models in AERMOD and the evaluation of their horizontal (resolution) and vertical (elevation) accuracy based on the development history was included in technical guide of AERMOD [22].

2. Materials and methods

2.1. Model evaluation databases

Accuracy assessment of the AERMOD model with regard to the used digital terrain models was conducted based on two field experiments, i.e. Martin’s Creek and Lovett. Both datasets were derived from the Model Evaluation Database (MED) provided by the U.S. EPA [23]. Graphic representation of the study area is shown in figure 1.

![Graphic representation of the study area for the Martin’s Creek (MC) and Lovett (LV) experiments.](image)
Martin’s Creek (MC) experiment was conducted in the Delaware Valley on the borders of Pennsylvania and New York states in the USA. In the area of study, several emission sources were located, which could influence the pollutants’ concentrations. Point emission sources included in the experiment had the height of 59.4-182.9 m, and the elevation varying from 73.2 to 173.7 m a.s.l. Meteorological data were collected from 10-meter-high meteorological tower and sodar, which recorded data at 13 layers in the atmosphere from 90 to 420 m a.g.l. with a vertical step of 30 meters. Sodar equipment was used to collect wind speed and direction data. Meteorological tower enabled measurements of wind speed and direction, standard deviation of the horizontal wind component and ambient temperature. Monitoring stations of the SO₂ concentrations, excluding the AMS-8 station, were located in the vicinity of Scotts Mountain in the south-eastern direction from the Martin’s Creek power plant. Sulfur dioxide measurements were conducted at the altitude of 340.2-376.7 m a.s.l., which is higher than the height of the Martin’s Creek (256.1 m a.s.l.) and Portland (213.3 m a.s.l.) power plants emitters [24,25].

The Lovett (LV) experiment was carried out in the Hudson River Valley in the south-eastern part of the New York state in the USA, about 70 km north of the New York city center. The area west and north of the power plant is dominated by three high hills. In the area of research, single dominant SO₂ emission source was located, in the form of a 145-meter-high point emitter with its base at the altitude of 1.8 m a.s.l. Wind and temperature profiles were derived from meteorological tower located about 1 km southwest of the Lovett power plant with its base at the altitude of 36.5 m a.s.l. Anemometers and thermistors provided measurements of wind speed and direction and ambient temperature at the layers of 10, 50 and 100 m a.g.l. In addition, the measurements of turbulence ($\sigma_w$, $\sigma_v$), i.e. standard deviations of the vertical and horizontal wind components, were conducted. Concentration levels of SO₂ were measured at 10 sites in the southern and northern directions from the Lovett power plant. Their elevation varied from 150 to 330 m a.s.l. [24,25].

2.2. Setup of the AERMAP/AERMET/AERMOD modeling system and computational variants
Simulation of pollutants’ propagation in the air was carried out for 5 computational variants with regard to the used digital terrain datasets, which are summarized in table 1. It should be emphasized that the considered databases differ both in horizontal resolution (precision of the surface representation) and in elevation accuracy. The AERMAP preprocessor was used to enable implementation of various DEM datasets into the AERMOD model.

AEROMET is a meteorological preprocessor handling meteorological data and calculating parameters of the planetary boundary layer for dispersion modelling with the AERMOD model. Configuration of the model settings was carried out in accordance with the developmental evaluation of the AERMET/AERMOD modelling system [25]. Therefore, when the information about turbulence measurements ($\sigma_w$, $\sigma_v$) is available, the surface friction adjustment method for low wind speed and stable atmosphere (ADJ_U*) is not applied. In addition to the on-site meteorological data discussed in chapter 2.1, for both experiments the upper air data for Albany, NY (WBAN: 14735) from the NOAA/ESRL Radiosonde Database was incorporated into the model. On the other hand, surface meteorological data for the MC and LV experiments were derived from the Integrated Surface Database for Allentown-Beth-Easton (WBAN: 14737) and Albany International Airport (WBAN: 14735), respectively.

Calculations of the concentration levels were carried out using AERMOD ver. 16216 stationary model for each dataset denoted in table 1 in order to verify whether using DEM data of different accuracy will impact the results of the AERMOD evaluation. The latest update of the model, to ver. 18081, is from 2018, however the modifications implemented in AERMOD could not affect the point source case analyzed in the study. This is confirmed by the results of the AERMOD evaluation included in appendix B of the model formulation [26]. Currently, as indicated in the introduction, intensive development works are carried out in order to implement a suitable approach for handling air pollution dispersion modelling under low wind speed (LowWind) [20]. In the applied version of the AERMOD model, three beta options for LowWind were available. However, they were not approved, because using these
methods does not result in unambiguous results of the model evaluation [19,26]. Consequently, the beta module available in the AERMOD model was not implemented in the calculations.

| Symbol | Description |
|--------|-------------|
| REF    | Reference data from the model evaluation database (MED). |
| NED    | National Elevation Dataset – USGS, resolution of approx. 10 m. |
| ASTER  | Aster Global Digital Elevation Model, resolution of approx. 30 m. |
| SRTM   | Shuttle Radar Topography Mission, resolution of approx. 90 m. |
| USDEM  | US GeoData Digital Elevation Models, data included in the model evaluation database (MED), resolution of approx. 90 m. |

2.3. Methodology of the model evaluation
Model evaluation was conducted using two methodological approaches [27,28]. First, the comparative analysis of the maximum 1-hour concentrations without pairing in space was performed. For each monitor the robust highest concentration (RHC) parameter was calculated. It provides a smoothed estimation of the highest concentration based on the adjustment to the exponential distribution of the highest concentrations. Using the highest values of RHC the absolute fractional bias was determined (FB\(_{RHC}\)). On the other hand, with pairing of the results in space, the model comparison measure (MCM\(_B\)) was calculated with the 95 % confidence interval. MCM\(_B\) constitutes a difference between mean absolute fractional bias (AFB\(_B\)) for two disparate models. In this case, results of the variant with reference data (REF) constituted the reference model. AFB\(_B\) was calculated as mean value from obtained [FB\(_{RHC}\)], which were determined for each computational receptor (with pairing of the results in space).

In the second approach the comparison of the 400 highest concentrations (observed, modelled) was conducted. The model accuracy evaluation parameters were applied, i.e.: fraction of predictions within a factor of two of observations (\(\text{FA}C2\)), fractional bias (\(\text{FB}\)), normalized absolute difference (\(\text{NAD}\)), geometric mean bias (\(\text{MG}\)), coefficient of efficiency (\(\text{COE}\)) and index of agreement (\(\text{IOA}\)) [28,29]. The abovementioned parameters were calculated in order to compare distributions of the 400 highest 1-hour concentrations. It was decided to limit the number of observations as it allowed to minimize the impact of the SO\(_2\) measurement uncertainty, as well as the uncertainty of the background levels determination on the results of the model accuracy evaluation. In this case, indicated uncertainties should constitute a small percentage of the observed values [30].

3. Results and discussion
In figure 2a the fractional bias values (FB\(_{RHC}\)) based on the robust highest concentration (FB\(_{RHC}\)) in relation to different dataset source (DEM) are presented. Outcomes show, that regardless of the DEM data used, values of the fractional bias generally fall in the range of |FB\(_{RHC}\)| ≤ 0.3. This indicates that for each DEM dataset and field experiment, similar results of the AERMOD accuracy evaluation were obtained. Therefore, it may be concluded, that the use of different DEM data does not determine the outcomes of the AERMOD accuracy evaluation in relation to predictions of the highest 1-hour concentrations. This is particularly noticeable in case of the LV experiment, where the FB\(_{RHC}\) values fall in the range from 0.26 to 0.31. The above statement is confirmed by the outcomes of the comparative assessment presented in figure 3. Values of the model comparison measure (MCM\(_B\)) showed, that the use of different DEM data does not determine significantly values of the mean absolute fractional bias (AFB\(_B\)) at the 95 % confidence level. Confidence intervals at the level of significance \(\alpha = 0.05\) for the model comparison measure (MCM\(_B\)) obtained for each case coincided with zero.
Figure 2. Graph presenting the $FB$ values calculated based on the maximum values of the robust highest concentration ($FB_{RHC}$) and for the 400 highest 1-h concentrations divided by terrain data for two dispersion model evaluation experiments (MC and LV).

It should be noted that the values of $|FB_{RHC}|$ calculated for each receptor fall in the range from 0.01 to 0.76 for the LV and from 0.01 to 0.25 for the MC experiment. This points out that when using the AERMOD model it is possible to predict the highest values of the maximum 1-hour concentrations with the accuracy of approximately $\pm 30\%$ (figure 2a). However, with pairing of the outcomes in space, it is possible to obtain results that differ almost 1.9 fold from the observed value. This indicates that a particular awareness should be maintained when interpreting the outcomes of the AERMOD dispersion model. Consequently, the outcomes from the AERMOD model, when pairing in space of the highest concentrations is applied, are characterized by much lower accuracy compared to the forecast of the maximum impact of the emission source, or sources, on air quality. This fact shows that we are able to forecast the value of the maximum impact of the source on air quality represented by concentration, but not necessarily to identify the exact location of this concentration’s origin.

Figure 3. The $MCM_R$ values with a 95% confidence interval for two experiments of the dispersion model evaluation (MC and LV) in relation to terrain data.
Results of the AERMOD evaluation obtained for the comparison of the 400 highest 1-hour concentrations informs as well, that the values of fractional bias fall in the range of $|FB| \leq 0.3$ (figure 2b). Negative values of $FB$ were obtained only for the REF variant for both field experiments. This denotes that the modeling values are higher than the ones recorded at receptors. It is widely recognized as an advantageous feature in case of the models used for regulatory purposes, which should not underpredict simulation results of the pollutants concentrations in the air [30,31]. Additional information is provided by the model evaluation parameters ($FAC2, NAD, MG, COE, IOA$) in table 2, which were determined in order to compare distributions of the 400 highest 1-hour concentrations. Values of $FAC2$ for each analyzed case indicate the ideal model. This proves that regardless of the experiment and DEM data used, the modeling outcomes of the highest 1-hour concentrations are within 2 fold over- and underestimation in relation to measurements. Determined values of $NAD$ and $MG$ fall in ranges of the acceptance criteria for the air quality models in rural areas ($NAD < 0.3, MG \leq 1.3$ and $MG \geq 0.7$) [28]. Values of the coefficient of efficiency ($COE$) and index of agreement ($IOA$) for the NED variant provide vital insights. High values of the index of agreement ($IOA \geq 0.78$) and coefficient of efficiency ($COE \geq 0.89$) for the NED variant in relation to other scenarios validate the assumptions from the technical guidelines of the AERMOD application, where it is advised to use NED data due to its high horizontal and vertical accuracy and their homogeneity [22]. However, the abovementioned recommendation is not supported by the studies on accuracy of the air pollution dispersion models. Hitherto studies are not conclusive whether the use of different datasets, e.g. SRTM, ASTER, USDEM – of generally lower accuracy (horizontal or vertical) is sufficient.

**Table 2.** The AERMOD model evaluation parameters determined to compare distributions of the 400 highest 1-hour concentrations divided into field experiments (MED) and the digital elevation model datasets used.

| Variant | MED | FAC2 | NAD | MG  | COE | IOA |
|---------|-----|------|-----|-----|-----|-----|
| REF     | MC  | 1.00 | 0.07| 0.87| 0.53| 0.77|
|         | LV  | 1.00 | 0.08| 0.84| 0.50| 0.75|
| NED     | MC  | 1.00 | 0.03| 0.95| 0.81| 0.91|
|         | LV  | 1.00 | 0.04| 1.05| 0.78| 0.89|
| ASTER   | MC  | 1.00 | 0.06| 1.12| 0.63| 0.82|
|         | LV  | 1.00 | 0.09| 1.17| 0.56| 0.78|
| SRTM    | MC  | 1.00 | 0.03| 0.97| 0.83| 0.91|
|         | LV  | 1.00 | 0.07| 1.12| 0.64| 0.82|
| USDEM   | MC  | 1.00 | 0.09| 1.18| 0.48| 0.74|
|         | LV  | 1.00 | 0.09| 1.17| 0.54| 0.77|

Accuracy of the elevation (denoted as RMSE) for the NED, SRTM and ASTER datasets is 4.5 m, 15.27 m and 18.52 m, respectively [32]. However, accuracy for the USDEM dataset is approximately 30 m [33]. Considering the above and the AERMOD evaluation outcomes in table 2, it can be concluded that in general, there is a unequivocal decrease in quality of the dispersion modeling outcomes with decreasing accuracy of the elevation for different DEM datasets. For example, in case of the LV experiment and the NED, SRTM, ASTER and USDEM datasets, the coefficient of efficiency (COE) values reached 0.78, 0.64, 0.56 and 0.54, respectively.

Descriptive statistics presented in table 3 show differences in the height determination of the receptors locations for analyzed datasets in relation to the reference data (REF). In order to calculate these parameters the elevation for each receptor was determined as the elevation of its base. The lowest mean deviation, equal to 12.2 and 33.89 m for the MC and LV experiments, respectively, was obtained.
for the NED dataset. On the other hand, the highest mean deviations were achieved for the USDEM data. Great disproportion between experiments is noticeable. In case of the MC experiment, mean differences range from 12.2 to 33.9 m, and for the LV experiment – from 33.89 to 48.11 m. It should be emphasized that the maximum differences of the receptor elevation determination reach more than 50 and 90 m for the MC and LV experiments, respectively. These difference are not, however, reflected by the outcomes of the AERMOD evaluation in table 2. For each dataset similar values of the model evaluation parameters for both experiments were obtained. The only exception is the SRTM dataset, for which the coefficient of efficiency (COE) reached 0.83 for the MC and 0.64 for the LV experiment.

Table 3. Mean, minimum and maximum values based on the absolute differences of the monitors elevation (REF variant was the reference data for calculating differences).

| MED Parameter | NED    | ASTER  | SRTM   | USDEM  |
|---------------|--------|--------|--------|--------|
| **MC**        |        |        |        |        |
| mean          | 12.2   | 30.1   | 12.4   | 33.9   |
| min           | 0.4    | 9.4    | 2.7    | 25.7   |
| max           | 27.0   | 57.9   | 25.8   | 44.7   |
| **LV**        |        |        |        |        |
| mean          | 33.89  | 45.53  | 44.86  | 48.11  |
| min           | 2.91   | 18.43  | 17.54  | 21.88  |
| max           | 80.34  | 95.86  | 94.97  | 99.31  |

Existing study comparing two DEM datasets, i.e. SRTM3 and MAPI (Israel Mapping Authority) with vertical accuracy of 2 m and horizontal of 50 m, on the example of an open pit source and AERMOD application demonstrated almost identical simulation outcomes for the TSP (total suspended particulate matter) concentrations [21]. The issue of using NED and SRTM3 data and their influence on the model accuracy was analyzed as well in case of the CALPUFF model. It was proved that the use of these two datasets results in almost equal outcomes of the CALPUFF evaluation parameters based on three experiments from the model evaluation database [12]. Therefore, it can be concluded, that dispersion models based on the Gaussian plume equation are not sensitive to different digital elevation model data, which vertical accuracy equals to approx. 15 m and horizontal – at least 90 m. Nevertheless, considering the obtained outcomes and general guidelines, the use of the NED data is recommended in case of the air pollution dispersion modeling in near field and complex terrain, since this dataset is characterized by high accuracy (both vertical and horizontal), and for this dataset the highest values of IOA and COE were obtained in the comparison of distributions of the 400 highest concentrations.

4. Conclusion

In the paper, the evaluation of the AERMOD model was carried out in relation to different digital elevation model data and two dispersion model evaluation datasets. Obtained results indicated, that despite differences in the receptors elevation between different DEM data, varying on average from 12.2 to 33.9 m for the MC experiment and from 33.89 to 48.11 m for the LV experiment, the model evaluation outcomes were comparable. This is especially visible for the predictions of the highest values from the maximum 1-hour concentrations with pairing in space. What is more, comparison of the concentrations distributions did not prove as well, that the use of different DEM data results in different outcomes of the model evaluation. However, it should be noted that, regardless of the experiment, for the NED data the model evaluation parameters (NAD, MG, COE, IOA) values were the closest to those representing the ideal model. Therefore, the use of the NED data is recommended. On the other hand, this dataset is limited only to the territory of the United States of America. In case of other study areas located in different regions in the world, the use of SRTM data is advised, since for this dataset slightly better outcomes of the AERMOD model evaluation were obtained compared to the ASTER data.

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