MODELLING THE EFFECT OF SUGAR REFINARY POLLUTION IN A RURAL AREA IN CENTRAL MEXICO

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ABSTRACT
Mathematical models for atmospheric dispersion are being used in a wide variety of industrial applications. One of the most used Gaussian models is AERMOD, recommended by the US EPA to determine air pollution dispersion in urban and rural areas. AERMOD is used to determine the expected impact on air quality due to the operation of a sugar refinery located in a rural village in central Mexico. Air pollutant emission due to fuel oil and bagasse combustion during the refining process is considered as well as pre-harvest sugarcane burning.

Keywords: air pollution, dispersion modeling, AERMOD, sugarcane processing, pre-harvest burning

1. INTRODUCTION

A high percentage of the sugar supply is obtained from sugar cane (*Saccharum officinarum*), which is one of the most extensively cultivated grasses in tropical and subtropical regions in the globe. Brazil is the major producer of sugar cane in the world, being Mexico the second most important producer in Latin America (CVCA 2010).

An efficient crop can produce from 100 to 150 tons of sugar cane per hectare per year, having an efficiency of 12 to 13% for the extraction of sugar. In the extraction process, the sugar cane is grounded and squeezed to obtain the juice, generating bagasse as the principal sub-product. Bagasse consists basically of cellulose fibers, lignin and pentosan and has an elevated percentage of humidity (50%), sugar (about 2% on average) and strange materials (0.5% on average). Depending on different factors, such as ripeness, percentage of strange material, extraction type, *etc*., up to 15-25% of the grounded sugar cane corresponds to bagasse. This material has been used traditionally as an energy source for the production process in sugar mills, due to their calorific power, converting these facilities in self-sufficient for power generation and thus *green*. As the production process in a sugar mill includes internal combustion, typically air pollutants as particulate matter, NO_x and SO_2 are emitted to the atmosphere.

The AERMOD dispersion model (US-EPA 2012) was used to estimate the effect of sugar cane processing in central Mexico; this model is a regulatory steady-state plume modeling system provided by the US-EPA that includes a wide range of options for modeling air quality impacts of pollution sources, making it a popular choice among the modeling community for a variety of applications.

AERMOD, as any other mathematical dispersion model, provides only an estimate of the atmospheric concentration of environmental pollutants, and its results depend on the quality of the corresponding input data, and the methodology used for its determination.

2. CASE STUDY

2.1. Study Area

Sugar cane was introduced in Mexico during the sixteenth century; sugar industry infrastructure has been developed since then. In the southern region of central Mexico, sugar production and commercialization has been one of the principal subsistence means since 1690. Different ancient haciendas are now industrialized sugar refineries. The process includes boilers which are operated under three different conditions: fuel oil only, bagasse only and mixed fuel (fuel oil and bagasse) feeding, so typical combustion pollutants such as fly ash, smoke and flue gases are expected to be emitted into the air in the region.

A typical sugar mill located in central Mexico at about 910 meters above sea level which has been working since approximately 75 years, is used to demonstrate the usefulness of the AERMOD. This sugar refinery is active during the sugar cane harvest time, which lasts 180 days (November – May). In this zafra period, the refinery works 24 hours a day and processes a daily average of 7 tons of sugar cane. Until two years ago, the plant was working with old processing units and 5 chimneys – including the original concrete chimney that has been in use since the mill started operations - using bunker oil fuel mixed with or without bagasse. Simple dust separators were used for controlling fly ash. However, as a response to claims of the surrounding local population, the process was improved, more efficient dust control equipment was installed and fossil fuel use was reduced, using at present mainly biomass fuel (bagasse). The original concrete chimney was closed in May 2011 after the zafra period; it was replaced by a new chimney that started operations on December 6th, 2012. Nevertheless, although process conditions were considerably improved, the local population still claims that the sugar refinery is the most important source of pollution in the area.

Another issue of importance is that usually the sugar cane is burned in the field previous to harvesting, in order to increase the efficiency of the refining process. The refinery can also process the so-called green or not burned sugar cane, which however lowers process efficiency as the direct harvesting generates a higher proportion of impurities as roots and leafs in the raw material.

The raw sugar cane is supplied by 11 thousand hectares of cane plantations, owned by local peasants and distributed in different rather small and often irregular parcels located at distances up to 50 km from the refinery. According to its ripeness, approximately 7 tons of sugar cane needed daily are selected from day to day. Generally, different parcels provide the daily need of raw sugar cane, so up to 12 different burning sites may be expected. The pre-harvest burning takes place during approximately one hour in the morning. As the harvesting season (November-May) coincides with the dry season and thus worst conditions for air pollutant dispersion, it is likely that this burning will have a negative impact on the air quality in the surroundings of the sugar cane parcels, emitting fly ash and smoke that are very visible to the local population.

Figure 1 presents a general view of the studied sugar refinery; a difference in strength of emitted air pollutants is clearly visible in the photo; this is due to the specific operating conditions of each processing unit, as for example the used fuel type or effectiveness of the emission control systems.

Figure 2 shows a map of the study area, indicating the distribution of the sugar cane plantations near the mill.

Figure 1. Studied Sugar Refinery

2.2. Aim of the Study

The general aim of the study is to determine the influence area for the dispersion of air pollutants emitted by a typical sugar refinery in a rural area in central Mexico, based on present operating conditions and the use of the Gaussian dispersion model AERMOD.

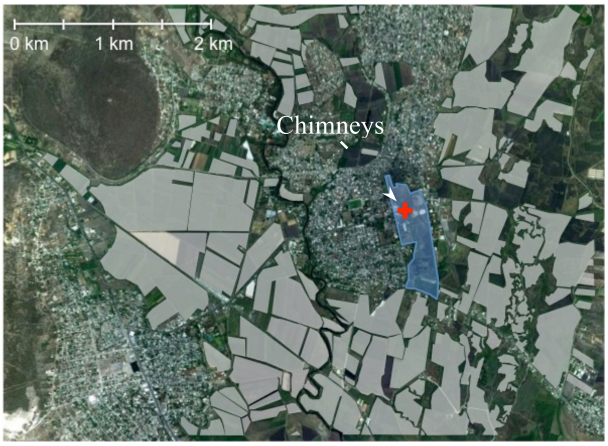

Figure 2. Map of the Sugar Factory and Surrounding Sugar Cane Plantations. The Shaded Area Marks the Property Limits of the Mill

Specific aims are:

- Estimate the surrounding air quality by means of mathematical dispersion modeling.
- Determine whether or not the observed air pollution in the area can be assumed to come from the refinery.
- Determine if recent changes in the process have resulted in improvements on local air quality.
- Estimate the importance of the on-site sugar cane burning during the harvesting period.

3. METHODS

The AERMOD model was used to compare the contribution of the sugar refinery before and after the process improvements. Also the influence of sugar cane burning during the sugar cane harvest period on the particle concentrations was studied. The simulated pollutants are particulate matter (≤ 80 μm in aero dynamic diameter), NO_x and SO_2. AERMOD is a steady-state plume model that assumes that concentrations at all distances during a modeled hour are governed by the temporally averaged meteorology of the hour. In the stable boundary layer (SBL), it assumes the concentration distribution to be Gaussian in both the vertical and horizontal. In the convective boundary layer (CBL), the horizontal distribution is also assumed to be Gaussian, but the vertical distribution is described with a bi-Gaussian probability density function. In addition, in the CBL, AERMOD treats "plume lofting," whereby a portion of plume mass, released from a buoyant source, rises to and remains near the top of the boundary layer before becoming mixed into the CBL. AERMOD requires only a single surface measurement of wind speed (measured between 7 z_o and 100m (where z_o is the surface roughness height), wind direction and ambient temperature. The general concentration equation used by AERMOD is:

$$C\{x, y, z\} = \frac{Q}{u} p_y\{y; x\} p_z\{z; x\} \quad (1)$$

where Q is the source emission rate, $\bar{u}$ is the effective wind speed, and p_y and p_z are probability density functions which describe the lateral and vertical concentration distributions, respectively.

3.1. Topography

AERMOD can run on flat terrain or considering the topographic elevations of the receptors and sources considered in the model; this information can be extracted from a digital elevation model (DEM), available from USGS topographic data. The sugar refinery is located in a flat area; however, east of the study region an area of rough topography can be observed (figure 3), so AERMOD was run in the complex orography mode. To introduce the topographic information, the digital elevation model corresponding to the region surrounding the sugar cane production facility was downloaded from the www.webgis.com site. This file was converted to the required AERMAP format and included in the modeling project.

Figure 3 represents the topography of the study area in three dimensions.

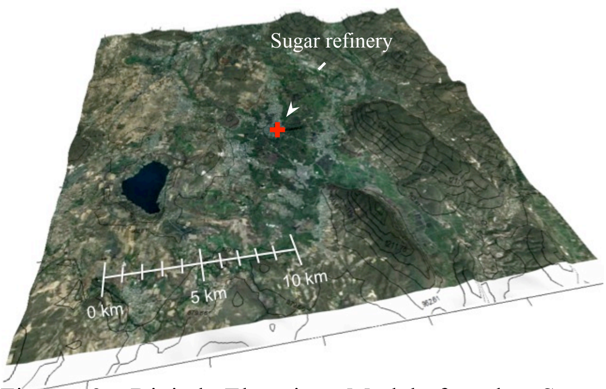

Figure 3. Digital Elevation Model for the Sugar Production Facility Surroundings (Vertical Exaggeration = 3x)

3.2. Meteorology

Meteorological information provided by the Forestry, Farm and Livestock National Research Institute (INIFAP), was analyzed for the year 2011, and statistical wind information for May 2011 was used to set a downwind air quality monitoring campaign for the most important ambient air pollutants and meteorological parameters during the last two weeks of the 2012 *zafra* and harvesting period.

Meteorological information of the study zone required by AERMOD includes: station number and location, year, Julian day, hour, temperature, wind speed and direction, precipitation, humidity, station pressure and cloudiness. The standard meteorological files are converted to ".sfc" and ".pfl" files, respectively for surface and upper air meteorological information. Cloudiness is not routinely measured in meteorological stations in Mexico, so it is assumed to be cero. For modeling effects, only events were considered where precipitation was cero, because particle transport reduces when precipitation exists.

To generate the required ".sfc" y ".pfl" files, typical albedo, Bowen ratio y roughness length values are needed; these values were chosen according to the land use in the area, corresponding to respectively cultivated land from North to ESE directions and urban land use for the rest (see figure 4). Table 1 indicates the resulting land use parameters used in the AERMOD runs.

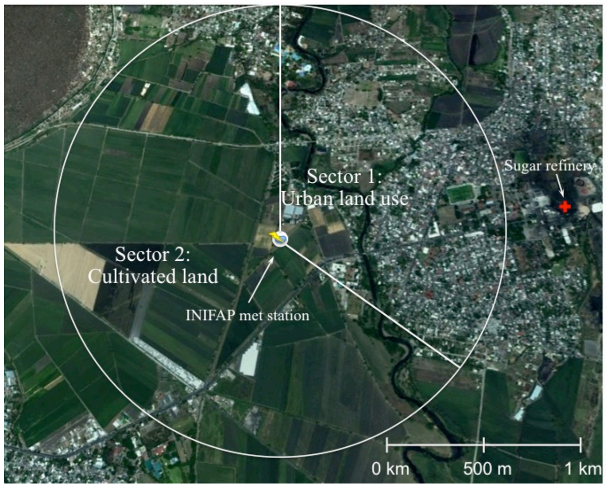

Figure 4. Land Use Sectors Specified in the Model

Table 1. Used Land Use Parameters

Sector	Albedo	Bowen ratio	Surface roughness length
1	0.28	0.75	0.0725
2	0.2075	1.625	1

3.3. On-site Monitoring

Preliminary AERMOD modeling was performed to be able to locate a temporary ambient air monitoring station in a specific site at the end of the harvesting period, in order to detect possible air pollutants transport from the refinery plant.

During May-June 2011, wind was coming prevailingly from ESE-E and WSW-SW directions. According to this information, the 2012 monitoring site was set within the INIFAP research site, located at about 1.5 km from the refinery in WSW direction. Therefore, both the pollutant concentrations due to the dispersion of the sugar mill emissions when the wind was blowing towards the INIFAP and the background concentrations registered when wind was blowing in the opposite direction could be observed. The monitoring station was an AIRPOINTER (figure 5), which is a compact multi gas air quality monitoring system capable of continuously measuring CO, $NO/NO_2/NO_x$, O_3, SO_2, and $PM_{2.5}$, and has meteorological sensors for wind speed, wind direction, ambient temperature, relative humidity, ambient atmospheric pressure, and precipitation.

An additional portable *DAVIS* meteorological station was set at the top of an elevated water tank (45 m) near the boiler stacks of the sugar refinery in order to check the representativeness of wind profile predictions of the model (figure 6).

Figure 5. Air Pointer Monitoring Station Installed in the INAFAP

Figure 6. Installation of a *DAVIS* Meteorological Station in the Sugar Refinery

3.4. Sugar cane burning

Sugar cane plantations in a 2 km radio area surrounding the plant were referenced geographically to be able to model the effect of daily sugar cane burning on air quality. Only the nearest plantations were considered, as parcels at further distances are not likely to affect air quality in the village.

A daily processing rate of 7 tons of sugar cane corresponds to about 69.1 hectares/day; among the parcels dedicated to sugar cane harvesting in the 2 km radius around the facility, a random area of 69.1 hectares was selected. Emission factors for pre-harvest sugar cane burning (US-EPA 2005; Ribeiro 2008; Hall *et al.* 2012) were used to estimate particulate and NO_x emissions generated by the burning and the affectation was determined by means of the AERMOD model. Used emission pre-harvest burning emission factors are specified in table 2.

Table 2. Emission Factors for Pre-Harvest Burning

Pollutant	Emission factor (g/s m^2)
PST	0.0092273
NO_x	0.0006944

3.5. Plant Emissions

Data of the emissions strength and physical characteristics of the 5 boiler stacks were provided by the staff of the sugar refinery. The physical characteristics of the sources are presented in table 3, while tables 4 and 5 indicate the emission strength before and after the change to the use of bagasse as a fuel. Note that emission source 1 corresponds to the concrete chimney that stopped working in May 2011; chimney 1b is the new chimney.

Table 3. Physical Source Characteristics

Characteristics	Emission sources					
	1	1b	2	3	4	5
Height (m)	30	30	30	36	30	36
Diameter (m)	0.6	2.3	1.62	1.6	1.6	1.6
Exit velocity (m/s)	5.94	18.5	9.16	9.16	8.20	9.14
Exit temperature (K)	399	458	433	494	427	458

Table 4. Average Source Emissions 2009-2011

Pollutant	Emission sources				
	1	2	3	4	5
SO_2 (g/s)	7.2	22.34	26.42	19.33	20.25
NO_x (g/s)	0.46	4.91	2.35	3.37	3.47
PST (g/s)	0.05	0.64	0.51	0.62	0.47

Table 5. Source Emissions 2012

Pollutant	Emission sources				
	1b	2	3	4	5
SO_2 (g/s)	91.75	NA	21.94	19.64	21.89
NO_x (g/s)	18.26	NA	4.31	3.84	4.41
PST (g/s)	23.17	NA	4.84	1.94	1.93

Tables 4 and 5 indicate that SO_2 concentration has stayed the same after the process improvements, while NO_x and PST concentrations have increased considerably. This is because bagasse has a lower calorific capacity, so more fuel is needed when using bagasse than when using fossil fuels.

3.6. AERMOD Implementation

To implement AERMOD, the following activities were performed:

- Obtaining of the DEM of the study region
- Mounting of the regional topography in the terrain preprocessor for its posterior use in the AERMOD dispersion model
- Obtaining of Google Earth maps for the study area and their geographical referencing
- Adaptation of the 2011 meteorological information with the meteorological preprocessor AERMET and introduction of the resulting data in AERMOD
- Specification of the modeling region and receptor grid
- Compilation of the physical characteristics and emissions values for the emission sources
- Physical determination of the geographical references of the emission sources and inclusion of the geo referenced elements in the dispersion model.

4. RESULTS

4.1. Meteorology

The wind speed in the area is quite low, presenting average wind speeds of 2.1 m/s, 42% of calms and over 80% of winds below 4 m/s. Predominant wind directions are from southeast in winter, and from southwest in summer, being the wind speed lower in winter. Figure 7 presents the wind rose for 2011.

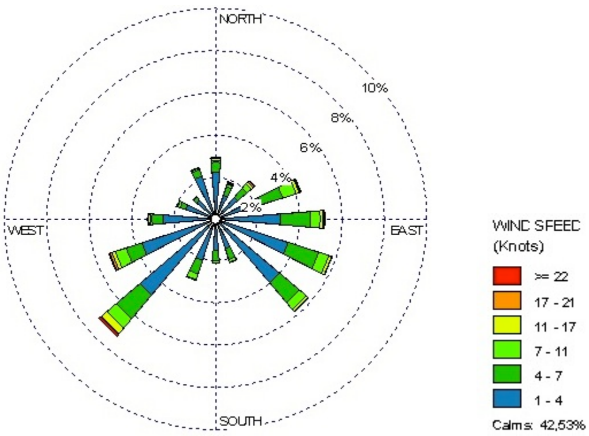

Figure 7. Wind rose in the study area, 2011

4.2. Particulate Matter Concentration

The 24-hour average PST concentration was estimated with AERMOD using the meteorological information for the 2011 *zafra* period. Operating conditions before and after the process improvements were modeled, using the land use parameters specified in table 1. Figures 8 and 9 respectively present the modeling results for the maximum 24-hour PST concentrations found during the *zafra* period, before and after the partial substitution of fossil fuel by bagasse.

Figures 8 and 9 indicate that maximum 24-hour PST concentrations were found to be respectively 6 $\mu g/m^3$ when only fossil fuel is used and 39 $\mu g/m^3$ when approximately half of the fossil fuel is substituted by bagasse. The increase of maximum PST concentrations is due to the lower calorific capacity of bagasse, so more bagasse than fossil fuel is needed for the sugar refining process. Still, the present fuel configuration generates local PST pollution far below the 210 $\mu g/m^3$ specified as the maximum concentration in the Mexican norm NOM-025-SSA1-1993.

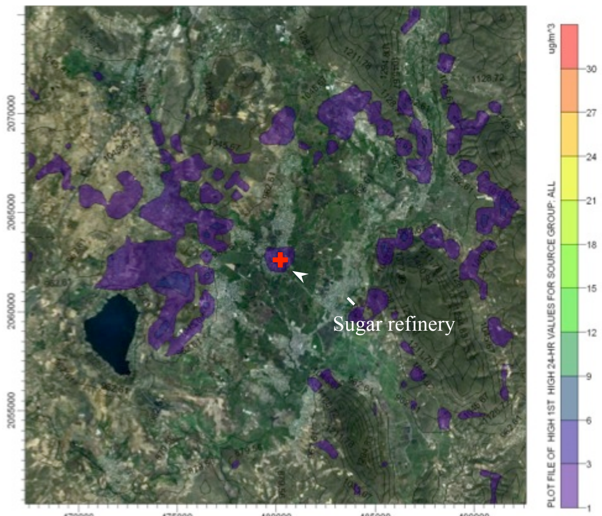

Figure 8. Maximum 24-hour PST Concentrations due to Sugar Refinery Operations, using Fossil Fuels. Ene-May 2011

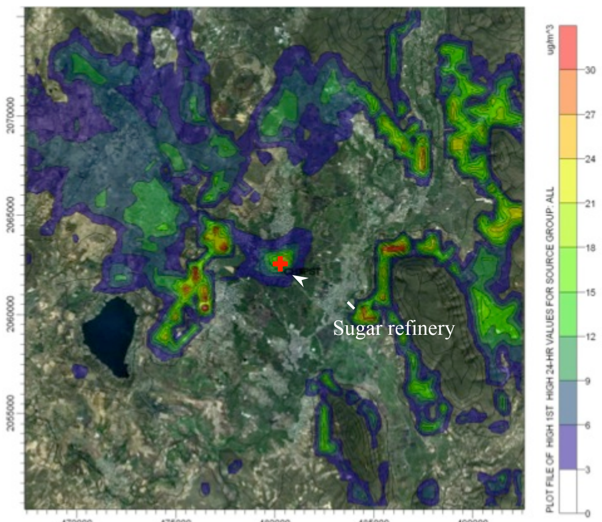

Figure 9. Maximum 24-hour PST Concentrations due to Sugar Refinery Operations, using Bagasse and Fossil Fuels. Ene-May 2011

4.3. Influence of the Pre-Harvest Burning

To analyze the influence of pre-harvest burning on the air quality in the region, 6 parcels with an approximate total surface of 7000 ha in the neighborhood of the mill were randomly selected, simulating the selection of daily sugar cane crops according to their maturity; the emission factors from table 2 were used.

Figure 10 presents the result of the corresponding AERMOD modeling for PST concentration; the sugar cane parcels are indicated in red. It indicates that pre-harvest burning in the fields near the refinery, although this last for only about an hour each morning, is generating huge hourly PST concentrations in nearby houses. Hourly concentrations over 175 000 μg/m^3 are found, corresponding to 24-hour concentrations of 730 μg/m^3, and thus to 3.5 times the national standard of 210 μg/m^3. Big sugar cane parcels will cause more harm than smaller parcels, as the PST emissions are spread; up to 2 km from the burning front concentration values over the 24-hour standard can be expected. For NO_x, a similar conclusion can be drawn, although NO_x concentrations are lower than PST concentrations.

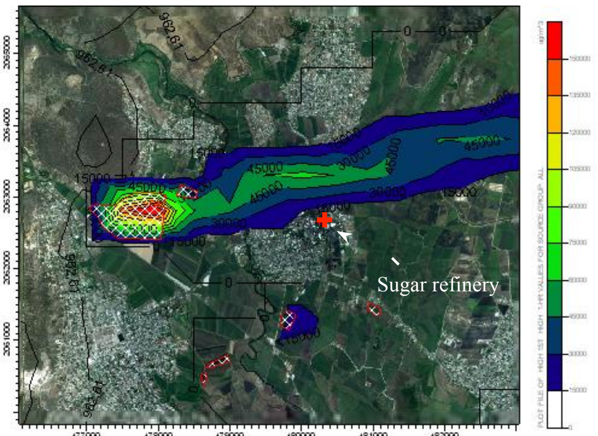

Figure 10. Influence of pre-harvest burning on particulate matter concentration, hypothetical run for December 3, 2011

It is important to note that 90% of pre-harvest burning PST corresponds to small particles (< 0.5 μm), which are dangerous to human health, as stated for example by Ribiero (2008).

5. CONCLUSIONS

AERMOD modeling indicates that pre-harvest burning of sugar cane presents local PST concentrations over 3.5 the national standard; this phenomenon is a lot more important than PST pollution originated in the refining process.

Although the use of bagasse in the extraction process is more sustainable than the use of fossil fuels, its use increments the PST concentrations expected in the surroundings of the sugar mill by approximately 6. However, none of the used fuel combinations generate PST concentrations that violate the national standard.

Future work includes comparison of AERMOD results with ambient air concentrations recorded in the Air Pointer monitoring station during the 2012 *zafra* period.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Alma Delia Baez-Gonzalez from INIFAP for the meteorological information provided for this study.

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