AIR DISPERSION MODELING OF MULTIPLE NATURAL GAS WELL PADS AT DIFFERENT TERRAIN CONDITIONS AND DETERMINATION OF INVERSE DISTANCE WEIGHTING FUNCTION EXPONENT

by

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Abstract

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The University of Texas at Arlington, 2016

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Natural gas production and development has been widely spreading all over the United States. Texas has been leading the nation in natural gas production by holding approximately twenty three percent of the nation’s natural gas reserves. However, natural gas exploration, drilling, production and distribution process have impacts on air quality and human health. The emissions from natural gas processes could be categorized as volatile organic compounds (including Hazardous Air Pollutants), methane, carbon monoxide, nitrogen dioxides, particulate matter and some other minor emitted pollutants, which have the potential of causing serious health problems and also impact air quality from an environmental point of view. There have been a lot of studies done about natural gas well activities and resulting air pollution, including a complete study on City of Fort Worth natural gas wells in 2011. However, the dispersion modeling of the Fort Worth study was done only on flat-elevated terrain for one well pad (or compressor station) in different scenarios, not including criteria pollutants.

Therefore tow main objectives of this study are:

1) To evaluate the impact of multiple natural gas well pad emissions together in various terrain conditions using the Gaussian dispersion model AERMOD (including criteria pollutants)
2) To determine the exponent in the inverse distance weighting function which applies to the dispersion modeling output.

It is expected that modeling multiple well pads will causes exceedances of NAAQS or ESLs, and it is expected that flat terrain will produce higher concentrations because in smooth surfaces, it is less probable to have strong vertical mixing and turbulence resulted from elevation difference, therefore there is not quick dilution into large volume of air, and as result the pollutant concentration at ground level will be higher in compare to other terrain types.

Based on the output results of the AERMOD, in all cases for all modeled pollutants, the maximum concentrations from high and low emissions rates were lower than standard levels and thresholds, except methane for which there is not fixed standard regulated level as local evaluation. Based on additional runs for three terrains with identical well pad arrangements and emissions rates, the inclined terrain had the highest maximum concentrations from flat and moderate terrains. The most proper exponent of IDW equation, based on evaluation of ten different reference points, was 4, which gave the closer value to expected concentration.

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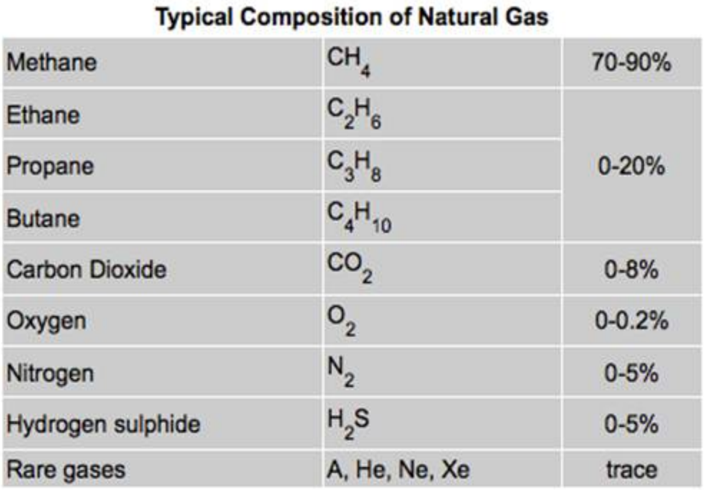
Chapter 1

Introduction

1.1 Background

Natural gas, as a source of energy, is one of the cleanest and most efficient sources of energy worldwide. Currently, in the US 25% of energy is supplied by natural gas, and 33 states are considered as gas producers in the US (American Gas Association, 2010)

Natural gas has important physical characteristics, as it is colorless, shapeless, and odorless in its pure form. The main composition of natural gas is a mixture of hydrocarbon gases. The main part of natural gas is methane, also some part ethane, propane, butane and pentane. The composition of natural gas can vary widely (Natural Gas, 2010). Figure 1-1 shows typical natural gas composition.



Typical Composition of Natural Gas

Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen sulphide	H_2S	0-5%
Rare gases	A, He, Ne, Xe	trace

Figure 1-1: Typical composition of natural gas (source NaturalGas.org)

Natural gas is highly combustible and one of its positive attributes is that while burning, it gives energy with fewer emissions compared with many other sources. Natural gas combustion causes little amounts of sulfur, mercury, and particulates, compared to other fuels like oil. However, by burning natural gas nitrogen oxides (NOx) are produced, which are precursors to ozone smog formation, but at lower levels than gasoline and diesel used for motor vehicles. Some recent analyses show that every 10,000 U.S. homes powered with natural gas instead of coal avoids annual emissions of 1,900 tons of NOx, 3,900 tons of SO_2, and 5,200 tons of particulates. (National Renewable Energy Laboratory, 1999) The emissions from production of natural gas are the focus of this thesis.

The total number of producing natural gas wells in the U.S., based on recent data of Dec. 2014, is 514,786. The total number of wells increased by 5.6% from 2013 to 2014. The state of Texas has 98,279 producing gas wells (American Gas Association website, 2014). Therefore, Texas has about 19% of total gas wells in the U.S., which is substantial. However there has been an increase in natural gas wells in Texas since 1936. Figure 1-2 shows the increase up to year 2010.

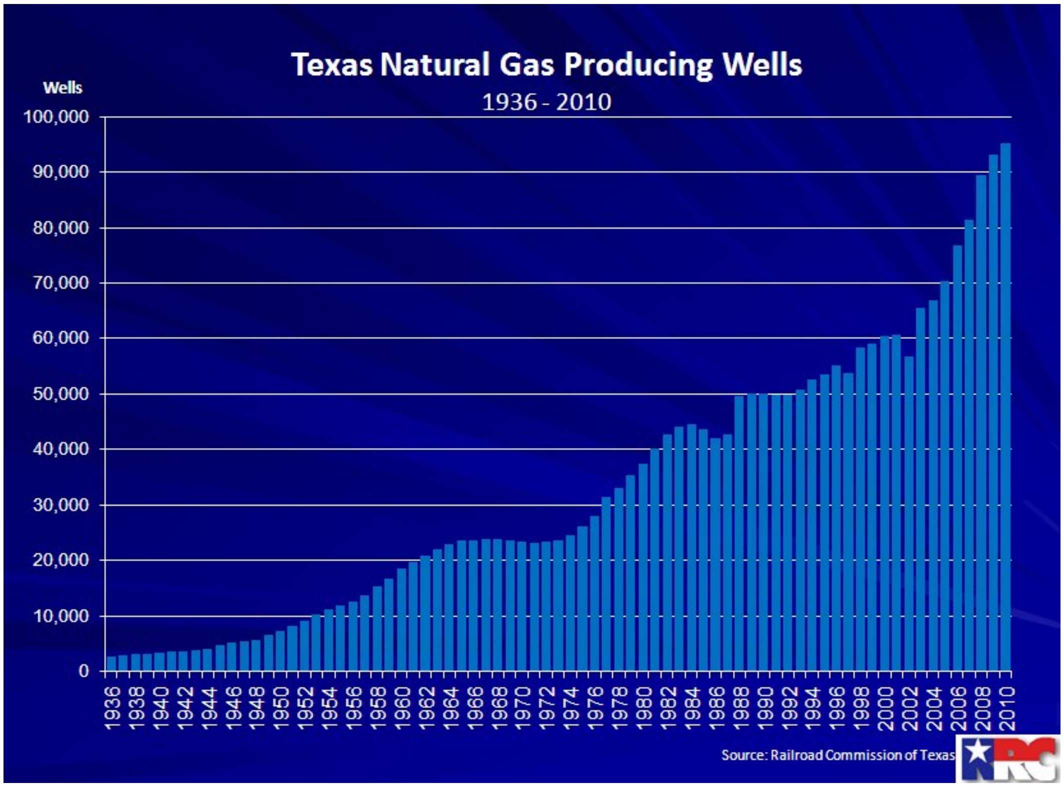


Figure 1-2: Natural gas well increase in Texas (Source: Texas Railroad Commission website, 2010)

1-2 Natural gas facility emissions:

The production of natural gas is presented in Figure 1-3. Emission sources from natural gas production include point sources, which include compressor engine exhausts and oil/condensate tanks; as well as fugitive and intermittent sources, which include production equipment fugitives, well drilling and hydraulic fracturing (fracing) engines, well completions, gas processing, and transmission fugitives. (Armendariz, 2009)

The production of natural gas industry is presented at Figure 1-3.

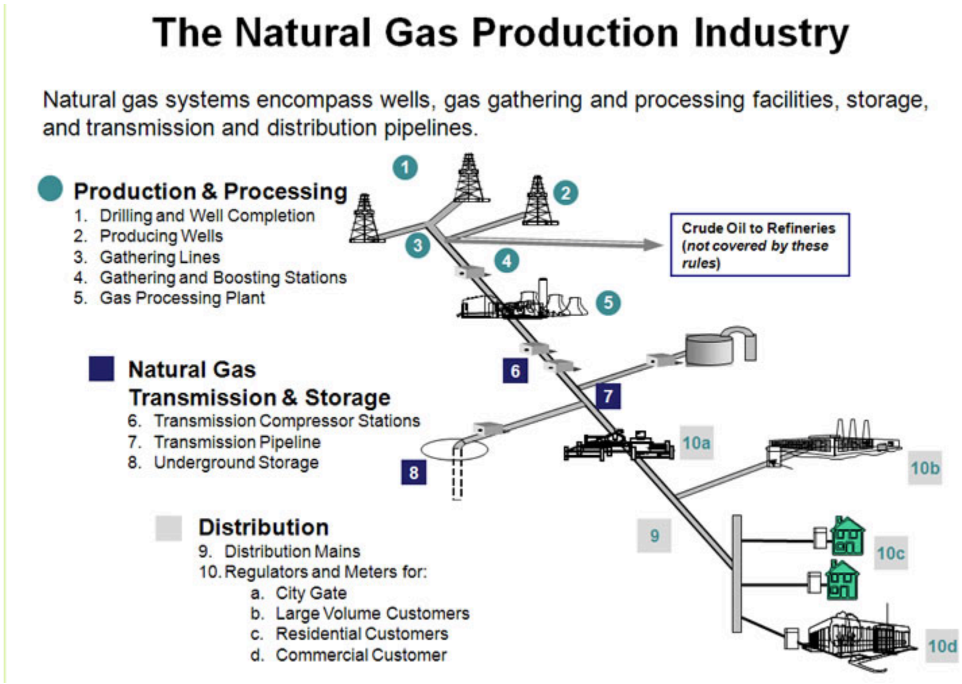


Figure 1-3 Natural gas production (Source: Adopted from American Gas Association and EPA Natural Gas Star program)

The typical emissions from natural gas facilities fall into three main categories:

1) volatile organic compounds, or VOCs, which contribute to ground-level ozone smog formation, and many of which are hazardous air pollutants (HAPs),
2) methane, a potent greenhouse gas, and
3) combustion byproducts, including nitrogen oxides and particulates.

Each of these categories is described in more detail below.

Based on estimation of EPA (2008), VOC emissions from the oil & natural gas industry are 2.2 million tons per year. VOCs exist in the gas phase or can evaporate from liquids. The VOCs can react with NOx in the atmosphere via a complex series of reactions to generate ozone and fine particulate matter. Methane and ethane are not considered as VOCs because they react slower than other VOC compounds to produce ozone and fine particles, but they do contribute somewhat to ozone formation.

Approximately 98 percent of VOCs from natural gas are the pollutants with low toxicities, like ethane, methane and propane. On the other hand, the remaining two percent of VOCs components are relatively high toxicities, such as benzene and acetone. Air pollutants with high toxicities, or HAPs, are believed to have the potential of causing serious human health effects even at low doses. Benzene is one of the most known examples of a HAP compound, which is an organic compound known to contribute to the development of cancer. (U.S. EPA, 2002)

Various other HAPs can cause damage to the kidney, liver, and central nervous system. A recent study about health impacts of natural gas facility emissions found that residents living less than half a mile from unconventional gas well sites have greater risk of health effects from air pollution than those living farther from the well sites. (McKenzie et al., 2012)

Methane, CH_4, is another significant source of emissions from the oil and natural gas industry. Based on the fifth assessment report, 2014, from Intergovernmental Panel on Climate Change (IPCC), methane as a greenhouse gas, is more than 28 times as potent than carbon dioxide, on a 100-year time scale.

Based on Environmental Protection Agency report summary 1995, Nitrogen dioxide belongs to a family of highly reactive gases called nitrogen oxides (NOx). NOx plays a major role in the atmospheric reactions that produce ground-level ozone (or smog). Nitrogen oxides contribute to ozone formation and can have adverse effects on both terrestrial and aquatic ecosystems. Nitrogen oxides in the air can significantly contribute to a number of environmental effects such as acid rain and eutrophication in coastal waters like the Chesapeake Bay. Eutrophication occurs when a body of water suffers an increase in nutrients that leads to a reduction in the amount of oxygen in the water, producing an environment that is destructive to fish and other animal life. And about Carbon monoxide, this is a colorless, odorless, poisonous gas formed when carbon in fuels is not burned completely. CO has mostly health risk issue. Carbon monoxide enters the bloodstream and reduces oxygen delivery to the body's organs and tissues. Particulate Matters, can be directly emitted or can be formed in the atmosphere when gaseous pollutants such as SO_2 and NOx react to form fine particles. (EPA, 2016)

1-3 Research objectives:

The objectives of this study are:

1) To evaluate the impact of multiple natural gas well pad emissions together in various terrain conditions using the Gaussian dispersion model AERMOD (including criteria pollutants).
2) To determine the exponent in the inverse distance weighting function which applies to the dispersion modeling output.

In terms of the first objective, a previous study (ERG and SAGE, 2011) evaluated impacts from one gas well pad and compressor engine station. Also the dispersion modeling of criteria pollutants were not performed in that study. It is hypothesized that multiple well pads will produce greater ambient air pollutant concentrations than a single well pad, and that these concentrations may exceed National Ambient Air Quality Standards or Texas Commission on Environmental Quality (TCEQ) Effects Screening Levels (ESLs).

In terms of the second objective, McKenzie et al. (2014) used the Inverse Distance Weighting function (IDW) to recommend a safe setback distance from gas well locations. The Inverse Distance Weighting equation can be a fast and easy method (compared to Gaussian dispersion modeling) to estimate the pollution concentration at different points from a source. However, the value of exponent α in the IDW equation is not a fixed determined value yet. Therefore, the second objective of this study is to determine an appropriate value of exponent α, by interpolating the output and results from the dispersion modeling of various pollutants at differ terrain conditions.

Chapter 2

Litrature Review

2.1 Natural gas drilling and production

During oil production process in North Texas, natural gas was discovered. In 1918, in Texas the first gas well was established and completed and the well production was estimated at 10 million cubic feet of natural gas per day. The numbers of completed wells increased gradually over time, and one of the wells was producing 107 million cubic feet of gas, which confirmed the presence of natural gas fields in Texas. By 1927, natural gas production exceeded 4 billion cubic feet per day. By 1994, gas production in Texas was more than 8 trillion cubic feet per day. By holding more than 22 percent of the U.S.'s natural gas sources, Texas has a major role in oil and gas industry in the country. The approximate amount of natural gas production in year 2009 was about 19.7 trillion cubic feet of gas per day, and this big number made Texas one of the largest gas producing states in the U.S. Natural gas is 14.9 percent of gross state product in Texas and consequently has contributed over $100 billion to the state's economy. The industry employs over 312,000 Texas residents. (Universal Royalty Co., 2013)

During recent decades, the natural gas exploration, drilling and production has increased dramatically in the United States in many areas. The Barnett Shale region in the northeast part of Texas is one of those areas, which contains a number of cities, including Dallas and Fort Worth. Traditionally natural gas exploration has been conducted in rural areas; however, during recent years gas drilling has started to encroach into the more urban areas of the Dallas-Fort Worth metropolis. It is important to consider the health and social impacts of natural gas wells in cities. While the environmental concerns of hydraulic fracturing – or fracking – get more headlines, the drilling, production and transportation of conventional natural gas pose concerns as well. The air emissions associated with drilling, compression machinery and the heavy truck traffic related to well sites generate potential environmental and health risks. During the construction and drilling phases of a well's life cycle, emissions are heaviest, especially when drilling machinery, diesel generators and heavy trucks for hauling equipment are needed. The operational phase of a well's life typically has fewer emissions, though compressors and gas transportation trucks are still present during this period. Additional impacts from urban wells include noise from drilling activity, compressors and trucks, and from increased heavy truck traffic on roads that do not normally experience industrial traffic. (Querejazu, 2012)

The public concerns about shale gas drilling are mainly about the chemical compounds used in fracking fluids, which includes the potential for ground and surface water contamination, the potential for negative health effects from hazardous air emissions, and the safe disposal of flow back fluids (Rahm, 2011; Howarth and Ingraffea, 2011). Non- disclosure of the chemical ingredients used in fracking fluids has resulted in limited research data on the potential health impacts and environmental effects of hydraulic fracturing (Thompson, 2012; although see Oswald and Bamberger, 2012; Osborn et al., 2011). Recent empirical research on shale gas extraction demonstrates other negative public perceptions of shale gas drilling. For example, Fry et al. (2012) present survey results showing that one-third of DFW residents believe shale gas drilling is the greatest threat to their water supply. Theodori (2012) finds that the duration of drilling activities affects how residents feel about shale gas drilling in general, with the most negative perceptions of the gas industry occurring among residents living in places where shale gas drilling is less established. It can be said that generally the placement of gas wells near homes is a major concern for residents.

The following Figure 2-1 shows the active natural gas and oil wells in Texas in the year 2014.

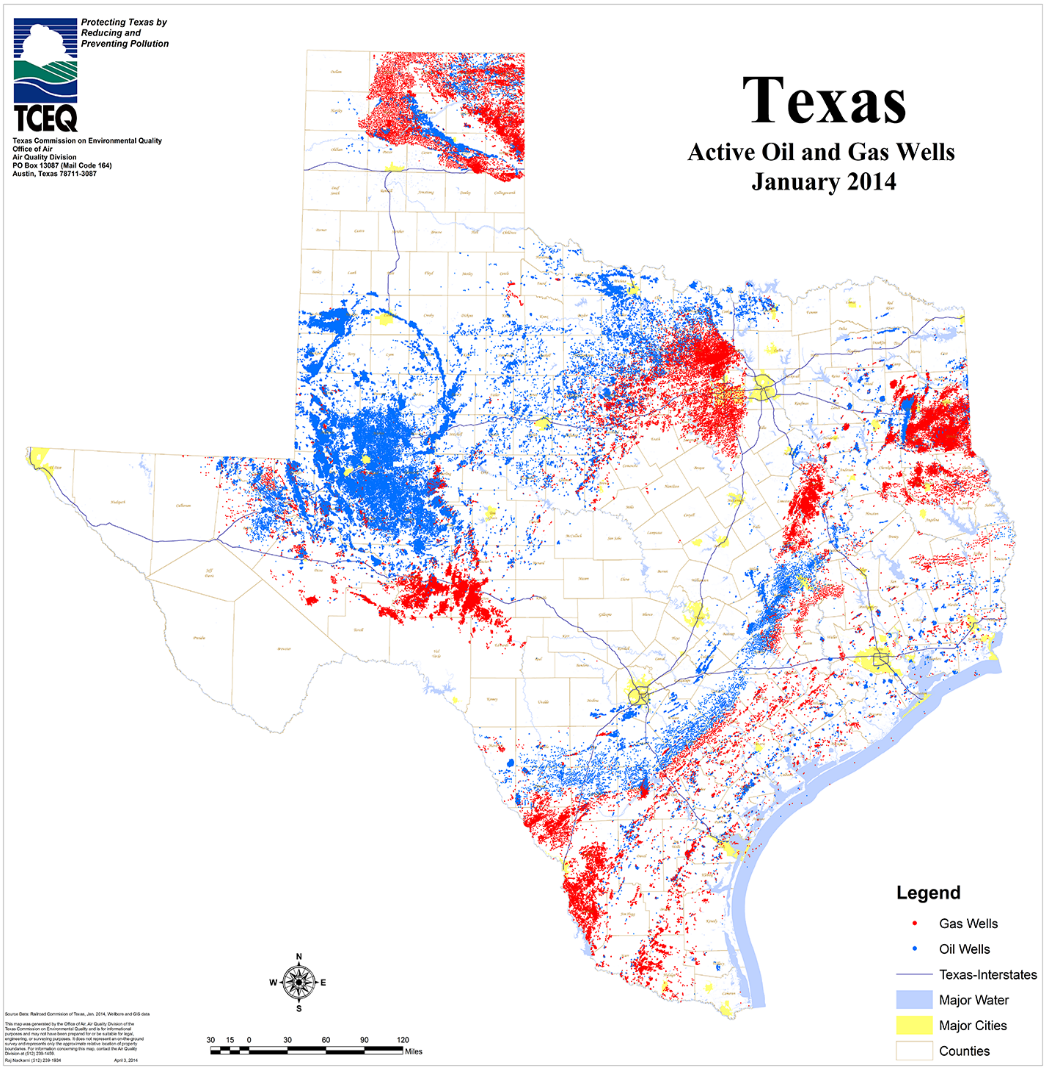


Figure 2-1: Texas active oil and gas wells, 2014 (Source: Texas Commission on Environmental Quality)

Natural gas (primarily methane) generally is formed and found underneath the surface of the earth. As natural gas has a low density, once formed it will rise toward the surface of the earth through loose, shale-type rock and other material. If the formation of natural gas traps are large enough, they can have a chance of being a source reservoir.

One of the most common natural gas reservoirs is impermeable sedimentary rock which forms a ‘dome’ shape, like an umbrella that catches all of the natural gas. One common location for oil or gas deposits is faults. A fault occurs when the normal sedimentary layers ‘split’ vertically. The picture below, Figure 2-2, shows how natural gas and oil can be trapped under impermeable sedimentary rock, in what is known as an anticlinal formation. Typically a hole is drilled through the rock bed in order to release the fossil fuels under pressure and have a successful extraction of gas to the surface. It is common in all reservoirs that natural gas is closer to surface, as it is less dense, followed by oil and some water underneath with higher density. Gas in these reservoirs is typically under pressure, allowing it to escape from the reservoir on its own (Naturalgas.org, 2014). Figure 2-2 shows a typical natural gas extraction process .

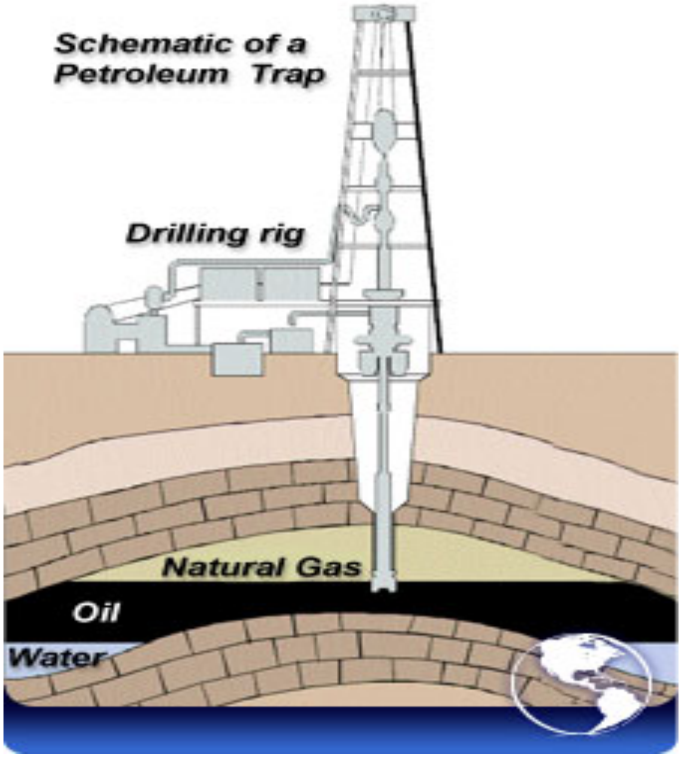


Figure 2-2 Natural gas extraction (Source: U.S. Energy Information Administration)

A team of drilling experts starts to dig down where the natural gas is thought to exist, based on suggestions of expert geologists and geophysicists. Based on recent technologies and advanced techniques, there are many new methods which decrease the cost and increase the efficiency of drilling for natural gas. The main reason is, as explained above, advantages of natural gas. There are many factors which should be considered in decided whether to drill or not, including the economic potential of the hoped-for natural gas reservoir. However, always there is a risk that no natural gas will be found. The nature of the potential formation to be drilled, the characteristics of the subsurface geology, and the depth and size of the target deposit from the dril site will impact the exact placement. The first step is defining the optimal well location by an expert geophysical team, and then the drilling procedure has to be reliable for all the necessary steps so that it can legally drill in that area. This process usually includes securing operation and extraction permits, selling the resources under a given area of land, and a designing gathering lines that will connect the well to the pipeline. (Natural gas website, Sep. 2013)

The oil and natural gas industry has various types of operations and equipment, including wells, gathering lines and processing areas, storage tanks, and finally transmission and distribution pipelines.

The process of unconventional natural gas development is typically divided into two phases: well development and production (US EPA, 2010a; US DOE, 2009). Well development involves pad preparation, well drilling, and well completion. The well completion process has three primary stages: 1) completion transitions (concrete well plugs are installed in wells to separate fracturing stages and then drilled out to release gas for production); 2) hydraulic fracturing (“fracking”: the high pressure injection of water, chemicals, and proponents into the drilled well to release the natural gas); and 3) flowback, the return of fracking and geologic fluids, liquid hydrocarbons (“condensate”) and natural gas to the surface (US EPA, 2010a; US DOE, 2009). Figures 2-3 to 2-5 present the natural gas production and wells in the US and Texas.

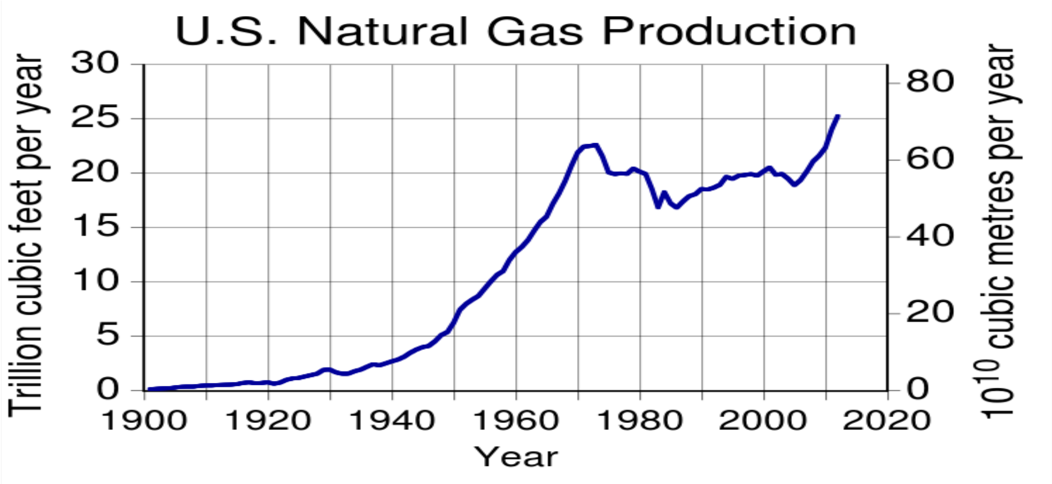
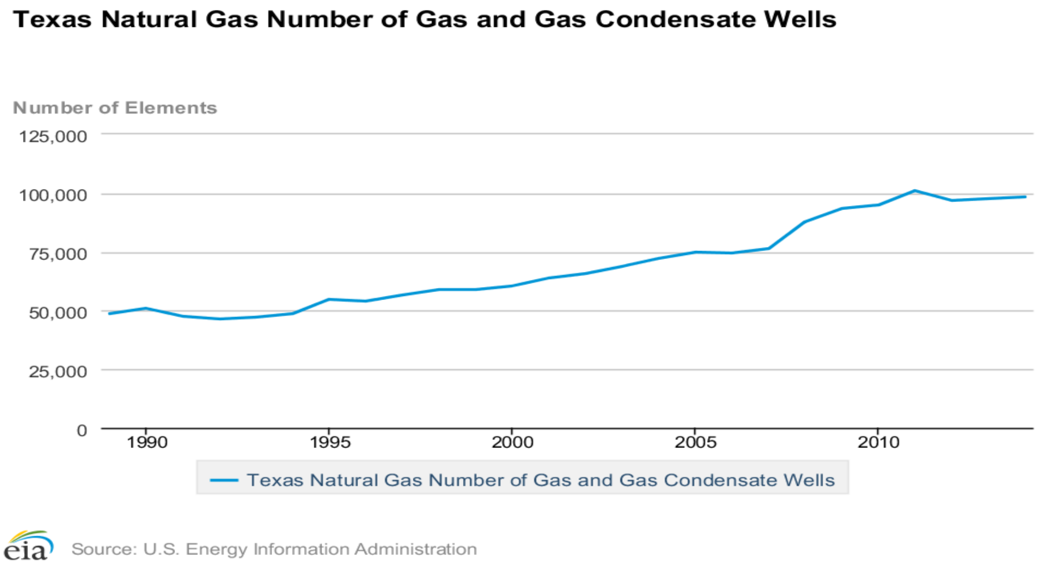

U.S. Natural Gas Production

Figure 2-3:U.S. natural gas production from 1900 to 2010 (Source: US EIA)


Texas Natural Gas Number of Gas and Gas Condensate Wells

Source: U.S. Energy Information Administration

Figure 2-4: Number of Texas natural gas and gas condensate wells (Source: US EIA)

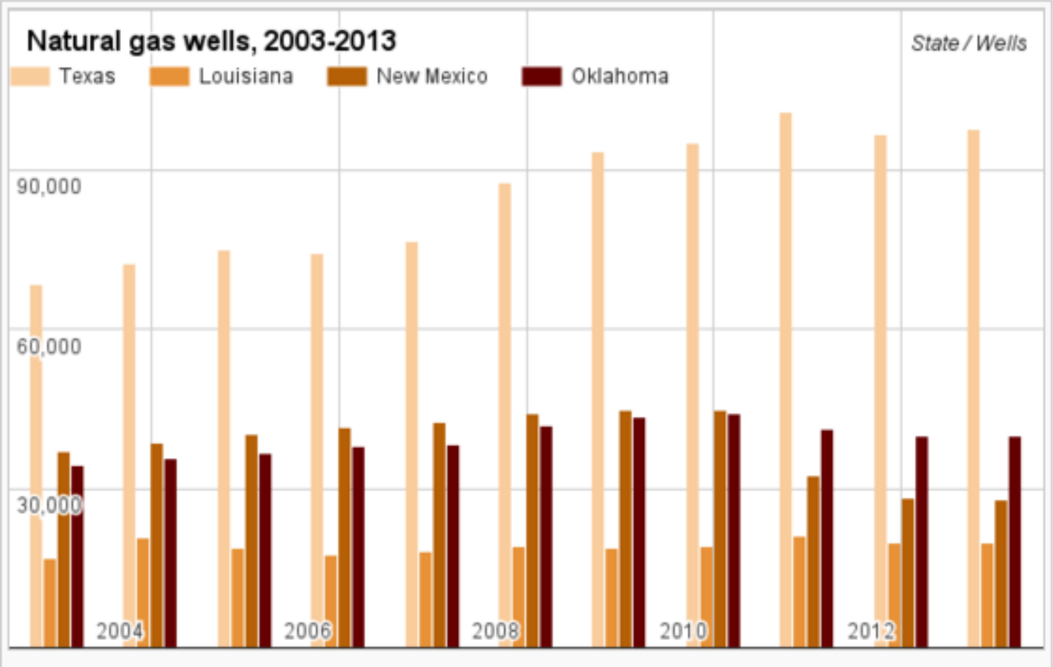


Figure 2-5: Comparison of number of natural gas wells in Texas and surrounding states (Source: US EIA)

2.2 Dispersion modeling

One of the most common methods to estimate and predict the pollutant concentrations from various types of sources like point, area and volume sources is dispersion modeling. The concentrations of different kinds of pollutants emitted into the atmosphere are estimated with dispersion modeling. Whenever a single type of pollutant is needed to be estimated at certain point, one equation for a specific receptor, based on dispersion method, can be easily used (a receptor is a determined area and place at which the concentration of pollutant is needed to be calculated). In other cases, having more than one pollutant or by considering many other factors which impact on the dispersion, a series of equations is used. When a series of equations is used, the most time- saving and more accurate method is using a computer program for modeling. By using computer modeling, in shorter time and with higher accuracy, lots of repeated equations for various receptors or different pollutants and different weather conditions can be solved. Computer modeling programs for dispersion use codes with series of equations. (Turner and Schulze, 2007)

AERMOD (Paine et al., 2003; U.S. EPA, 2002) is an Eulerian computer program model which can estimate the impact of multiple sources of pollution considering many receptors. The Eulerian models define specific reference points in a gridded system that monitors atmospheric properties, including temperature, pressure, chemical concentration of tracers, over time. The capacity of program is about modeling 50 sources at 500 receptors per hour of a year, which means about 8760 hours (Turner and Schulze, 2007) Dispersion modeling has been considered as a helpful engineering tool since the 1920s. Figure 2-6 shows the structure of dispersion modeling.

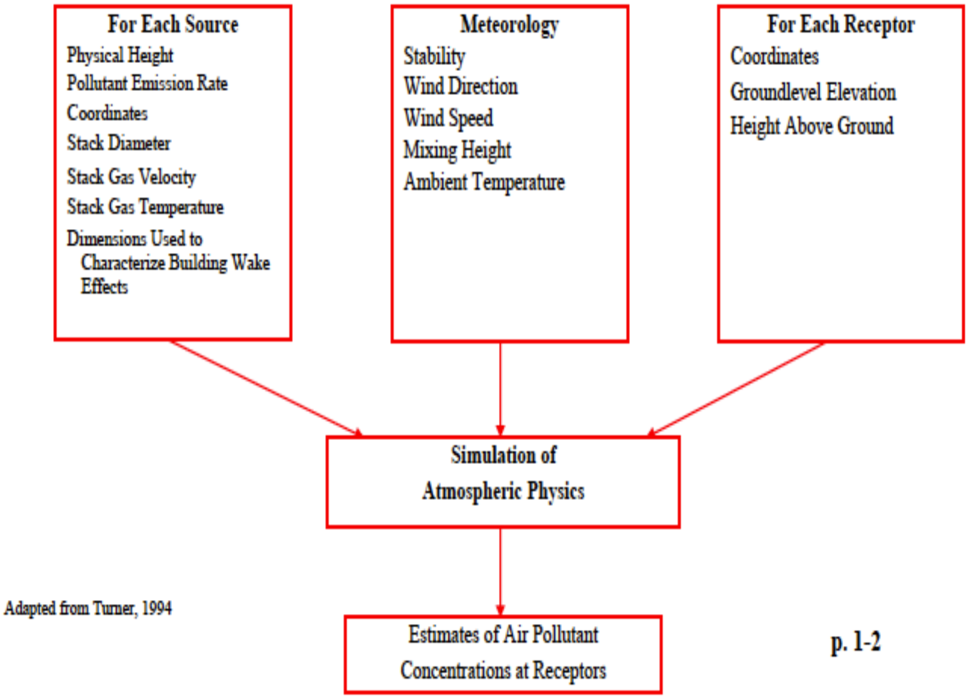


Figure 2-6: Structure of a dispersion model (Source: adopted from EPA website)

A simple general explanation of dispersion modeling according to EPA is: "Dispersion modeling is a mathematical simulation of emissions as they are transported throughout the atmosphere." One method to simulate atmospheric conditions is dispersion modeling, including wind speed and direction, air temperature and mixing height. Dispersion modeling also can provide an estimate of the concentration of pollutants as they travel away from an emission source. Simple secondary formation of pollution by considering atmospheric chemistry is also possible by using dispersion modeling. Whenever it is important to know whether a new source can impact an area adversely or to predict the efficiency of a control method, the dispersion modeling is typically used. Therefore, for review of new source or evaluating emissions reduction plants, dispersion modeling is very useful.

There are various types of dispersion models with different levels of complexity. In general, most of the models require meteorological data, emissions data, and details about the facilities in question (such as stack height, gas exit velocity, etc.). In some of the more complex models, topography information, individual chemical characteristics, and land use data are also needed. The output from this type of model is a prediction of the concentration of the pollutant in question throughout the appropriate region (which depends on the model chosen). (U.S. EPA)

The science of mathematically modeling of the air pollutant dispersion in the ambient atmosphere is called "atmospheric dispersion modeling". The computer programs are used to model and solve the mathematical equations and algorithms, which simply simulate the dispersion of pollutants. The major goal of dispersion models is to estimate the downwind ambient concentration of air pollutants or toxins emitted from various types of sources. The other use of dispersion modeling is to predict and estimate the future concentrations of specific pollutants under specific scenarios.

These benefits of dispersion modeling make this method widely used as a tool in air quality policy making. Dispersion modeling is useful for types of pollutants, which have simple first-order reactions in the atmosphere over large distance of dispersion. Therefore, for most governmental agencies, dispersion models are important and used for managing and protecting ambient air quality. The main reason for using these models is to determine whether existing or future industrial facilities are or will be in compliance with the National Ambient Air Quality Standards (NAAQS) in the United States and other nations. One another main reason is to help for designing effective control devices and strategies in order to reduce harmful and toxic emissions.

Public safety responders and emergency management personnel also have used air dispersion modeling for planning controls of accidental chemical releases, along with determination of consequences of hazardous material releases. Accidental releases may cause fires, spills or explosions from some hazardous and toxic materials. Therefore, dispersion modeling is very helpful to plan responses to these kinds of disasters. At industrial facilities, this type of consequence assessment or emergency planning is required under the Clean Air Act (CAA) codified in Part 68 of Title 40 of the Code of Federal Regulations. (Fensterstock et al., 1971)

Since the late 1960s, the EPA (Environmental Protection Agency) has initiated applications and methods for roadway dispersion modeling. The location of impacted areas with high pollutant concentration can be determined from dispersion modeling in the case accidental releases. Consequently, protective actions can be designed and used properly in the impacted areas. Appropriate protective actions may include evacuation or shelter for persons in the downwind direction or installing air pollution control devices for pollutant reduction. Exposure of persons living or working near roadways can also be assessed, and building setback distances away from roadways can be recommended.

2.2.1 Advantages of dispersion modeling:

This is obvious that actual measuring methods at site are more accurate and reliable for any proceeding actions rather than modeling. The advantage of modeling is noticeable for cases, which are not constructed or preceded yet; therefore to study the future impact of emissions, the best method is modeling. Another advantage of dispersion modeling is that it is much less expensive rather than actual measuring. Another advantage of modeling is for cases that the ambient air measurements are not available; dispersion modeling can provide a reliable means to estimate the ambient air concentrations. (Turner and Schulze, 2007)

2.2.2 Limitations of Gaussian dispersion modeling:

Despite positive and useful features of Gaussian dispersion modeling, there are three main situations where this method is less reliable for atmospheric behavior:

1- Surface release
2- Independence of horizontal and vertical dispersion
3- Convective condition (unstable atmosphere)

(Turner and Schulze, 2007)

The limitations of Gaussian air pollution dispersion models have been discussed in light of sensitivity to inputs, questionable accuracy, and limitations regarding predictions. Most Gaussian-based models use the Pasquill Gifford stability classification scheme, which considers only ambient temperature gradient as its variant. There are meteorological parameters, i.e., wind speed and direction, solar radiation, potential temperature gradient, etc., which are taken into account by other stability classification schemes. Besides, This model does not take into account the inversion conditions chemical transformation, wet deposition or inhomogeneous terrain. (Awasthi et al., 2006)

2.2.3 Gaussian distribution:

The Gaussian distribution model is the most common method for calculating the concentration at different distances from the source, resulting from various conditions. This method is based on the statistical bell-shaped distribution (Normal or Gaussian distribution). There are some assumptions for this method, including:

- Steady-state conditions, which imply that the rate of emission from the point source is constant.
- Homogeneous flow, which implies that the wind speed is constant both in time and with height (wind direction shear is not considered).
- Pollutant is conservative and no gravity fallout.
- Perfect reflection of the plume at the underlying surface, i.e. no ground absorption.
- The turbulent diffusion in the x-direction is neglected relative to advection in the transport direction, which implies that the model should be applied for average wind speeds of more than 1 m/s (> 1 m/s).
- The coordinate system is directed with its x-axis into the direction of the flow, and the v (lateral) and w (vertical) components of the time averaged wind vector are set to zero.
- The terrain underlying the plume is flat.
- All variables are ensemble averaged, which implies long-term averaging with stationary conditions. (Turner and Schulze, 2007). Figure 2-7 is scheme of Gaussian plume.

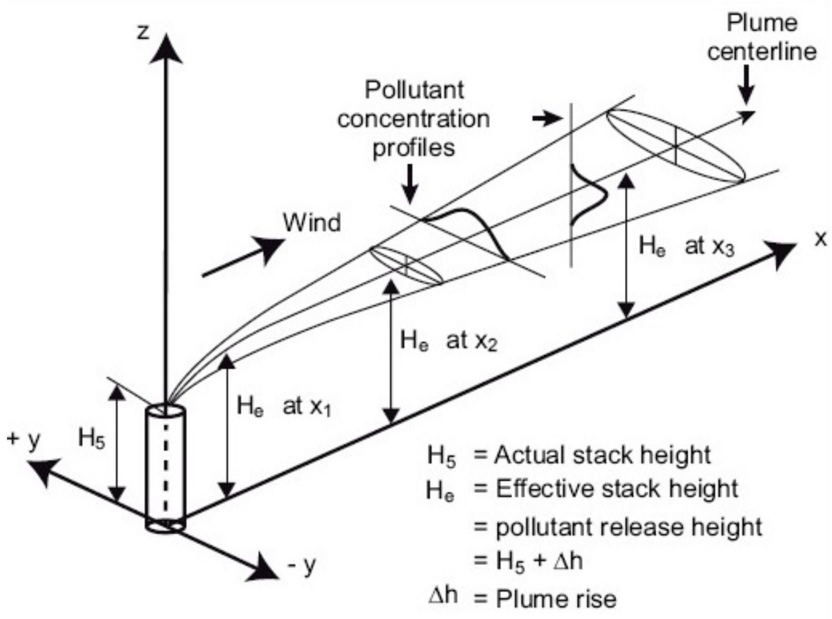


Figure 2-7: Gaussian plume schematic (Source: adopted from Schulze and Turner, 1996)

To calculate the concentration at any point (x,y,z), based on Figure 2-2, with effective height H $(H = \Delta h + h)$, the equation below is used:

$$C(x,y,z) = \frac{Q}{u2\pi\sigma_y\sigma_z} exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\left\{exp\left[-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right] + exp\left[-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right]\right\}$$

Units of the concentration are mass per volume (usually grams per cubic meter or micrograms per cubic meter).

The above equation indicates that the pollutant concentration depends on four main factors including:

1- Emission rate: the concentration is directly proportional to emission rate.

2- Downwind factor: the concentration is inversely proportional to wind speed (based on downwind dilution at the point of the release by the wind speed)

3- Crosswind factor: the concentration is inversely proportional to magnitude of the horizontal spreading, σ_y (exponential describes the concentration decrease for receptor position away from plume centerline).

4- Vertical factor: it contains two exponential parts for considering the effect of the eddy reflection at ground level (except for large particles).

The heat balance of the atmosphere and surface roughness cause variations in the vertical thermal structure of the atmosphere. This impacts the vertical distribution of wind speed, wind direction, horizontal and vertical fluctuations and also temperature. Therefore each of these influences the plume rise and atmospheric transport and dispersion. There will be more vertical exchange when the atmosphere is more unstable. (Turner and Schulze, 2007)

2.2.4 Area source modeling

In some situation, a point source is not applicable for modeling to simulate the emission situation because of its large dimensions more than a few meters (i.e. condensate tanks, or parking lots). Therefore, the source is modeled as area source. In this case, the model calculates the area source by considering each one of the numbers of finite line sources oriented perpendicular to wind direction. The integration upwind is the sum of the results from each line. (Turner and Schulze, 2007)

2.2.5 AERMOD Program

The AERMOD dispersion model is based on the Gaussian plume model (GPM), which is a stable state (time-independent) atmospheric dispersion model. This program has new and improved algorithms for following procedures:

- Dispersion in convective and stable layers
- Plume rise and buoyancy
- Plume penetration into elevated inversions
- Wind, turbulence and temperature vertical profile computation
- Urban nighttime boundary layer
- Receptors treatment on all types of terrain from surface up to above the plume height
- Building wake effects treatment
- Improved approach for characterizing the fundamental boundary layer parameters
- Plume meander treatment

AERMOD is used as the replacement for ISC3. This model is also applicable to rural, urban, flat, elevated area and for surface and elevated releases, for multiple sources (including, point, area and volume sources). Every effort has been made to avoid model formulation discontinuities wherein large changes in calculated concentrations result from small changes in input parameters.

AERMOD is a steady-state plume model. It is assumed that in both vertical and horizontal the concentration distribution is Gaussian, in stable boundary layer (SBL). 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 (pdf). In convective boundary layer, the distribution of concentration was determined by Willis and Deardorff (1981) and Briggs (1993).

In the CBL condition, this program treats plume lofting, where a part of plume mass, released from a buoyant source, rises to and approximately near the top of the boundary layer prior to mixing in the CBL. It is also possible in AERMOD to define any plume mass that penetrates into the stable layer, and again after that to re-enter the boundary layer whenever it is proper. AERMOD treats the improvement of lateral dispersion from meander for sources in both convective boundary layer and stable boundary layer.

In complex terrain, AERMOD uses a very simple and effective method about flow and dispersion of emissions by incorporating current concepts. The plume will be modeled as impacting and/or following the terrain whenever it is proper. By using AERMOD, the demand for defining complex terrain regimes can be avoided. However, all terrain is handled in a consistent and continuous method while considering the dividing streamline concept (Snyder et al., 1985) in stably- stratified conditions.

The most important advantage of dispersion modeling by AERMOD is the ability to determine the PBL through both surface and mixed layer scaling. This program has the potential and ability to make vertical profiles of required meteorological variables based on measurements and extrapolations by using similarity (scaling) relationships. Vertical profiles of wind speed, wind direction, turbulence, temperature, and temperature gradient are estimated using all available with minimum available observed meteorological data. AERMOD can also be considered as a good replacement for the ISC3 model, due to data availability for a program from National Weather Service (NWS) stations.

For calculating the convective mixing height during a day, the program needs to have a full morning upper air sounding (RAWINSONDE). Also, in order to make relevant similarity PBL parameters profiles, this program need the surface characteristics (surface roughness, Bowen ratio, and albedo). AERMOD has another unique advantage as it accounts for the vertical inhomogeneity of the PBL in its dispersion calculations. This is accomplished by "averaging" the parameters of the actual PBL into "effective" parameters of an equivalent homogeneous PBL.

Figure 2-8 shows the flow and processing of information in AERMOD. The modeling system consists of one main program (AERMOD) and two pre-processors (AERMET and AERMAP). The major purpose of AERMET is to calculate boundary layer parameters for use by AERMOD. The meteorological INTERFACE, internal to AERMOD, uses these parameters to generate profiles of the needed meteorological variables. In addition, AERMET passes all meteorological observations to AERMOD. (U.S. EPA, 2004)

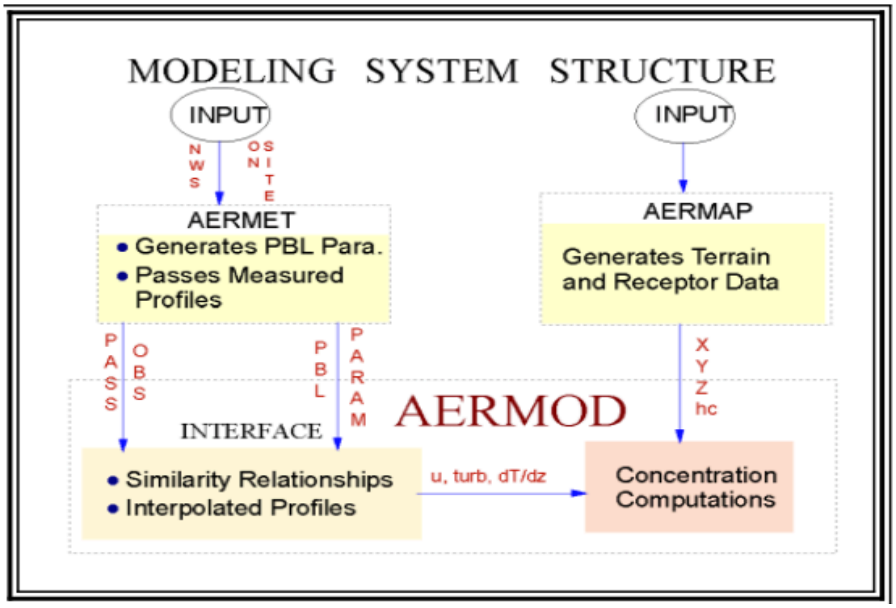


Figure 2-8: Data flow in the AERMOD modeling system (Source: EPA, 2004)

The AERMOD program has the capability of pollution calculation in either flat or complex terrain in the same area of computing frame. This feature makes the AERMOD more practical and useable for different situation and various terrain types. (Cimorelli et al., 2004; Perry et al., 2005).

2.3 City of Fort Worth case study:

This study is based on dispersion modeling performed for the City of Fort Worth Natural Gas Air Quality Study by Eastern Research Group and Sage Consulting (July 2011). The City of Fort Worth has extensive natural gas storage and potential of production, because it is located on the top of the Barnett Shale, a productive natural gas shale source in the north central of Texas. The ERG estimated emissions for 375 well pads, eight compressor stations, one gas processing plant, one saltwater treatment facility, a drilling operation, a fracking operation, and a completion operation. ERG used both ambient air monitoring and also air dispersion modeling methods to measure and estimate the pollutants. Based on the this study, ERG by relying on the modeling analysis, indicated that Fort Worth ‘s 600-foor setback distance is safe enough in order to avoid health problems.

Point source testing was performed in order to determine the amount of air pollution released by natural gas exploration in City of Fort Worth, and also study the impact of natural gas extraction and processing in light of the environmental regulations and public health. ERG subcontracted the point source testing task to Sage Environmental Consulting LP (Sage). Seven main sources of emissions were considered and measured as point sources in this study. The point source measurements and calculations by teams fell into two main categories: Direct and Indirect. Direct emission calculations were based upon the analytical results of the canister samples. Indirect emission measurements were derived from several sources, including the emission results from the canister sampling, correlation equations, calculated surrogate emission rates, EPA emission factors, and engine emission data for both natural gas and diesel powered engines. To calculate the emissions (VOCs, TOC and HAPs) from compressor engines on the well pads, field data, vendor specification sheets and published emission factors were used.

In this study, for pollution estimation was performed by air dispersion modeling under Point Source Testing to estimate how releases from natural gas sites affect off-site air pollution levels. ERG used the latest version of the AMS/EPA Regulatory MODel (AERMOD), to estimate pollutant impacts for four different well pad and compressor station layouts.

- Scenario 1 (Typical Well Pad): In this scenario a typical well pad is modeled without any compression, but includes storage tanks and fugitive emission points.
- Scenario 2 (Worst-Case Well Pad): In this scenario, a worst-case well pad is modeled including storage tanks, fugitive emission points, and two compression engines (250 hp each).
- Scenario 3 (Worst-Case Compressor Station): In this scenario, a worst-case compressor station with six compression engines (1,775 hp each), fugitive elevated area and storage tanks are modeled.
- Scenario 4 (Co-located Worst-Case Well Pad and Worst-Case Compressor Station): The last modeling scenario quantifies the combined impacts of the worst-case well pad in Scenario 2 and the worst-case compressor station in Scenario 3.

The ambient air monitoring data did not reveal any evidence of pollutants associated with natural gas exploration and production activity reaching concentrations above applicable screening levels. Modeling showed that benzene emissions from tanks could have the potential of air pollution levels slightly higher than TCEQ’s short-term ESL, but this happened infrequently and only in close proximity areas to the highest-emitting tanks. Also based on modeling, the cases with multiple, large line engines can emit acrolein and formaldehyde at levels that would cause offsite ambient air concentrations to exceed TCEQ's short-term and long-term screening levels over various distances. However, for the rest of remaining pollutants, the modeling method found no evidence of short-term or long-term air quality impacts at levels of health concern.

2.4 Health impacts from natural gas well activities

Based on air quality studies in different states as Colorado, Texas, and Wyoming, producing natural gas has direct and indirect emissions (fugitive air emissions). These emissions are complex mixture of pollutants from the natural gas resource itself as well as diesel engines, tanks containing produced water, and on-site materials. The materials mentioned are used in production, such as drilling muds and fracking fluids (CDPHE, 2009; Frazier, 2009; Walther, 2011; Zielinska et al., 2011). The various and complex mixture of chemicals and resultant secondary air pollutants, such as ozone, from natural gas production activities can be transported to nearby residences and population centers (Walther, 2011; GCPH, 2010).

The emissions from natural gas production activities are mostly petroleum hydrocarbons. There are some possible health problems for residences near the natural gas and oil production facilities: eye irritation and headaches, asthma symptoms, acute childhood leukemia, acute myelogenous leukemia, and multiple myeloma (Glass et al., 2003; Kirkeleit et al., 2008; Brosselin et al., 2009; Kim et al., 2009; White et al., 2009). Many of the petroleum hydrocarbons observed in these studies are present in and around NGD sites (TERC, 2009). Pollutants such as benzene, ethylbenzene, toluene, and xylene (BTEX) have stronger exposure and toxicity knowledge bases; however for other pollutants such as heptane, octane, and diethylbenzene, toxicity information is more limited.

One study and assessments in Colorado concluded that ambient benzene levels could potentially lead to an increased potential risk of developing cancer as well as chronic and acute non-cancer health effects in areas of Garfield County Colorado where natural gas production activities is the only major industry other than agriculture (CDPHE, 2007; Coons and Walker, 2008; CDPHE, 2010). Benzene as a pollutant causes severe health problems, including acute and chronic nonlymphocytic leukemia, acute myeloid leukemia, chronic lymphocytic leukemia, anemia, and other blood disorders and immunological effects. (ATSDR, 2007a, IRIS, 2011). Moreover, it has been recently recognized that there would be an increase in birth prevalence of neural tube defects for maternal exposure to ambient levels of benzene (Lupo et al., 2011).

Additionally, exposure to xylene, another pollutant generated from natural gas production activities, can cause eye, nose, and throat irritation, difficulty in breathing, impaired lung function, and nervous system impairment (ATSDR, 2007b). The nervous system can be affected negatively by inhalation of xylenes and benzene (Carpenter et al., 1978; Nilsen et al., 1988; Galvin and Marashi, 1999; ATSDR, 2007a; ATSDR, 2007b).

By using air quality data collected at area near wells, it would be possible to distinguish between risks from ambient air pollution and specific natural gas development activities stages, such as well completions or risks between residents living near wells and residents living further from wells. This risk assessment can be used as a tool in order to identify where and when public health is more likely to be affected and therefore find the proper time to inform risk prevention strategies to reduce health problems. The residences who live more near to wells and development facilities are more likely in risk of negative exposures. Risk prevention efforts should be directed towards reducing air emission exposures for persons living and working near wells during well completions. (McKenzie et al, 2011)

In the United States, many natural gas reserves are kept in deposits, which are hard to extract. However, by advanced technologies such as horizontal drilling and hydraulic fracturing, it gets much more feasible to access unconventional sources of natural gas found, for example, in shale deposits, coal beds and tight sands. In one study in a site in Colorado, USA, for two groups of residents: those living less than half a mile from the site and those living more than half a mile away from the site, it was concluded that people who lived within half a mile of the wells had a greater risk of developing non-cancer health effects from hydrocarbon air emissions than those living further away. Especially during the well completion period, the greatest health risks came from short-term exposure to the high emissions released. However, in the later fracking and other activities, the greatest risk was from exposure to trimethylbenzenes, aliphatic hydrocarbons and xylenes.

As mentioned above, all these hydrocarbons affect the nervous and/or respiratory systems. Residents reported headaches and throat and eye irritation during well completion activities. For residents living within half a mile of the wells, exposure to ethylbenzene also contributed to an increased risk of cancer, while for people living more than half a mile from the wells, exposure to 1,3-butadiene was as primary cause of an increased risk of cancer. This study found that air emissions are a source of risk to the community around the gas wells. In order to minimize, limit and control the health risks for nearby residences, methods during completion activities should be applied and also the local community should be informed during development. (McKenzie et al., 2012)

Another aspect of health issues concerning natural gas activities is that children are at higher risk from environmental influences rather than adults because of immature and developing body systems. The reason is that children and infants have faster respiratory and metabolic and therefore they breathe more air, eat more food, and drink more water per pound of body weight than adults, which will result more exposure to greater quantities of environmental pollutants. In addition, as children are in developing stages of immune, respiratory systems, they are more vulnerable to the health impacts of pollutants and toxic substances (Zartarian, 2005).

2.5 Inverse Distance Weighting function application

2.5.1 Introduction

One of the most common methods to interpolate data is Inverse Distance Weighting, IDW. To perform this method, an area about the interpolation point should be identified and a weighted average will be taken of the observation values within this area. The weights are a decreasing function of distance. The factors, including mathematical form and size of area (radius or number f points), can be controlled by the user.

The simplest weighting function is inverse power:

$$w(d) = \frac{1}{d^p}, p > 0$$

User can determine the p value. In most cases p is considered as p=2. When the p value is considered as 1, the function is called "cone-like" in the vicinity of the data points, where it is not differentiable.

Shepard's method (Shepard, 1968) is a variation on inverse power, with two different weighting functions using two separate neighborhoods. The default weighting function for Shepard's method is an exponent of 2 in the inner neighborhood and an exponent of 4 in the outer neighborhood. The form of the outer function is modified to preserve continuity at the boundary of the two neighborhoods. (Fisher, et al., 1987)

The number of points determines the area size considered in the inverse distance weighting function. To be more specific about area size, the radius (i.e. in km), the number of points, and combinations of both need to be determined. It is possible to define the maximum or minimum number of points with fixed area radius or expand /contract the radius based on the fixed number of points. In Shepard's method, there are two neighborhoods; the inner neighborhood is taken to be one-third the radius of the outer radius. (Fisher et al., 1987)

There is a main limitation for inverse distance weighting functions. This method always needs to have a maximum or minimum at the data points (or on a boundary of the study region). The more detailed formula for Inverse Distance Weighting function is as below:

$$u(x) = \frac{\sum_{i=1}^{N} w_i(x) u_i}{\sum_{i=1}^{N} w_i\,(x)}\; for\ all\ i, if\ d(x, x_i \neq 0)$$

in which :

$$w_i(x) = \frac{1}{d(x, x_i)^p}$$

Interpolated value u at a given point x

$$u_i = u(x_i)\ for\ i = 1,2,3, \ldots,$$

Figure 2-9 is a simple diagram about how an IDW function works.

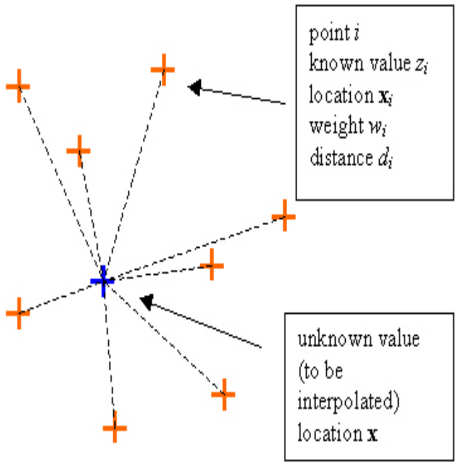


Figure 2-9 Simple diagram of Inverse Distance Weighting function (Source: University of California at Santa Barbara website)

2.5.2 IDW applicaton for pollutant concentration

The general idea of interpolation can be simply explained by considering some points as i where the value of specific variable is known and measured, and one point as j where the value is unknown, and then evaluating what would be the value at j from the values of the of the variables at points i. Based on geoscience, pollution can be evaluated at the "reference point" (in Shepard's 1968a words) from the measured values from monitoring stations. Generally, there are two common methods for interpolation of data in geoscience: 1) Shepard's method, which also is called Inverse Distance Weighting, denoted as IDW, and 2) Kriging or Optimal Interpolation. In Inverse Distance Weighting (IDW), the weights depend on the distance between monitoring stations with an arbitrary exponent and also are exogenous with respect to the data. This method considers that the exogenous weights should not be arbitrary but definitely should vary with the problem in order to choose the best exponent for IDW, depending on form of pollution type, instead of arbitrarily choosing an exponent. (Mesnard, 2012)

For air pollution studies using IDW method, a reference point is any point on a surface at which the pollution level is unknown, that is, it is one of many points which are not equipped with a monitoring station. In other cases, by using IDW method for air pollution studies, the average pollution of the area is determined, which may be a geometrically square area with different sizes (from 25mx 25m to a zip-code area). In both ways of using the IDW method, interpolating or mean value evaluation, the measurement is sometimes limited to a circle, centered on the reference point, the radius of which is given, as in Figure 2-8. In this case, there are some monitoring stations, which are not considered when evaluating the level of pollution at the reference point: stations too far away are excluded for convenience (even if their influence is very low anyway with inverse distance weighting). (Mesnard, 2012)

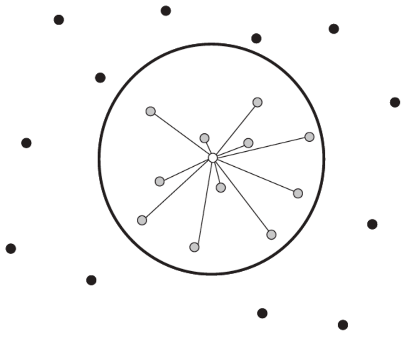


Figure 2-10: Monitoring stations within a given radius. Black dots are excluded measurement stations; gray dots are included measurement stations; white dot is a reference point; and bold ring is circle centered on the reference point and separates excluded and included stations.

In IDW less importance is given to the more distant points by weighting each point with the inverse of the distance or by sophisticated function. In the equation below, the index I denotes monitoring stations, and j is the index of a reference point and n_j is the number of monitoring stations related to reference point j. Therefore, each measurement is multiplied by the inverse distance of d_{ij} from the station I to reference point j with exponent α, and each product is divided by the sum of the $1/d_{ij}^{\alpha}$ over all stations.

$$W_{ij} = \frac{\frac{1}{d_{ij}^{\alpha}}}{\sum_{k=1}^{n_j} \frac{1}{d_{kj}^{\alpha}}}$$

Based on above equation. Pollution $\bar{P_j}$ at the reference point j equals:

$$\bar{P_j} = \sum_{i=1}^{n_j} W_{ij} P_{ij}$$

The Pij is pollution at the monitoring station I based on reference point j. Therefore:

$$\bar{P_j} = \frac{\sum_{i=1}^{n_j} \frac{1}{d_{ij}^{\alpha}} P_{ij}}{\sum_{k=1}^{n_j} \frac{1}{d_{kj}^{\alpha}}}$$

Pij is weighted by inverse of distance given the mean pollution $\bar{P_j}$ at reference point j. In above method and equation, first concerning problem is that the arbitrary character of exponent of distance. Mostly take $\alpha = 1$. However, take value of 2, 3 or 4 for α values. The second problem is related to monitoring stations, which are very close to reference points. These points are weighted by a very short distance value, and when the mean pollution of an area is computed this will be a serious problem. (Mesnard, 2012)

2.5.2.1 Exponent of distance in IDW determination:

IDW can be used for various pollutant situations, including radiant pollution, air pollution and polluted rivers. However, for some types of pollution like carbon dioxide, distance does not matter at all.

- Radiant Pollution:

The front of a radiant phenomenon in 3D world (i.e. light, atomic radiation or sound) that has been emitted from the center is spherical. Based on the practical conclusion, for the radiant pollution the value of exponent is $\alpha = 2$.

- Air pollution:

Based on the practical conclusion, for the air pollution elementary reasoning indicated that it should be $\alpha = 3 \text{ or } \alpha = 2$; however, more sophisticated considerations based on the Gaussian model of plumes showed that the upper bound exponent may vary between nearly 3 to 1, the real value being lower. The same model showed that, for a puff or a cloud, the upper bound should vary between nearly 4 to 2, the real value being lower.

- Polluted rivers:

Based on the practical conclusion, for the polluted river $\alpha = 1$ is correct when the pollution is from a point source or $\alpha = 0$ when pollution is permanent.

2.5.2.2 General conclusion for exponent of IDW:

As the general conclusion, the case $\alpha = 2$ is not the most common, contrary to Shepard's empirical findings and even if in most of the studies, authors and researcher use $\alpha = 2$, all the more so because the default choice is most software packages such as ArcGIS $\alpha = 2$. It is also possible that based on the type of pollution, other values may be chosen. No justification for $\alpha = 4$ and beyond has not been found. Overall, it would be better to model pollution, or to refer to existing studies, or to perform simulations, to reflect the reality and complexity of pollution situations, prior to choosing an exponent. (Mesnard, 2012)

2.5.2.3 The zero distance in IDW:

In this case the classical discrete problem is that the mean level of pollutant is equal to the level of pollution at the reference point. In this case, the monitoring case is confused with reference point of the area. Although this case fails to interpolate correctly when a monitoring station is located at reference point, the case of a continuum of monitoring stations performs successfully. In the discrete case this station imposes its measurement on the whole area regardless of measurements made at other stations when the mean level of pollution is computed for an area; this implies that this mean may be false. Again, it is true that the continuum of monitoring stations is completely theoretical, while the discrete case is the one that happens in real life. However, the continuum of monitoring stations is interesting because it can be considered as the limit of the discrete case. (Mesnard, 2012)

2.5.3 Birth Outcomes and Maternal Residental to Natural Gas Development by IDW function:

McKenzie et al. (2009) examined the prevalence of congenital heart defects (CHDs) with exposure tertile, with an odds ratio (OR) of 1.3 for the highest tertile. Neural tube defects (NTDs) prevalence was associated with the highest tertile of exposure, compared with the absence of any gas wells within a 10-mile radius. Exposure was negatively associated with preterm birth and positively associated with fetal growth, although the magnitude of association was small. In this case, the IDW of well count was calculated for each maternal residence with greater than 1 gas wells within 10 miles, the final distribution then was divided into tertiles (low, medium, and high) for subsequent logistic and linear regression analysis, as following equation:

$$IDW\ well\ count = \sum_{i=1}^{n} \frac{1}{d_i}$$

So based on the results from the above methods, crude and adjusted estimates indicate a monotonic increase in the prevalence of CHDs with increasing exposure to natural gas development. Births to mothers in the most exposed tertile (greater than 125 wells/mile) had a 30% greater prevalence of CHDs than births to mothers with no wells within a 10-mile radius of their residence. About NTDs, this was positively associated with only the third exposure tertile, based on crude and estimated adjusted ORs. Births in the highest tertile (greater than 125 wells/mile) were 2 times more likely to have NTD than those with no wells within a 10-mile radius. (McKenzie et al., 2009)

2.6 Previous studies of natural gas development impact on air quality:

Boothroyd et al. (2016) evaluated the fugitive emissions of methane from abandoned, decommissioned oil and gas wells. The study wells were selected from the 66% of all onshore wells in the UK, which appeared to be properly abandoned, and came from 4 different basins and were between 8 and 79 years old. The fugitive emissions of methane (CH_4) from former oil and gas exploration were considered.

Cheng et al. (2015) established a statistical method and associated tool to evaluate the impact of oil and natural gas exploration and production activities on local air quality. Bootstrap hypothesis was combined with nonparametric regression of pollutant concentrations on wind direction, which was used to provide statistical inferences regarding the existence of a local/regional air quality impact.

Vinciguerra et al. (2015) mentioned that during recent decades, the concentrations of many anthropogenic pollutants have been successfully reduced, improving air quality. However, a new influx of hydraulic fracturing and shale natural gas operations emissions could impact adversely some of these benefits. Hourly measurements from Photochemical Assessment Monitoring Stations (PAMS) in the Baltimore, MD and Washington, DC areas were used.

Carreras-Saspedra et al. (2015) evaluated the effects of liquefied natural gas (LNG) on pollutant emission inventories and air quality in the South Coast Air Basin of California.

Chang et al. (2014) developed a method to determine shale-to-well energy use and air pollutant emissions of shale gas production in China.

Querejazu (2012) evaluated the possible environmental impacts of urban gas wells, and also examined the established regulations in City of Fort Worth for drilling within the city. The regulations form other cities were also considered in this study from the Barnett Shale area and compared to those of Fort Worth.

Rich et al. (2012) performed canister sampling at thirty six sites in six different counties in the Barnett Shale, and as the result 50 data sets were generated for statistical analysis. The analysis showed a particular chemical fingerprint attributable to compressor engines.

Armendariz (2009) evaluated the emissions of NO_x, VOCs, HAPs, methane, and carbon dioxide from natural gas drilling and production in the Barnett Shale.

2.7 Current study of natural gas development impact on air quality:

The City of Fort Worth Natural Gas Air Quality Study, discussed in Section 2.3, evaluated impacts from one gas well pad and compressor engine station. It did not, however, evaluate the impact of multiple gas well pads. It is hypothesized that multiple well pads will produce greater ambient air pollutant concentrations than a single well pad, and that these concentrations may exceed National Ambient Air Quality Standards or Texas Commission on Environmental Quality (TCEQ) Effects Screening Levels (ESLs). In addition, the City of Fort Worth Natural Gas Air Quality Study did not consider the impact of terrain conditions in dispersion modeling, it is assumed as hypothesis that elevation of terrain impacts the dispersion of pollutant concentrations, and in non-elevated terrains the pollutants can disperse far in compare to the other types. Besides, in this mentioned study the criteria pollutant emissions from compressor engines were not considered and modeled.

McKenzie et al. (2014) used the Inverse Distance Weighting function (IDW) to recommend a safe setback distance from gas well locations. The Inverse Distance Weighting equation can be a fast and easy method (compared to Gaussian dispersion modeling) to estimate the pollution concentration at different points from a source. However, the value of exponent α in the IDW equation is not a fixed determined value yet. Interpolating the output and results from the dispersion modeling of various pollutants at differ terrain conditions could provide a useful estimate of α.

Thus, building on the previous Fort Worth Natural Gas Air Quality Study and the work by McKenzie et al. (2014), the objectives of this study are:

1) To evaluate the impact of multiple natural gas well pad emissions together in various terrain conditions using the Gaussian dispersion model AERMOD,
2) To determine the exponent in the inverse distance weighting function which applies to the dispersion modeling output.

Chapter 3

Methodology

3.1 Introduction

This study was done in order to evaluate the dispersion of pollutants from multiple natural gas well pads, working simultaneously, in different terrain and topographical conditions with EPA dispersion modeling program AERMOD. Previously, the impact of only one well pad, or one compressor station was modeled at none-elevated area in the AERMOD, based on The Fort Worth Natural Gas Air Quality Study (2011), conducted by Eastern Research Group, and only the total VOCs were considered, without modeling the criteria pollutants. Therefore, three different scenarios with different topographic areas from city of Fort Worth were selected for this study. The detailed information about selected areas and other features for modeling are discussed in the following part.

The other goal of this study is interpolation of results from the output of modeling, in order to find out a most proper power, α, in the Inverse Distance Weighting, or IDW. As discussed in Chapter 2, IDW is one of the most common methods to estimate the value for a special point with known distances from other points with known values. In the IDW function, the value at a point has an inverse relationship with distances from points, as shown in the following equation:

$$\bar{P}_j = \frac{\sum_{i=1}^{n_j} \frac{1}{d_{ij}^{\alpha}} P_{ij}}{\sum_{k=1}^{n_j} \frac{1}{d_{kj}^{\alpha}}}$$

Mostly the value for α is chosen as 1 and 2. However, for air pollution dispersion modeling and the Gaussian equation, the α is between 2 or 3 (de Mesnard, 2012). In this study, it is considered to find out the best α value for different pollutants at three selected terrain conditions in the city of Fort Worth. The IDW method can be very useful and time saving to estimate the pollution value by knowing the distances of points and at least one known value of pollutant, especially when on-site monitoring data or dispersion modeling is not available. However, the main limitation of IDW is uncertainty of α value (the power value in the equation), so here this study tries to find an appropriate value for the terrain and meteorological conditions of Fort Worth, Texas. The value could be presumed to apply in areas with similar terrain ad meteorology. Also, for general area and projection the North American Datum 1983 and UTM Zone = 14 North was used.

Generally. Four different scenarios are defined and evaluated in this study as following:

Scenario 1: 21 well pads at flat terrain

Scenario 2: 20 well pads at moderate scenario

Scenario 3: 6 well pads at inclined scenario

Scenario 4: 6 well pads in each flat, moderate and inclined terrain with same emission rates.

The detailed information about each terrain type, well pas arrangements and emission rates are as following:

3.2 Terrain and topographic conditions

3.2.1 Flat terrain topographic area:

The whole area of the City of Fort Worth covers different types of terrain conditions, flat, moderate, and inclined levels. The dispersion of pollutants can be varied by different terrain conditions, as theoretically in the flat terrain area the pollutants can dispread more and easily; however the elevation differences can make the pollution disperse shorter distances from the source. For the first scenario, a flat area was randomly selected based on DFW area maps website (www.dfw.maps.com). There were a lot of options for each condition, including flat areas. The flat terrain area was defined as approximately smooth surface in which the vertical change in elevation per horizontal change was not a large number in compare to the other two scenarios (the average vertical change in elevation per 100 m horizontal distance was not high value).

An area was selected that was not too wide or too small, and an area was also chosen with multiple natural gas well pads (more than for example five well pads), from natural gas well log locations from the website of the Railroad Commission of Texas (wwwgisp.rrc.texas.gov/GISVIEWER2/).

Among the choices, including all above factors, finally an area was selected with approximately 3.9 km x 2.8 km area. To obtain the exact location of the selected area, the coordinates were taken from the DFW area maps website and then the latitude and longitude values were converted into UTM (Universal Transverse Mercator) coordinate system (by using the website www.latlong.net).

Below is the UTM coordination of Southwest and Northeast of the two end points of this area:

Southwest end point: UTM (m) = 650301.42, 3646493.09 (N, E)

Northeast end point: UTM (m) = 654240.65, 3649309.80 (N, E)

Generally the area is located at northwest of the City of Fort Worth. The elevation difference between points is very small (780 feet – 750 feet= 30 feet); therefore this area can be considered as a semi-flat area. The change per 100 feet horizontal distance is about 0.94 feet (the average horizontal distance between highest and lowest points is 3200 feet). Figures 3-1, 3-2 and 3-3 are a map, aerial photo, and aerial photo with terrain data for the flat area, respectively.

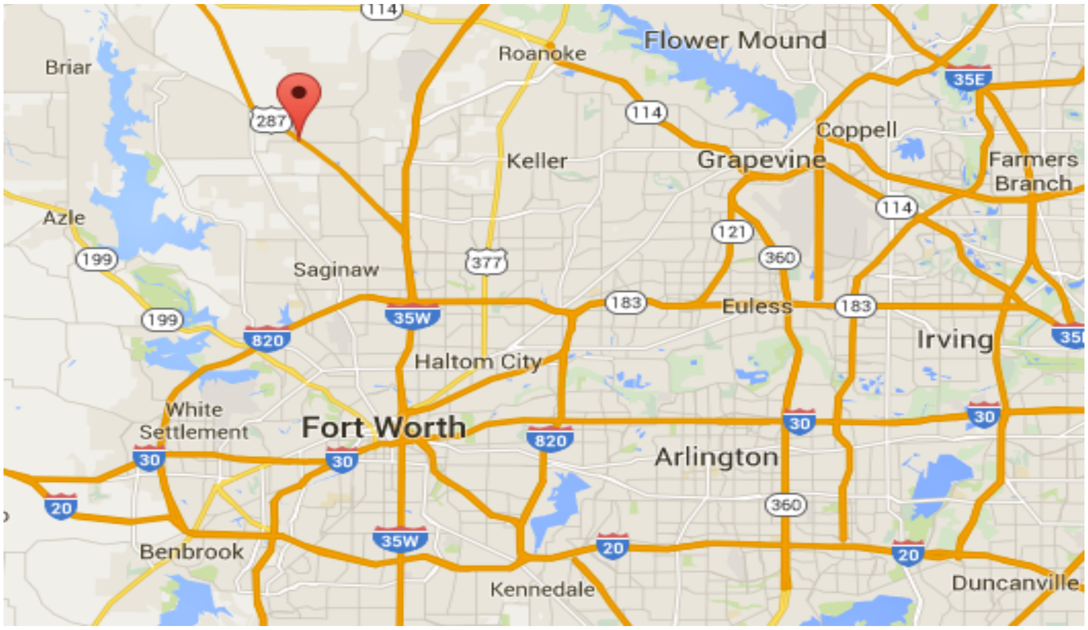


Figure 3-1 : General location of the scenario 1

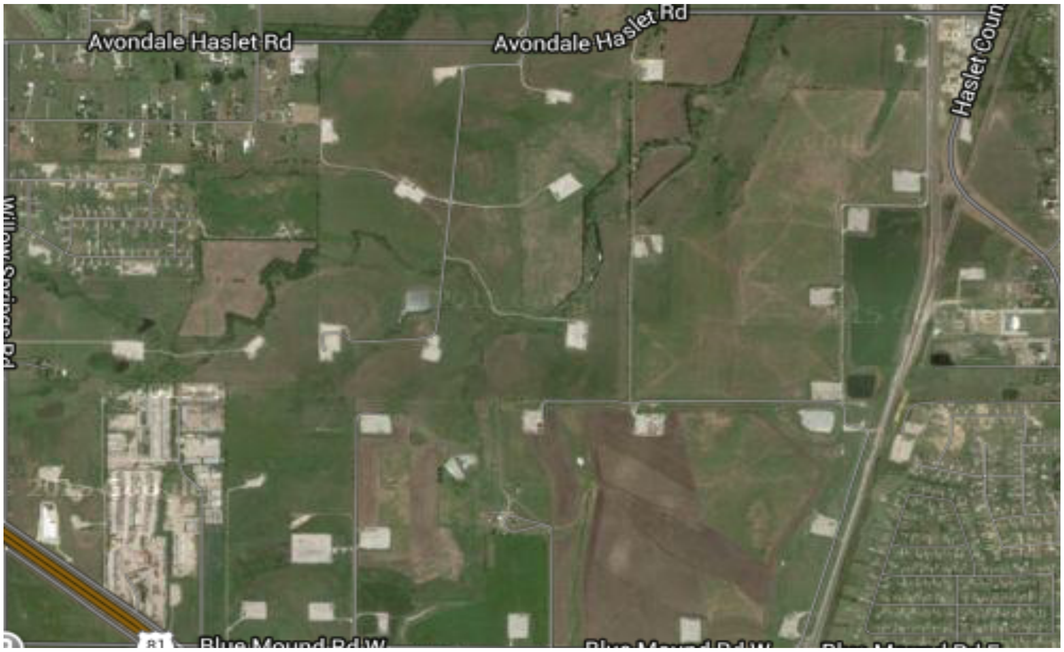


Figure 3-2: Aerial mage location of scenario 1

Figure 3-3 : Elevation map of scenario 1

3.2.2 Moderate terrain topographic area:

The area was taken based on DFW area maps website. The moderate terrain area was chosen randomly from the moderate areas all over the city (in between flat and inclined). The moderate terrain area was defined as a terrain in which the vertical change in elevation per horizontal change was not a large or small number in compare to the other two scenarios (the average vertical change in elevation per 100 m horizontal distance was a value between the other two terrain types). As for flat terrain, an area was selected that was not too wide or too small, including multiple natural gas well pads (more than for example five well pads).

For locations of well pads, the natural gas well logs from the website of the Railroad Commission of Texas, (wwwgisp.rrc.texas.gov/GISVIEWER2/) were used. Among the choices, including all above factors, finally an area was selected of approximately 5.1 km x 2.7 km. The size of the area is different form the flat terrain area, because, if the exact size was chosen, the number of well pads would be less than twenty well pads, and there were twenty well pads in the flat terrain area. To obtain the exact location of the selected area, the coordinates were taken from the DFW area maps website and then the latitude and longitude values were converted into UTM (Universal Transverse Mercator) coordinate system (by using the website www.latlong.net). Below is the UTM coordination of Southwest and Northeast of the two endpoints of this area:

Southwest end point: UTM (m) = 643804.91, 3641490.96 (N, E)

Northeast end point: UTM (m) = 648904.91, 3644224.89 (N, E)

Generally the area is located at northwest of the City of Fort Worth. The elevation difference between points is around 80 feet (840 feet - 760 feet= 80 feet), and the change per 100 feet horizontal distance is about 10 feet (the average horizontal distance between highest and lowest points is 770 feet). Figures 3-4, 3-5 and 3-6 are map, aerial photo, and aerial photo with terrain data for the moderate area, respectively.

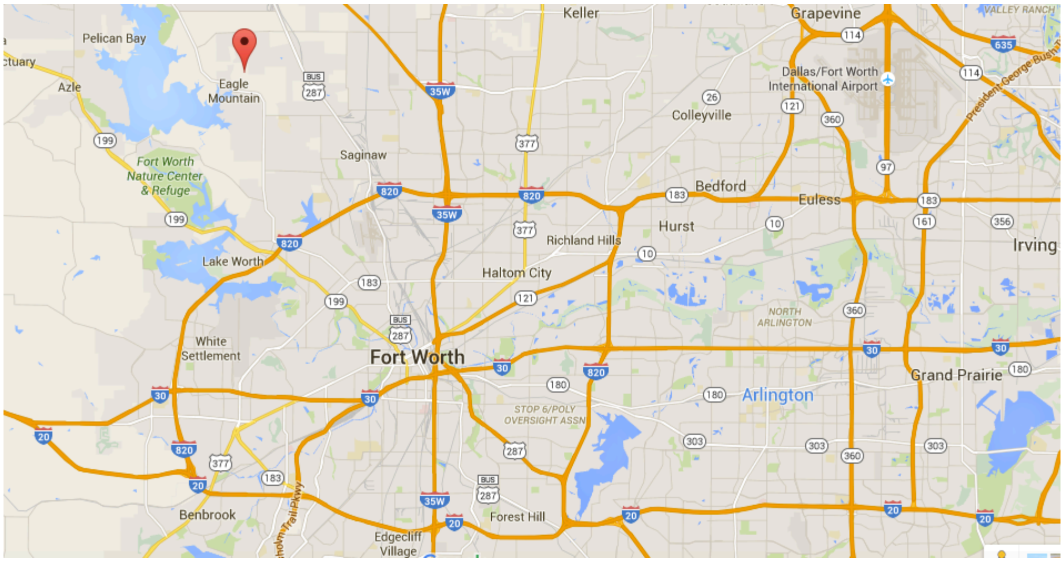


Figure 3-4 : General location of scenario 2

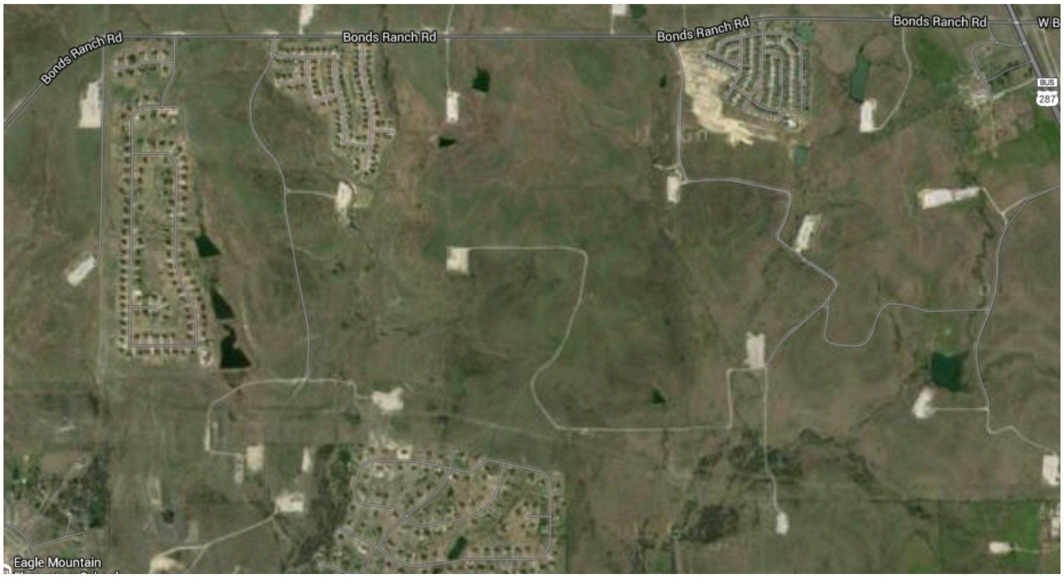


Figure 3-5 : Aerial image location of scenario 2

Figure 3-6 : Elevation map of scenario 2

3.2.3 Inclined topographic area:

The inclined terrain was selected randomly from DFW area maps website. In this research, the inclined terrain area was defined as an area in which the vertical change in elevation per horizontal change was a large number in compare to the other two scenarios (the average vertical change in elevation per 100 m horizontal distance was large number). The inclined terrain area was chosen randomly from the inclined areas all over the city. It is should be mentioned that in all inclined areas, there were few natural gas well pads, so in no case there were a whole inclined area with approximately twenty well pads. Therefore, a inclined terrain area with the most number of well pads was chosen. The well pad locations were checked from website Railroad Commission of Texas.

The selected area was approximately 2.6 km x 1.7 km. The size of the area is different form the flat and moderate terrain areas, because, if the exact size were chosen, the number of well pads would be less than twenty well pads. To obtain the exact location of the selected area, the coordinates were taken from the DFW area maps website and then the latitude and longitude values were converted into UTM (Universal Transverse Mercator) coordinate system (by using the website www.latlong.net). Below is the UTM coordination of Southwest and Northeast of the two end points of this area:

Southwest end point: UTM (m) = 660269.82, 3624385.4 (N, E)

Northeast end point: UTM (m) = 662834.82, 3626052.39 (N, E)

Generally the area is located at center of Fort Worth. The elevation difference between points is much higher than the flat and moderates area (642 feet – 510 feet = 132 feet), and the change per 100 feet horizontal distance is about 30 feet (the average horizontal distance between highest and lowest points is 450 feet).

Figures 3-7, 3-8 and 3-9 are map, aerial photo, and aerial photo with terrain data for the inclined area, respectively.

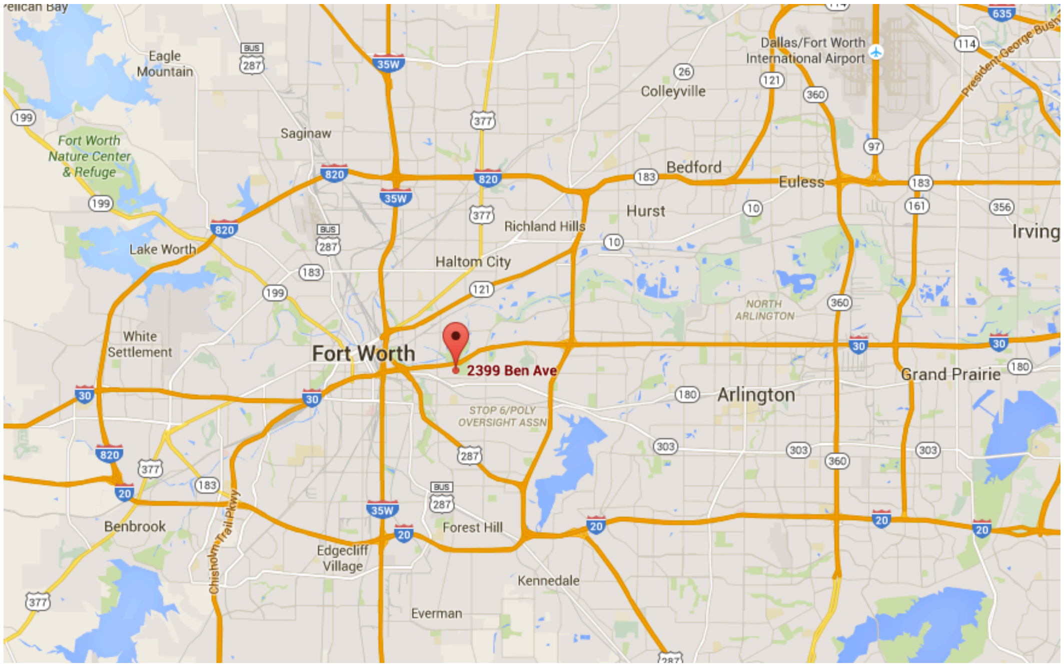


Figure 3-7 : General location of inclined area

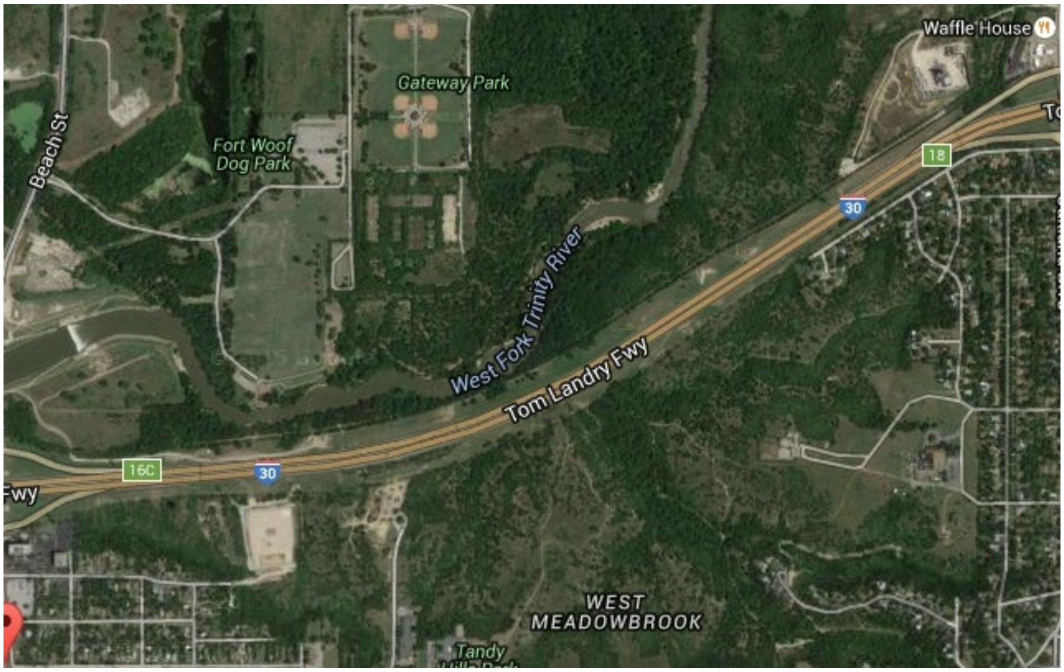


Figure 3-8: Aerial image location of inclined area

Figure 3-9: Elevation map of inclined area

3.3 Meteorological input data

Hourly surface meteorological data from Dallas-Fort Worth International Airport (station number 03927) was used from the Lakes Environmental web site (www.weblakes.com) for year 1992. This year and data is currently used and applied for air quality permit application modeling in Texas. Hourly upper air meteorological data was obtained for the Stephenville weather station, the closest station to DFW region with upper air data of year 1992. AERMET processor was used to preprocess the meteorological data and then the data was used in AERMOD. The base elevation (MSL) was considered as 540 feet and the anemometer height was 22 feet, which is equal to 6.7 meters.

3.4 Source types and emissions

This research considers natural gas production only; drilling and fracturing are not considered, because those processes happen at the beginning of natural gas exploration. Drilling of a new well is typically a two to three week process from start to finish and involves several large diesel-fueled generators.

Four main categories of emission sources are considered: wellhead, storage tanks, fugitive emission points, and compressor engines. Based on the City of Fort Worth Natural Gas Air Quality Study (ERG and SAGE companies, 2011), typically each well pad has a group of wellheads, between 3 to 10 storage tanks, a one group of piping valves and vent equipment as fugitive sources, and between 0 to 6 compressor engines. In this study, for each topographic area, group of well heads as one source, between 3 to 5 storage tanks, one fugitive source and between one to 3 compressor engines were modeled, based on aerial photos of selected places taken from map of DFW region (www.dfwmaps.com) which was used in order to see the number of storage tanks and compressor engines in each well pad and also the well log location in City of Fort Worth from the Texas Railroad Commission website (Texas Oil and Gas Division, GIS viewer).

In addition to the different topographic terrain conditions, modeling was done also for maximum and minimum emission rates separately for each pollutant. To be conservative and have the worst case, in the maximum emission rate condition, compressor engines were considered for all well pads, although typically only one-third of the well pads have compressor engines. The compressors in the well pads are used to increase a well's gas production rate. However, the compressor stations typically have one or more large (generally greater 250 horsepower (hp)) line compressors, which provide the necessary pressure to move the natural gas through many miles of transmission lines. The compressor stations were not modeled based on the City of Fort Worth study (ERG and SAGE companies 2011); among 375 well pads, there were only 8 compressor stations, which means only approximately 2 percent of the well pads.

For first and second scenario, twenty-one and twenty well pads were modeled. For third scenario, six well pads were modeled. In third scenario (inclined terrain), there are much fewer s well pads in compare to flat and moderate terrains in the City of Fort Worth area, based on the well log locations from the Texas Railroad Commission website. Arrangements of equipment on well pads (including the well heads, storage tanks, fugitive sources, and compressor engines) were modeled, using the real locations of well pads. The arrangement including numbers of storage tanks and compressor engines was tried to be compatible with the related aerial photo of their locations, in order to be make the models more similar to reality.

Groups of wellheads were assumed to include a combination of six wellheads, based on the average wellhead number for each well pad from 2011 City of Fort Worth Air Quality study. Each well pad in each scenario was assumed to include one fugitive area source, one group of wellheads as a volume source, storage tanks as pseudo-point sources, and compressor engines as point sources. Figures 3-10, 11 and 12 show the location and the numbers of storage tanks and compressor engines modeled for each well pad for scenario 1, 2 and 3. The detailed information about each pollution source is described in the next section.

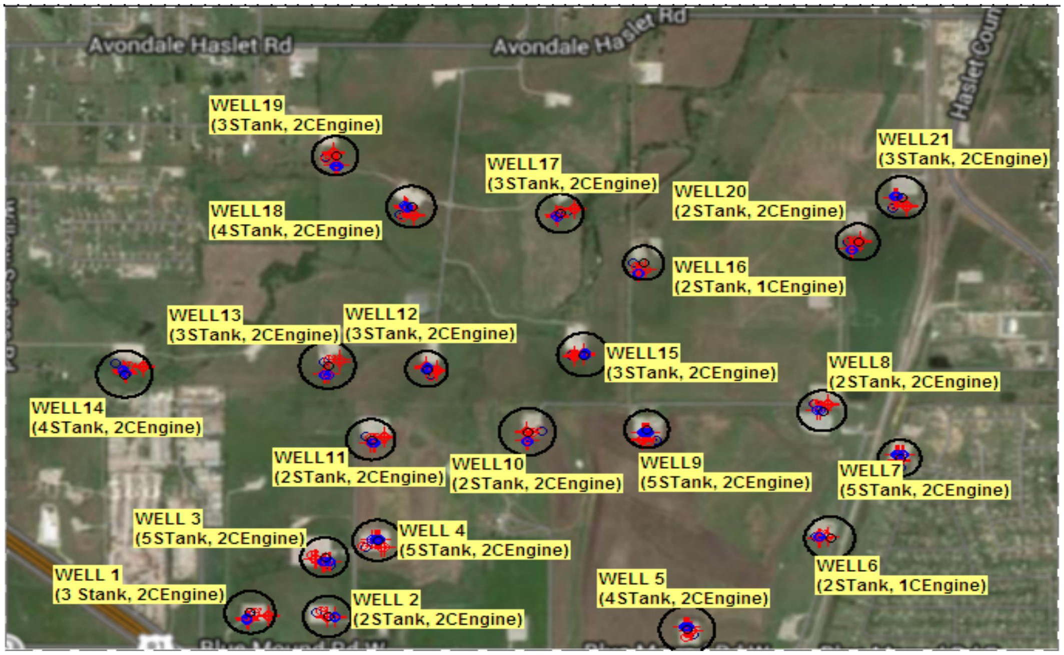


Figure 3-10: Number of storage tanks and compressor engines modeled for each well pad for scenario 1

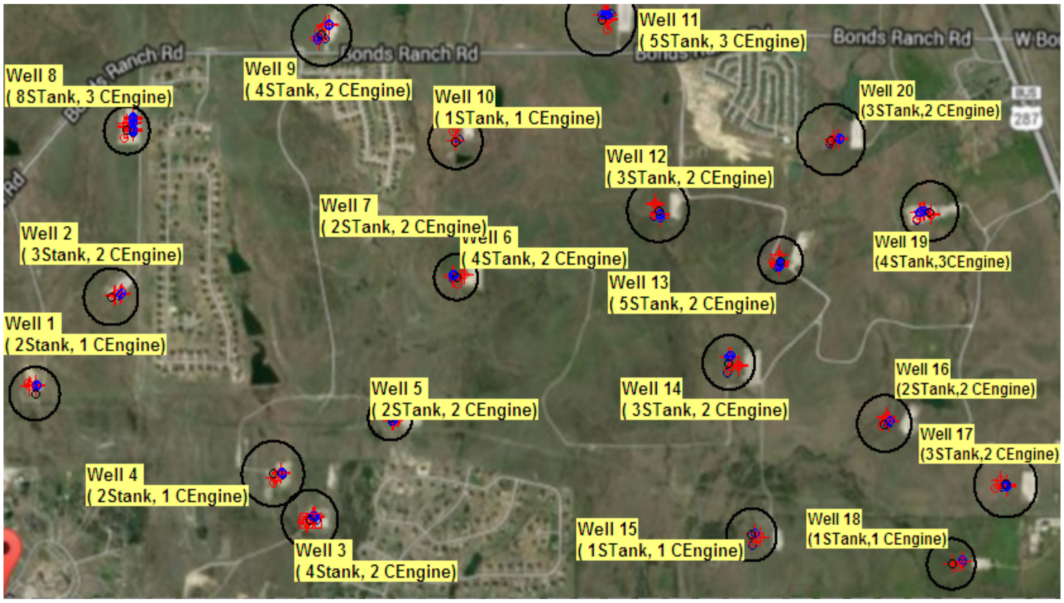


Figure 3-11: Number of storage tanks and compressor engines for each well pad for scenario 2

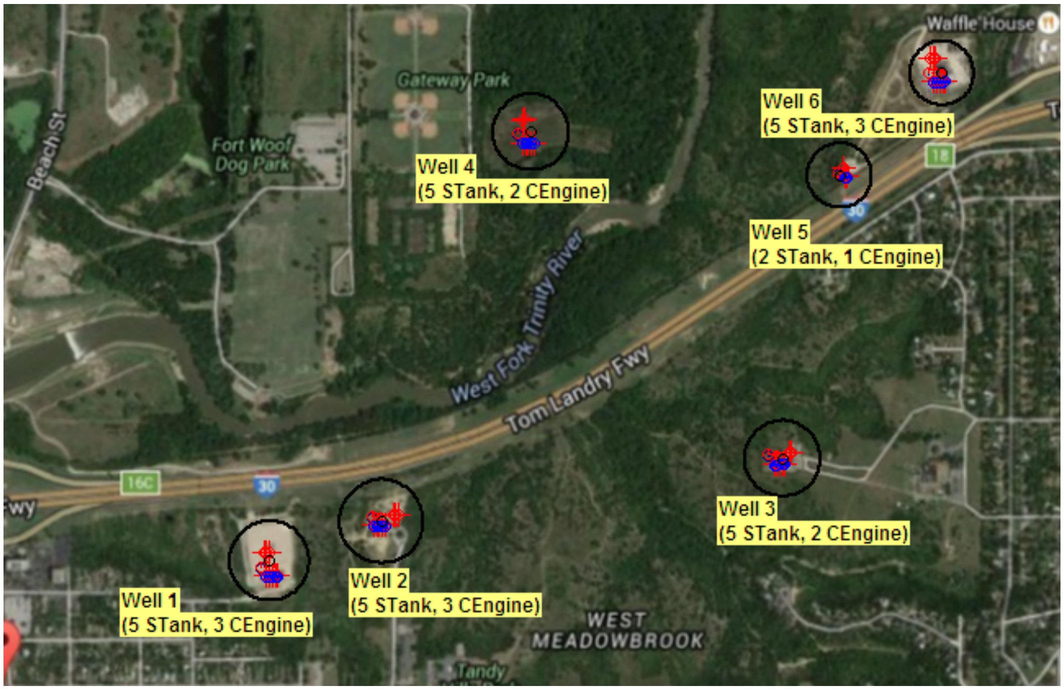


Figure 3-12 : Number of storage tanks and compressor engines modeled for each well pad for scenario 3

Table 3-1 to 3-3 summarize components modeled for each scenario. For all of these well pad components, the different pollutants, including VOCs, CH_4, CO, NOx and PM, for all of these components with maximum and minimum emission rates were modeled. In Scenario 3 arrangement, Table 3-3, well pads 1, 5 and 6 were modeled based on aerial photo and location of real well pads, and well pads 2, 3 and 4 are added as hypothetically in order to have more than three well pads.

Table 3-1: Summary of well pad components modeled for scenario 1

Terrain type	Number of well pads	Well pad ID	Number of storage tanks	Number of fugitive area source	Number of compressors	Well-head group
Flat	21	Well pad 1	3	1	2	1
		Well pad 2	2	1	2	1
		Well pad 3	5	1	2	1
		Well pad 4	5	1	2	1
		Well pad 5	4	1	2	1
		Well pad 6	2	1	1	1
		Well pad 7	5	1	2	1
		Well pad 8	2	1	2	1
		Well pad 9	5	1	2	1
		Well pad 10	2	1	1	1
		Well pad 11	2	1	1	1
		Well pad 12	3	1	2	1
		Well pad 13	3	1	2	1
		Well pad 14	4	1	2	1
		Well pad 15	3	1	2	1
		Well pad 16	2	1	1	1
		Well pad 17	3	1	2	1
		Well pad 18	4	1	2	1
		Well pad 19	3	1	2	1
		Well pad 20	2	1	1	1
		Well pad 21	3	1	2	1

Table 3-2: Summary of well pad components modeled for scenario 2

Terrain type	Number of well pads	Well pad ID	Number of storage tanks	Number of fugitive area source	Number of compressors	Well-head group
Moderate	20	Well pad 1	2	1	1	1
		Well pad 2	3	1	2	1
		Well pad 3	4	1	2	1
		Well pad 4	2	1	1	1
		Well pad 5	2	1	2	1
		Well pad 6	4	1	2	1
		Well pad 7	2	1	2	1
		Well pad 8	8	1	3	1
		Well pad 9	4	1	2	1
		Well pad 10	1	1	1	1
		Well pad 11	5	1	3	1
		Well pad 12	3	1	2	1
		Well pad 13	5	1	2	1
		Well pad 14	3	1	2	1
		Well pad 15	1	1	1	1
		Well pad 16	2	1	2	1
		Well pad 17	3	1	2	1
		Well pad 18	1	1	1	1
		Well pad 19	4	1	3	1
		Well pad 20	3	1	2	1

Table 3-3: Summary of well pad components modeled for scenario 3

Terrain type	Number of well pads	Well pad ID	Number of storage tanks	Number of fugitive area source	Number of compressors	Well-head group
Inclined	6	Well pad 1	5	1	3	1
		Well pad 2	5	1	3	1
		Well pad 3	5	1	2	1
		Well pad 4	5	1	2	1
		Well pad 5	2	1	1	1
		Well pad 6	5	1	3	1

In order to evaluate the impact of multiple gad well pads in aspect of maximum pollutant concentration, three hypothetical Scenarios 1, 2 and 3 for different terrain conditions and 5 various pollutants (a VOCs component, methane, NOx, PM_{10}, and CO) using maximum and minimum emission rates were defined and modeled. However, in Scenario 4, in order to evaluate the impact of terrain type on pollutant dispersion, the well pads arrangements and emissions rates were considered exactly same from inclined terrain for flat and moderate terrains. The reason that the flat and moderate terrains were modeled same as inclined, was that the area of selected inclined terrain is smaller than the other two types, and it was not possible to accommodate the twenty or twenty one well pads arrangements in the inclined terrain. Also, in all over the city of Fort Worth, there was not a inclined terrain area approximately as large as flat or moderate terrain, including twenty or more well pads.

In general, for all scenarios, the emissions from wellheads, storage tanks, and fugitive areas are mostly VOCs and methane. The combustion of natural gas at compressor engines generates some VOCs (presented in Appendix A), methane and the critical nonvolatile emissions include NO_x, PM_{10} and CO. For VOCs, among all the pollutants including non-hazardous and hazardous, benzene was chosen to be modeled, because is a Hazardous Air Pollutant (HAP), which can cause health risks. Also this pollutant is generated from all emission sources modeled in this study. The other important factor is that the ratio of benzene emission factor to Effects Screening Level (ESL) of benzene in each emission source of pollution was higher than the rest, which means it has the potential to cause higher health impacts than any other VOC emitted from well pad components. Texas Commission on Environmental Quality (TCEQ) has developed separate ESLs for short-term and long-term exposure durations, where short-term values are typically used for assessing 1-hour average concentrations and long-term values are typically used for assessing annual average concentrations. The short-term and long-term ESLs for benzene are 170 and 4.5 $\mu g/m^3$, respectively.

3.4.1 Storage tanks:

Storage tanks are modeled as pseudo-point sources. Almost all the storage tanks have a cover and a small vent on top; therefore the area or volume source type is not a suitable model type. Also, a single point source is not a good representative of storage tank, because the effect of diameter and downwash of tanks would not be considered. Lakes Environmental Company was contacted about this type of emission source, and they replied that there is not a single defined source type in AERMOD for these sources (storage tanks). However, the best way to model the storage tanks is a pseudo-point source, as a combination of point source and a circular building with the same height and diameter as the tank. The pseudo-point source is assumed to have an exit velocity of 0.001 meters per second and a stack diameter of 0.01 meters, with ambient exhaust temperature. These parameters were chosen to have conservative estimates from the tank's impact. These values and parameters eliminate the impact of vertical displacement on the plume by negating any airflow from the source. These numbers are widely used, and are considered standard modeling practice for sources of this type. A hypothetical tank layout for each site with hypothetical height = 10 feet, and diameter = 15 feet was used to determine the potential for downwash effects using AERMOD's included Plume Rise Model Enhancements (PRIME) algorithms. The storage tanks can be assumed to be the only sources, which would greatly impede the free airflow, so other sources do not need to be considered in terms of downwash.

In this study, two different ways were considered to calculate the storage tank emissions, because the modeled conditions are hypothetical and it is preferred to have the maximum input data to be conservative. However, to have a more complete picture, the minimum emission rates were also considered for each pollutant at each terrain condition.

First method: In this method, hypothetical storage tank with 10 feet height and 15 feet diameter was assumed, which has the approximate volume of 13,200 gallons or 314 bbl. The typical condensate tank volumes in the Barnett Shale range from 10,000 to 20,000 gallons (Armendariz, 2009). Based on the study by Pring et al. (2010) on emission factors for oil and gas production equipment in Texas, prepared for TCEQ, the emission factor for benzene is 0.19 lbs/bbl.

Armendariz (2009) estimated the condensate and oil tank emission factors for the Barnett Shale, using a methane emission factor of 1.7 lbs/bbl.

Second method: The Fort Worth Natural Gas Air Quality Study (2011), conducted by Eastern Research Group includes refined emission factors for volatile organic compounds (VOCs) and other emissions based on measurements from real point sources in the city of Fort Worth under contract with the Texas Commission on Environmental Quality (TCEQ). Based on this study, the point source results of all 375 well pads were carefully studied and the maximum and minimum emission rates for benzene and methane from a single typical storage tank (with height 10 feet and diameter 15 feet) were chosen.

Table 3-4 is the summary of storage tank pollutant emission rates from two above methods.

Table 3-4: Emission rates for storage tanks from different methods

Pollutant	Maximum emission rate from first method (lb/hr)	Maximum emission rate from second method (lb/hr)	Minimum emission rate from second method (lb/hr)
Benzene	0.007	0.006	$5.6\text{x}10^{-6}$
Methane	0.06	1.67	$9.1\text{x}10^{-3}$

Based on Table 3-4, the highest values for both pollutants for maximum and minimum emission rates were selected as an input for dispersion modeling

3.4.2 Fugitive emissions:

Generally based on surveys and studies, natural gas wells include various types of individual components, including pumps, flanges, valves, gauges, pipe connectors, and other pieces. These components are supposed to be tight, but most of the time leaks happen. Therefore from these leaks, there would be large emissions of hydrocarbons (methane) and VOCs to the atmosphere. These kinds of emissions from natural gas well pads are called “fugitive emissions”. The reason for fugitive emission release can be routine wear, rust and corrosion, improper installation or maintenance, or overpressure of the gases or liquids in the piping.

For each well pad, the fugitive emission points were modeled as a single elevated area source with a height of six feet. This height is chosen based on an assumption of representative approximate height of piping and valves, and it is not very close or far from the surface. The six-feet height was selected based on the assumption used in the City of Fort Worth Air Quality study (ERG and SAGE, 2011) for a fugitive area source, which is representing the average height of all the piping and associated equipment taken from the all studies well pad sites. This source also includes VOCs component (benzene) and methane not modeled in the storage tanks and compressor engines.

In this study, two different methods were considered to calculate the fugitive emissions, because the modeled conditions are hypothetical and it is preferred to have the maximum input data to be conservative. However, to have a more complete output, the minimum emission rates are also considered for each pollutant.

First method: Emissions from fugitive source were calculated using the below equation based on 2008 CENRAP study (Bar-Ilan, et al., 2008):

$$E_{fujitive\ j} = \sum_i EF_i * N_i * t_{annual} * Y_j * 0.0011$$

in which:

$E_{fugitive,j}$ is the fugitive emissions for a single typical well for pollutant j (ton/yr/well)

EF_i is the emission factor of Total Organic Carbon (TOC) for a single component I (kg/hr/component)

N_i is the total number of components of type i

t_{annual} is the annual number of hours the well is in operation (8760 hrs/yr)

Yj is the mass fraction of pollutant j to TOC in the vented gas

0.0011 is the conversion factor from tons to kilograms

The list of AP-42 emissions factors from EPA website were used to calculate fugitive emissions from equipment leaks at oil and gas production sites. Emissions factors are referenced from the AP-42 Chapter 5and supporting document entitled "Protocol for Equipment Leak Emission Estimations" and summarized in Table 3-5 below:

Table 3-5: Emission Factor for fugitive components (Source: EPA, AP 42 Chapter Five)

Component Type	Emissions Factor (kg-TOC/hr)
Valves	0.0045
Pump Seals	0.0024
Others	0.0088
Connectors	0.0002
Flanges	0.00039
Open-ended Lines	0.002

Based on The 2008 CENRAP study (Bar-Ilan, et al., 2008), the total number of components per well from survey data was obtained from basin-level data. However, the CENRAP data did not contain information on component counts for “Pump Seals”, or “Others”. Therefore, an estimate of 2 “Pump Seals” and 10 “Others” were used to complete the CENRAP data (Maldonado, 2010). The typical numbers of each component of fugitive source are shown in Table 3-6.

Table 3-6: Typical number of each component of fugitive sources per well pad

Component Type	Component number
Valves	12
Pump Seals	2
Others	10
Connectors	35
Flanges	18
Open-ended Lines	6

The 2008 CENRAP study (Bar-Ilan, et al., 2008) obtained basin-level data for the fraction of VOC to TOC in the vented gas from survey data. Based on “Characterization of Oil and Gas Production Equipment and Develop a Methodology to Estimate Statewide Emissions” study provided by ERG (Pring et al., 2010), the basin level data was used as a basis for the fraction of VOC to TOC in the vented gas, and a weighted average based on the number of wells at each basin was calculated.

As a result, the ratio of Y, as mass fraction of pollutant to TOC in vented gas, is 0.15 for VOCs from the study provided by ERG. However, as discussed previously, the benzene is considered as a representative VOC emission in this study. Based a careful investigation on point source tests results from City of Fort Worth Natural Gas Air Quality study, (ERG and SAGE, 2011), the approximate benzene percentage in VOCs of fugitive sources was between 0.5 to 0.9 percent, so the value 0.6 is assumed for percentage of benzene in VOCs. TOC is sum of non-VOCs and VOCs; therefore, 0.85 of TOC is none-VOCs, and the major component of non-VOCs is methane. Therefore, it is assumed that the Y in above equation is equal to 0.6 percent of 0.15 for benzene and 0.85 for methane.

Second method: The results from point source tests of City of Fort Worth Natural Gas Air Quality Study (ERG and SAGE, 2011), over 375 well pads were carefully studied. There were many options similar to sources modeled in this study. Therefore after a careful investigation, the maximum emission rates of fugitive sources were selected to be compatible with the each modeled sources as a group of wellheads, storage tanks and compressor engines. For minimum emission rates of pollutant, the best source of more reliable data is point source test results of the study; therefore the assumed input data for minimum emission rates of each pollutant was chosen from that data.

The summary of fugitive emissions for each method are shown in Table 3-7:

Table 3-7: Emission rates for fugitive sources from different methods

Pollutant	Maximum emission rate from first method (lb/hr)	Maximum emission rate from second method (lb/hr)	Minimum emission rate from second method (lb/hr)
Benzene	3.4×10^{-4}	0.02	1.5×10^{-5}
Methane	0.32	40	3.6

Based on Table 3-7, the second method has the highest values for both pollutants; therefore this data is used as an input for dispersion modeling, along with the minimum emission rates values.

3.4.3 Compressor engines:

In order to drive gas field compressors, normally natural gas fueled spark-ignited internal combustion engines are used. The gas can be injected to higher-pressure gathering lines from wellhead by using the natural gas compressors. These compressor engines burn wellhead natural gas and can represent a significant NO_x area emissions source category, as they generally operate 8,760 hours per year with minimum downtime. (Bhandari et. al, 2005)

The fugitive emissions of natural gas from piping associated with the gas compression process are included with the fugitive emission points discussed in previous part above. Engines are also used to power compressors that move natural gas in large pipelines to and from processing plants and through the interstate pipeline network. The major emissions from compressor engines, as point sources are VOCs (benzene), NO_x, PM and CO.

For all pollutants, the minimum emission rates were taken from the result of City of Fort Worth Natural Gas Air Quality Study (ERG and SAGE, 2011) from 375 well pads all over the City of Fort Worth. Also, based on this study investigation, the well pads have the compressor engines with power of minimum 145 hp and maximum 1849 hp. The 1849 hp engine types were only in one well pad. Therefore, for minimum emission rates from a 145 hp compressor engine were calculated.

For maximum emission rates, the 255 hp compressor engine was selected because the majority of compressor engines in well pads have the power of 145 hp, some have 255 hp and a very few a power between 380 to 400 hp. Therefore, for maximum emission rates of pollutants the 255 hp compressor engine was selected in order to not be too far away from real conditions. It was assumed that each well pad has at least one and maximum three compressor engines, in order to consider the impact of the compressor engines on dispersion modeling.

Generally, in well pads with one or two storage tanks, only one compressor engine was modeled, but for well pads with three, four, five and six storage tanks two compressor engines were modeled. For each well pad, 255 hp or 145 hp compressor engines are modeled as point sources with stack height of 25 feet and diameter of 10.5 inches (based on data sheet of specific compressor, presented at reference section). The temperature of exit gas is assumed to be fixed at 600℃ with velocity of 50 m/s.

It should be mentioned that, for compressor engines and emissions from combustion of natural gas, there is a defined method and equation for emission factors based on US EPA, and compressor engine type (based on factory); therefore different methods are not considered. The following equation is used for calculating the VOC emissions:

$$E_{VOC} = \sum EF_{VOCi} * hp * F * 10^{-6}$$

In which:

E_{VOC} is the emission rate of VOC component (lb/hr)

EF_{VOCi} is the emission factor of each VOC component from Appendix A (lb/million Btu)

hp is the horse power of compressor engine (145 or 255 hp)

F is fuel consumption of engine from data sheet of compressor (Btu/hp. hr)

10^{-6} is conversion of Million Btu to Btu

All emission factors for each VOC component are presented in Appendix A and are from U.S.EPA's Compilation of Air Pollutant Emission Factors (AP-42), Chapter 3.2, "Natural Gas-Fired Reciprocating Engines", Tables 3.2-1, 3.2-2, and 3.2-3. The emission factors were taken for worst cases from four-stroke rich burn engines (SCC 2-02-002-53). As discussed above, a representative VOC component in this study is benzene; therefore the equation above is calculated for benzene with emission factor equal to 1.94×10^{-3} (lb/million Btu).

The detailed information about compressors was obtained from the Caterpillar Engine Specifications (website: www.catoilandgas.cat.com/industries/gas-compression-power).

The information for compressor engine was taken from the manufacturer data sheet for model G3406, with 255 hp, and G3306 for 145 hp engine models, with fuel consumption of 7361 (Btu/bhp-hr). To calculate the non-volatile critical pollutants emissions, including PM, NO_x and CO, the following equation is used:

$$E_i = EF_i * hp * \frac{1}{453.59}$$

In which:

E_i is the emission rate of each of the NOx, CO or PM (lb/hr)

EF_i is the emission factor (g/hp.hr)

hp is the horse power of compressor engine (145 or 255 hp)

1/453.59 is conversion of gram to pound

The emission factors for each pollutant are shown in Table 3-8.

Table 3-8: Emission factors for natural gas engine combustion

Pollutant type	Emission Factor (g/hp.hr)
NO_x	0.50
PM	0.0319
CO	1.4

- The emission factor for CO is obtained from Caterpillar company catalog, Mfg data sheet for G3406 for a 255 hp engine and G3306 for a 145 hp engine.
- The PM emission factor is taken from TCEQ report, Table 4-3. ("Characterization of Oil and Gas Production Equipment and Develop a Methodology to Estimate Statewide Emissions", 2010)
- For NO_x , the emission factor is EF = 0.5 g/hp-hr based on Texas Administrative Code, Chapter 117, Subchapter D, Division 2, Rule §117.2110.

The manufacturer data sheet only provided an emission factor for CO, so the PM and NOx emission factors had to be taken from other sources. Table 3-9 summarizes the calculated emission rates for compressor engines in each well pad.

Table 3-9: Emission rates for compressor engine source

Pollutant	Maximum emission rate (lb/hr)	Minimum emission rate (lb/hr)
Benzene	$3.7x10^{-3}$	$5.4x10^{-4}$
NO_x	0.28	0.08
PM	0.02	0.006
CO	2.5	0.8

3.4.4 Wellhead groups:

Generally the wellhead is considered in the category of fugitive emission sources; however, in this study for each well pad, one separate wellhead is modeled as a volume source, representing a group of six wells. The number of six is assumed based on a carful investigation of City of Fort Worth Air Quality study (ERG and SAGE, 2011) data. Based on this study, the number of wells for each well pads various between one to 12; however only 10 of 375 well pads have the number of wells greater than ten. The majority of well pads have 3, 2, 4 o 5 wells. Therefore, it is assumed each well pad has a group of 6 wellheads, as a worst-case scenario reasonably likely to occur.

This source type is modeled as a single volume source rather than a point source, as there is not special and clear information for stack height and diameter for wellhead components as a point source. Therefore, the wellheads are modeled as volume sources and close to the surface, with assumed height of one meter from the surface.

The emissions for wellheads are mostly methane and a very few VOCs. Modeling local methane emissions from this source is important because other VOCs with health impacts can be rationed to methane, and therefore they do not need to be modeled individually. The modeled methane concentration can be multiplied by percentage of methane in natural gas, to give the concentration of asked VOCs/HAPs.

The emission rates for a wellhead group source were obtained from point source test data from Fort Worth Study (ERG and SAGE companies, 2011), because the data was taken directly from sites over 375 well pads with various well pad configurations and emission rates. Table 3-10 shows the model input data for maximum and minimum emission rates for wellheads.

Table 3-10: Emission rates for wellhead source

Pollutant	Maximum emission rate (lb/hr)	Minimum emission rate (lb/hr)
Benzene	2.1×10^{-3}	3.5×10^{-7}
Methane	2.2	1.7×10^{-4}

3.5 Terrain input data

Three different scenarios with different areas from City of Fort Worth were selected for modeling as discussed in Section 3.2 above. The required topographic information and elevations were taken from map type “NED GEOTIFF” and NED 1/3 (USA – 10 m) data from WebGIS part of AERMOD, which automatically uploaded the related maps including designated elevations at all points.

3.6 Other model options

The AMS/EPA Regulatory MODel (AERMOD), Version 9.0.0, was used to estimate pollutant concentrations. 1-hour and annual averaging times were chosen. Receptor grids of different resolutions were used to predict the maximum ambient concentrations around each site. A uniform spacing (varied with site domain) was used in each modeling and the maximum spacing was 100m. Table 3-11 summarizes the spacing and number of points for each receptor.

Table 3-11: Receptor grid spacing and number of points for each modeled terrain

Terrain type	Number of points	Grid spacing (meters)
Flat	Horizontal= 41 Vertical= 31	Horizontal= 95 Vertical= 90
Moderate	Horizontal= 53 Vertical= 30	Horizontal= 98 Vertical= 96
Inclined	Horizontal= 28 Vertical= 22	Horizontal= 95 Vertical= 79

Chapter 4

Results

4.1 Dispersion modeling output

The AERMOD dispersion modeling program was run thirty times for five different pollutants at three different scenarios with maximum and minimum emission rates (5 x 3 x 2 = 30), based on values of previous section 3.6 input data in three different scenarios. Also, ten additional runs were done for low and moderate terrains with the same well pad numbers and emission rates as for inclined terrain, to facilitate comparison of the impact of terrain on dispersion as Scenario 4. These additional runs were for maximum emission rates of benzene, PM, CH_4, NOx and CO for flat and moderate terrains with same well pads as inclined terrain.

Tables 4-1 and 4-2 show the one-hour and annual maximum concentrations, respectively, of all 5 pollutants for scenarios 1, 2 and 3, for the cases with identical emission rates of each emission source type but different well pad arrangements. It should be mentioned that methane is defined as “simple asphyxiant” in the ESL list, therefore no standard level is defined because concentration levels causing asphyxiation would only occur in confined spaces indoors. In addition, the other problem with methane is climate change, which is a global concern and problem not a local one.

Table 4-1: Hourly modeled pollutant concentrations for all three scenarios

Pollutant	**1-hour NAAQS or Short-Term ESL** ($\mu g/m^3$)	**Maximum concentration ($\mu g/m^3$)**					
		Scenario 3		**Scenario 2**		**Scenario 1**	
		High emission rate	**Low emission rate**	**High emission rate**	**Low emission rate**	**High emission rate**	**Low emission rate**
Benzene	170	39.8	0.04	29.2	0.02	84.9	0.07
CH_4	-	26,900	2257	34,712	2991	57,124	5521
NO_x	188	12.3	3.1	11.7	3.2	7.51	2.4
PM	150	0.94	0.19	0.83	0.23	0.56	0.17
CO	$40x10^3$	77	29.9	83.2	27.3	55.7	23.6

- Note: for conversion of ppm to $\mu g/m^3$ the conversion equation at standard temperature and pressure is used. ($C\left(\frac{\mu g}{m^3}\right) = {(1000 * Cppm * Mw)}/{24.42}$)

Table 4-2: Annual modeled pollutant concentrations for all three scenarios

Pollutant	**Annual NAAQS or Long-Term ESL** ($\mu g/m^3$)	**Maximum concentration ($\mu g/m^3$)**					
		Scenario 3		**Scenario 2**		**Scenario 1**	
		High emission rate	**Low emission rate**	**High emission rate**	**Low emission rate**	**High emission rate**	**Low emission rate**
Benzene	4.5	3.22	0.006	3.27	0.004	3.6	0.009
CH_4	-	2813	223	2822	247	10258	935
NO_x	99.7	1.8	0.60	2.7	0.52	1.7	0.51
PM	150	0.17	0.04	0.20	0.05	0.15	0.04
CO	$10x10^3$	16.7	6.5	19.3	4.7	12.8	5.1

- Note: for conversion of ppm to $\mu g/m^3$ the conversion equation at standard temperature and pressure is used. ($C\left(\frac{\mu g}{m^3}\right) = {(1000 * Cppm * Mw)}/{24.42}$)

Based on Tables 4-1 to 4-2 above, both hourly and annual concentrations of pollutants at three different scenarios have the lower levels of concentration compared to the National Ambient Air Quality Standards (NAAQS) established by the United States Environmental Protection Agency under authority of the Clean Air Act (42 U.S.C. 7401 et seq.). Also, the model output concentrations of benzene at maximum and minimum emission rates, in all three different scenarios are lower than ESLs for benzene, both hourly (short-term) and annually (long-term effect). Based on the above tables, benzene in both hourly and annually concentrations has the closest value to its standard level of ESL. However, still those maximum concentration values are located near the fugitive sources, within the setback area. The rest of pollutants have the maximum concentration values much lower than standard levels.

All the graphical outputs for above Table 4-1 are presented at Appendix B, including the 600 feet radius setback area around each well pad. The city of Fort Worth based on ORDINANCE No. 18449-02-2009, has established a setback of 600 feet around protected uses in order to ensure the public health. A protected use is defined as a residence, religious institution, hospital building or public park.

For scenario 4, in order to better evaluate the impact of terrain condition on pollution dispersion, Figures 4-1 to 4-15 present the dispersion modeling output from all terrains, using the same emission source and rates values for all terrains (for flat and moderate terrains the sources and rates were exactly modeled as inclined terrain).

The first hypothesis was that multiple natural gas wells emissions would cause exceedances of pollutant standard levels (either NAAQS or ESL levels). However, this hypothesis was not true based on Scenarios 1, 2 and 3. The second hypothesis was that maximum pollutant concentrations would occur in flat terrain. However,based on Scenario 4, inclined terrain gave the highest concentration compared to flat and moderate terrains with same emission rates and source arrangements. The reason could be that in inclined terrain, there are large vertical elevations differences all over the area (average 2.7 feet per 100 feet) compared to the two other terrain types, and therefore it is less possible for pollutants to disperse from higher elevations to lower and visa versa, which resulted in accumulation of pollutants.

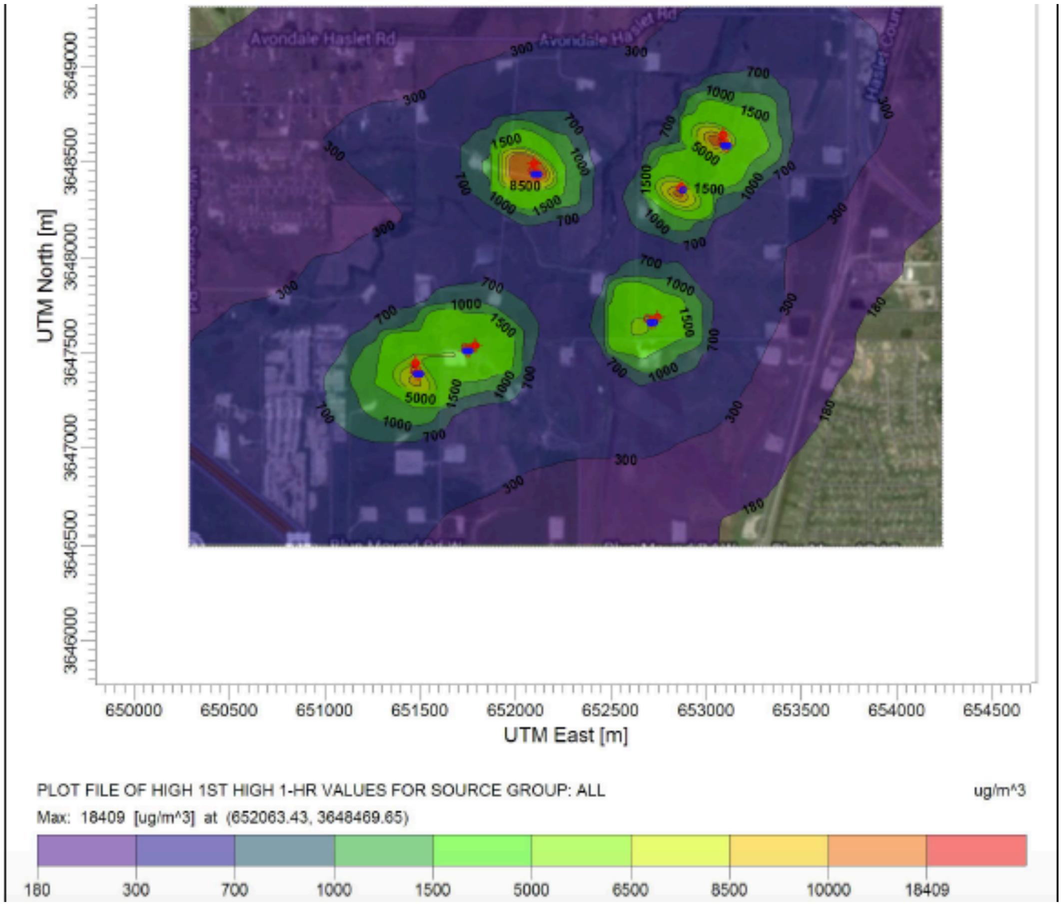


Figure 4-1: Methane concentrations for flat terrain, high emission rate

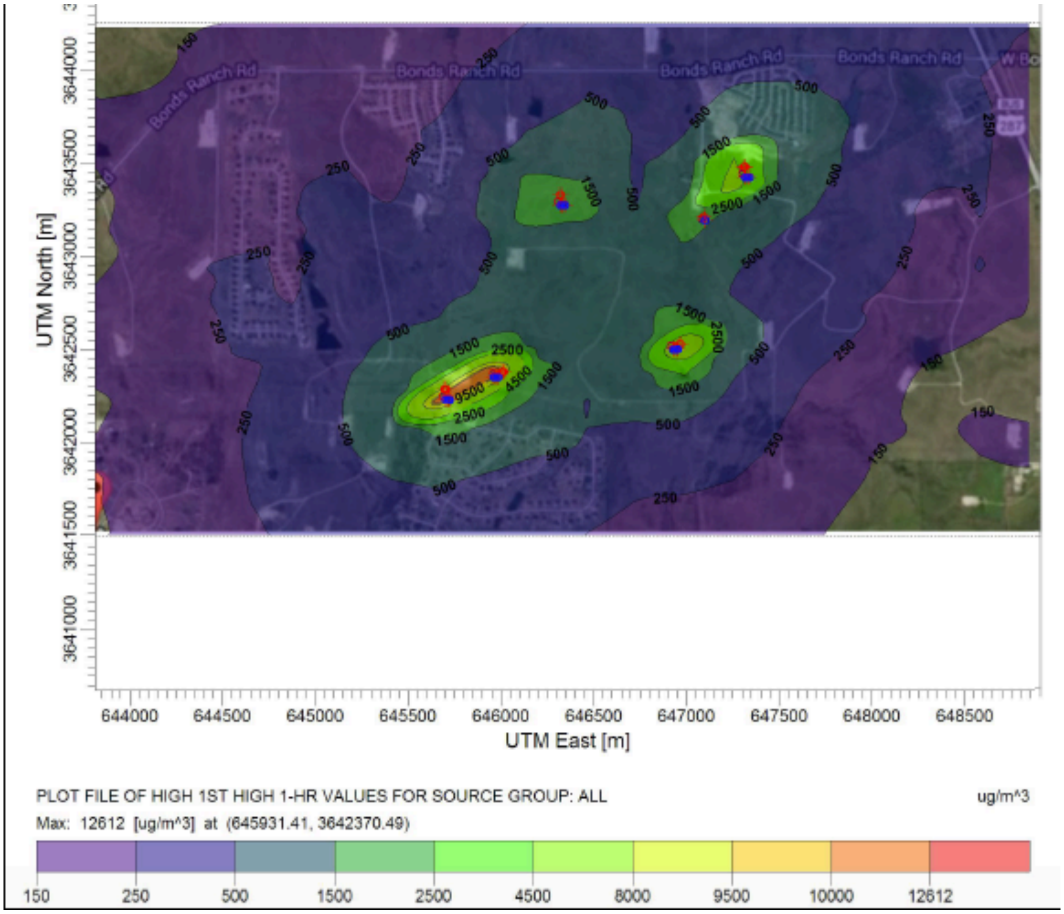


Figure 4-2: Methane concentrations for moderate terrain, high emission rate

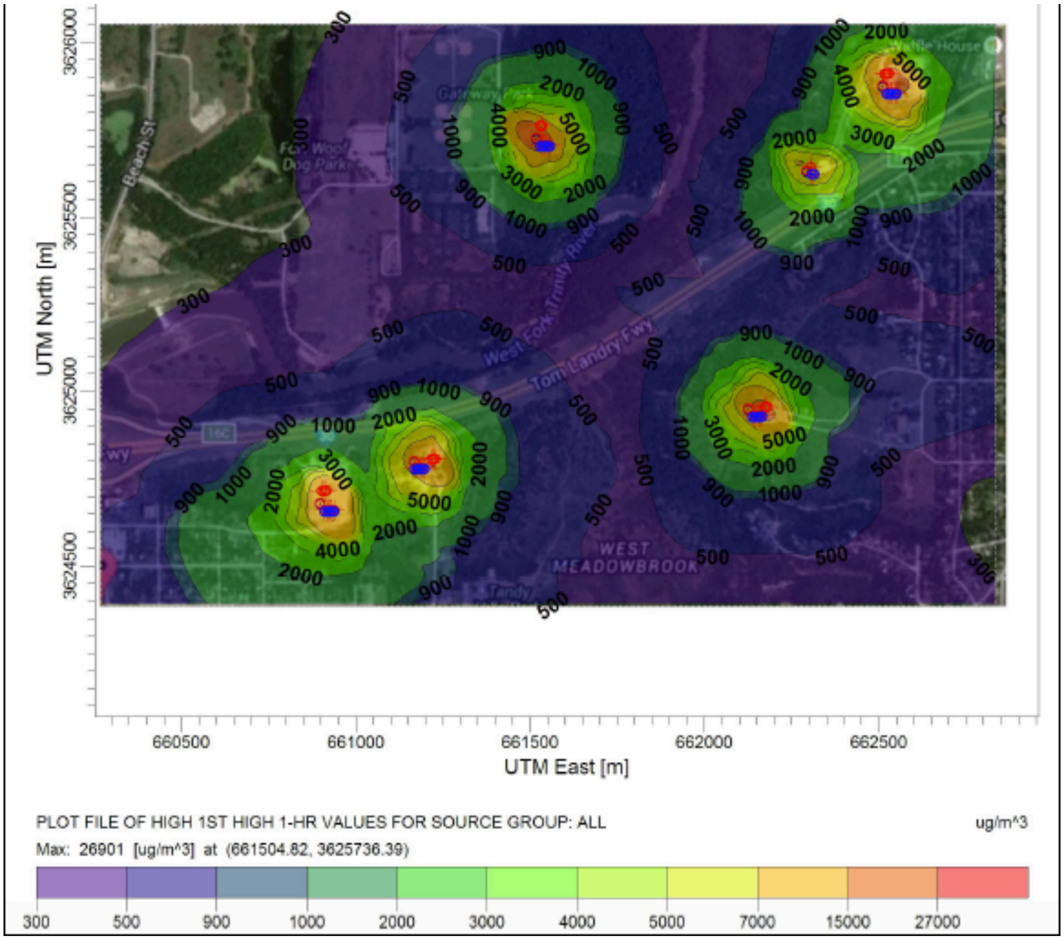


Figure 4-3: Methane concentrations for inclined terrain, high emission rate

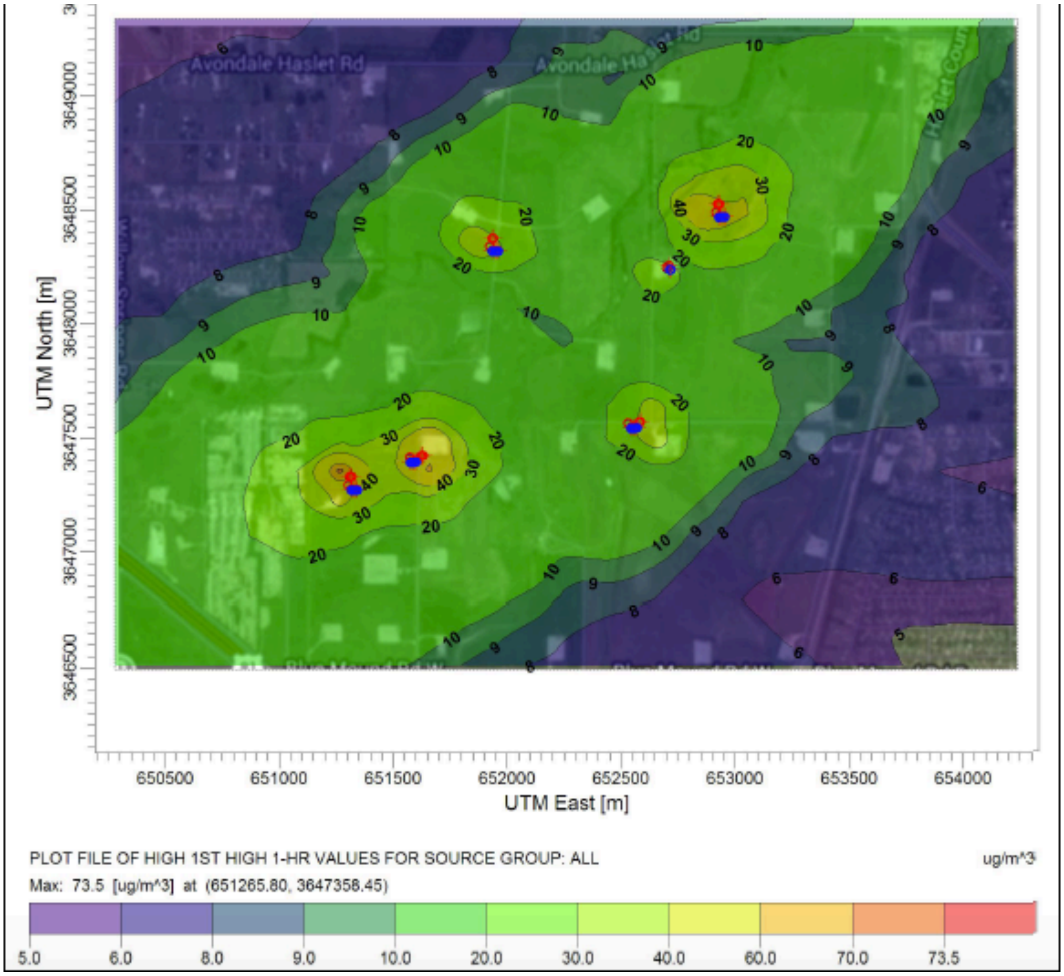


Figure 4-4: Carbon monoxide concentrations for flat terrain, high emission rate

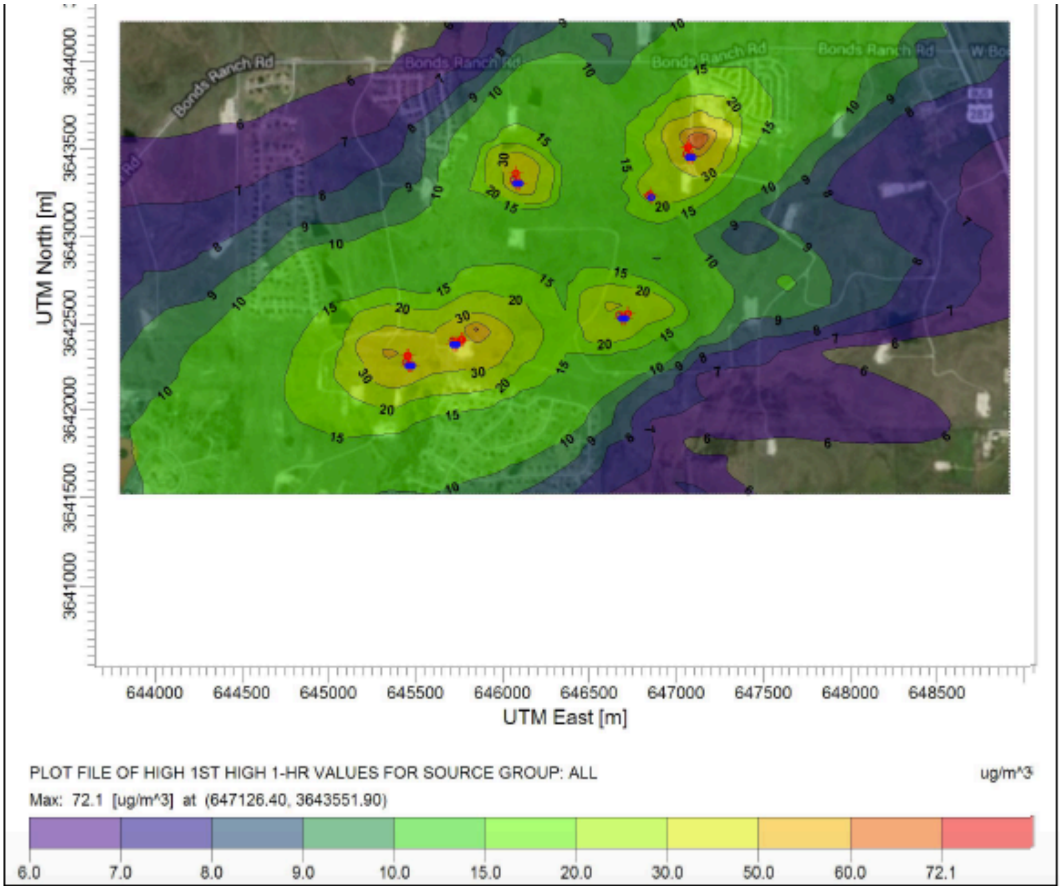


Figure 4-5: Carbon monoxide concentrations for moderate terrain, high emission rate

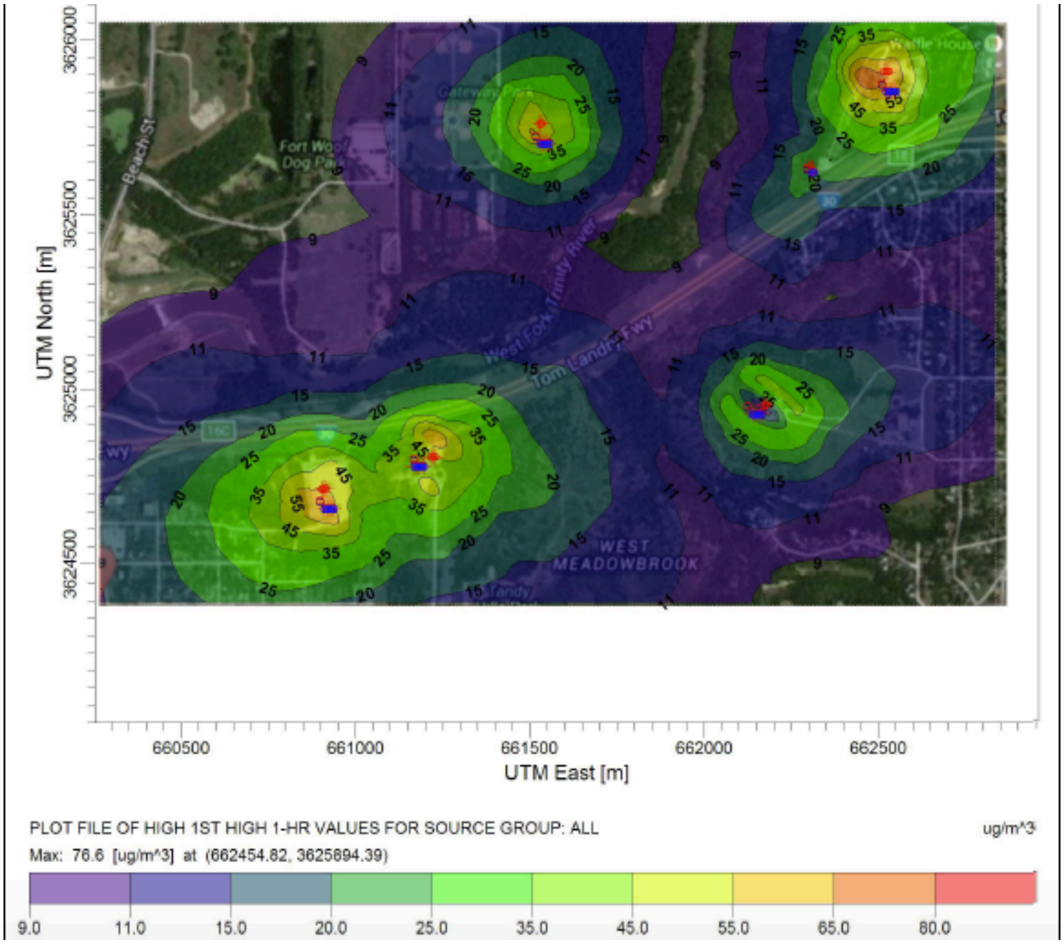


Figure 4-6: Carbon monoxide concentrations for inclined terrain, high emission rate

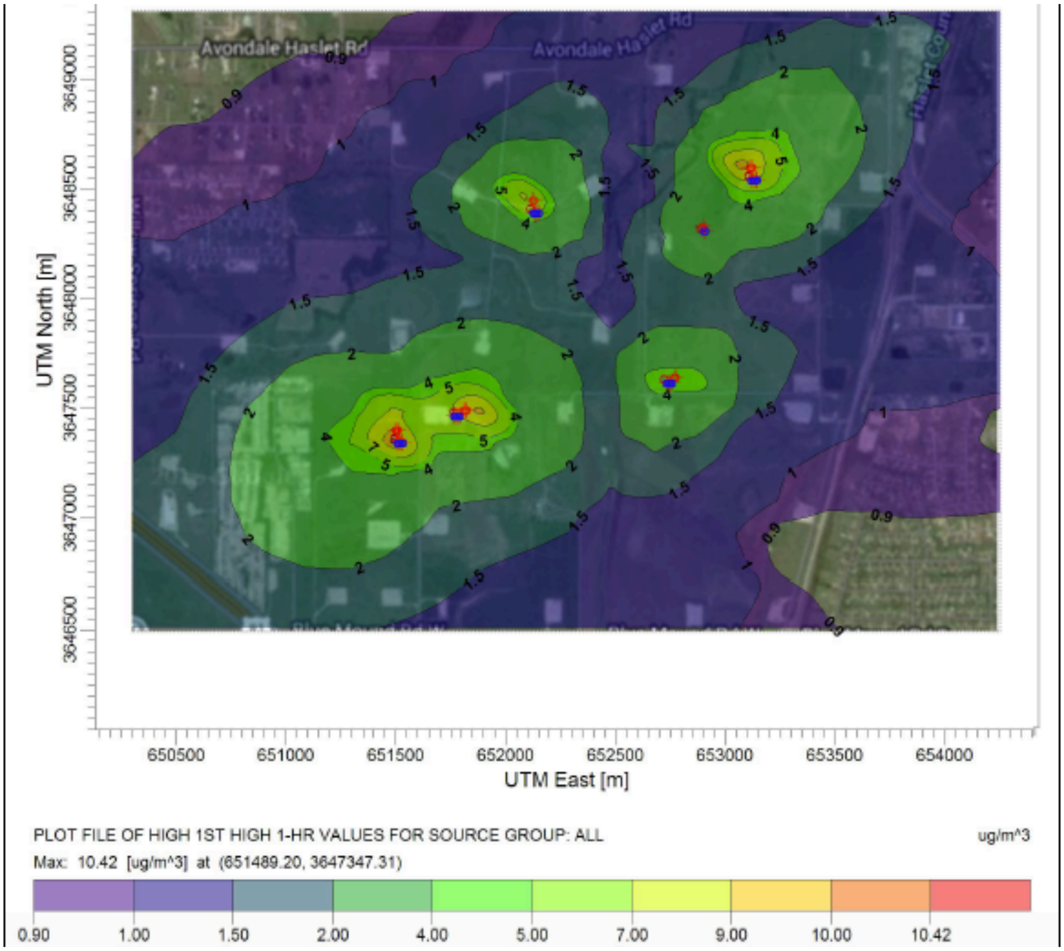


Figure 4-7: Nitrogen oxide concentrations for flat terrain, high emission rate

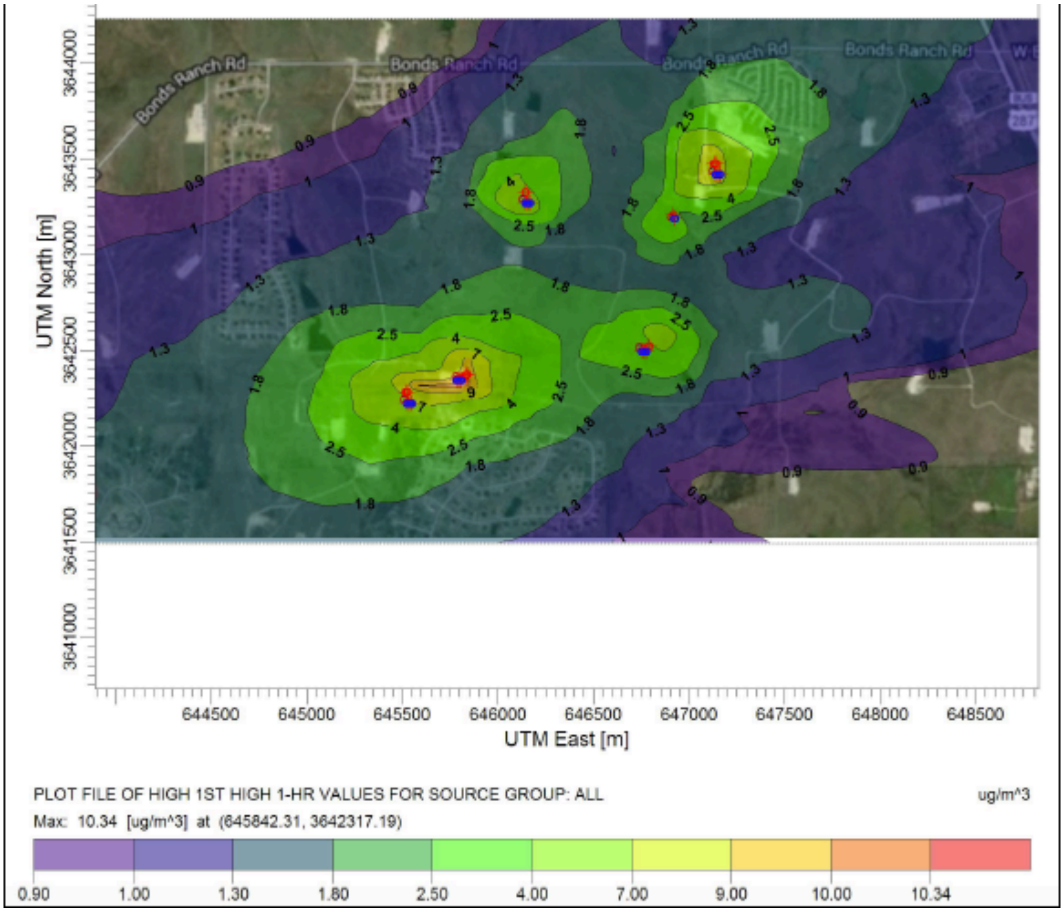


Figure 4-8: Nitrogen oxide concentrations for moderate terrain, high emission rate

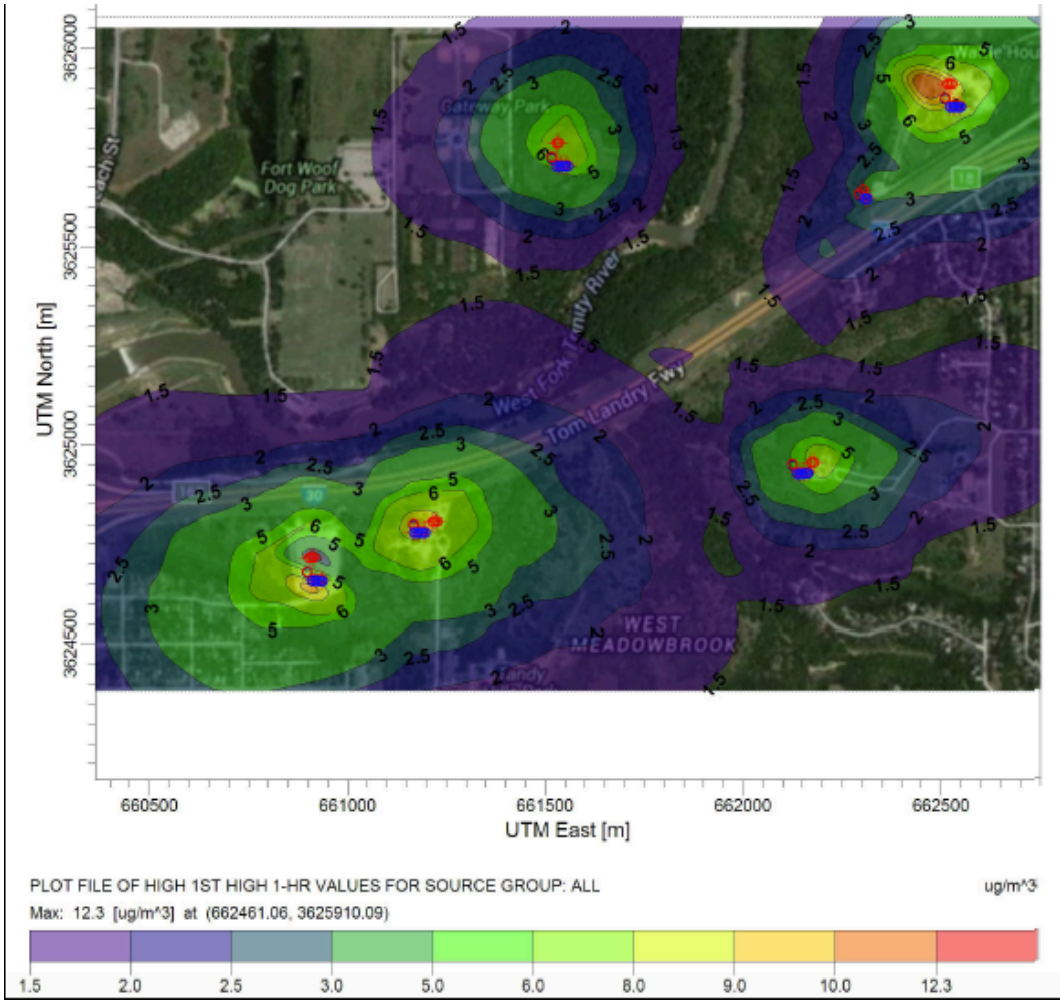


Figure 4-9: Nitrogen oxide concentrations for inclined terrain, high emission rate

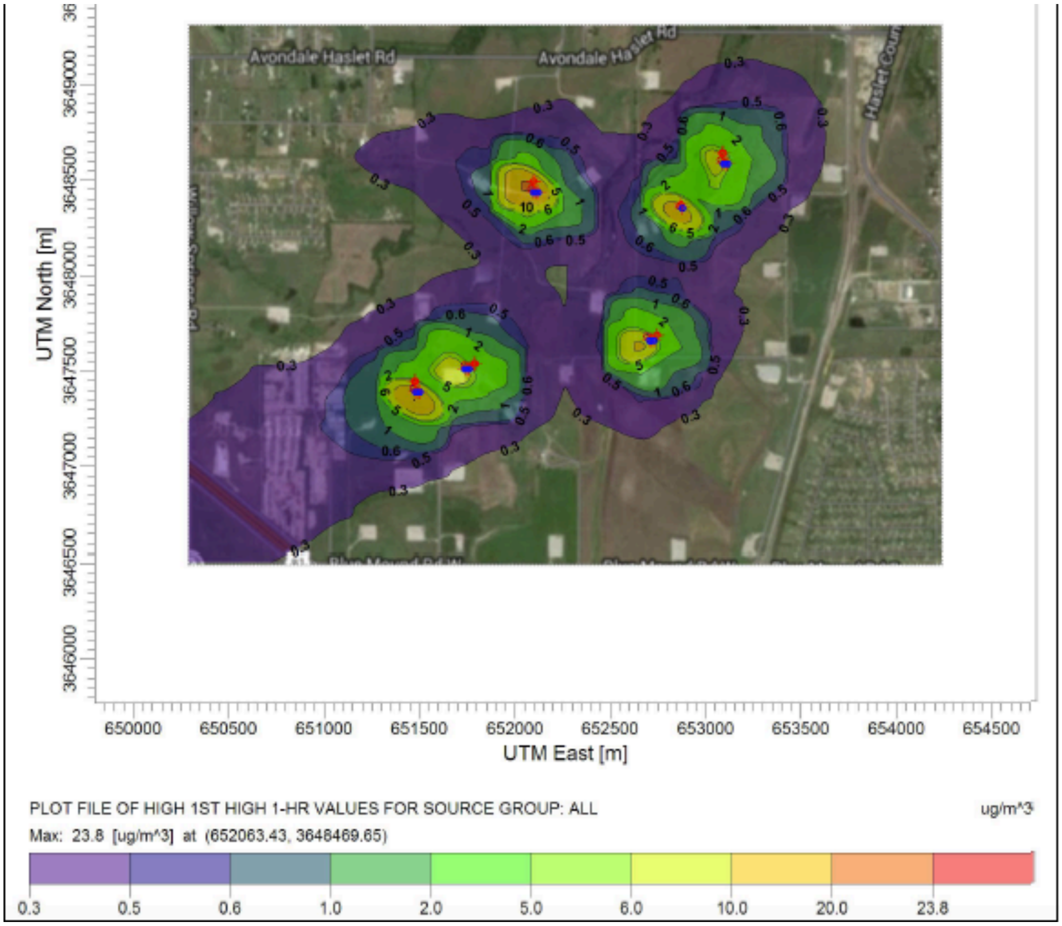


Figure 4-10: Benzene concentrations for flat terrain, high emission rate

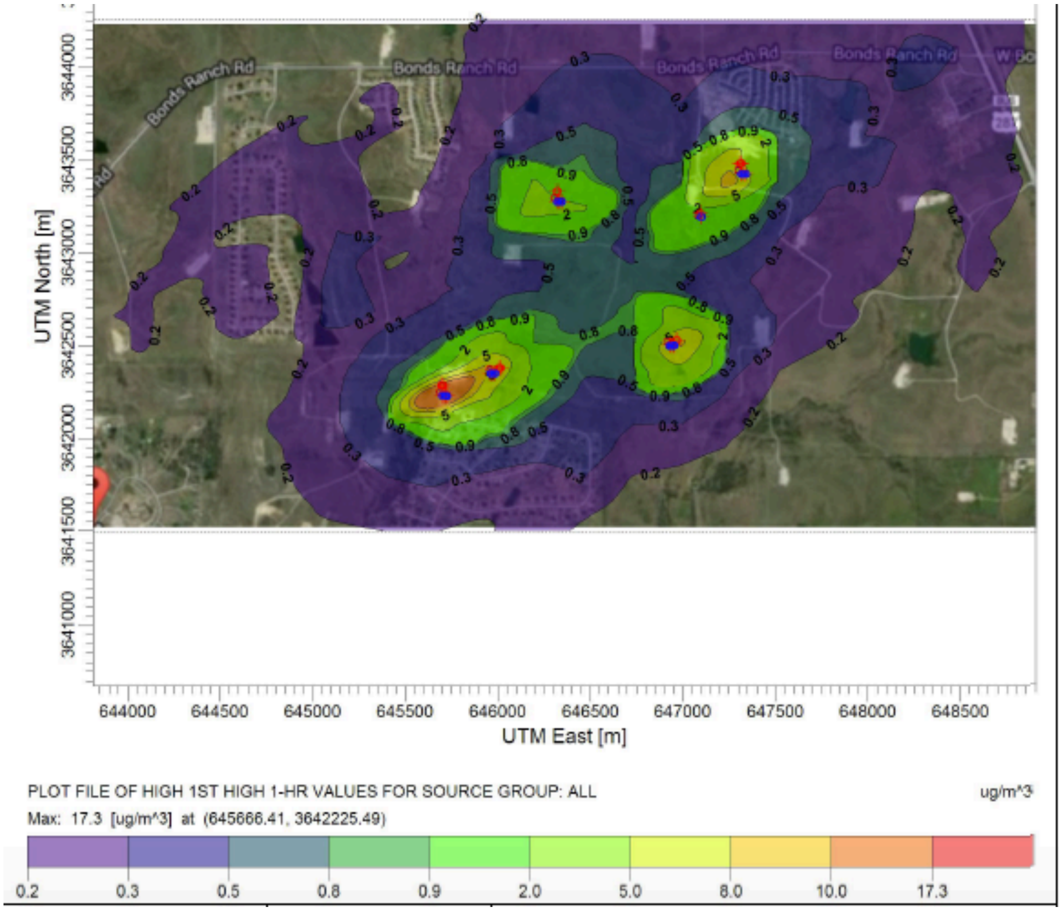


Figure 4-11: Benzene concentrations for moderate terrain, high emission rate

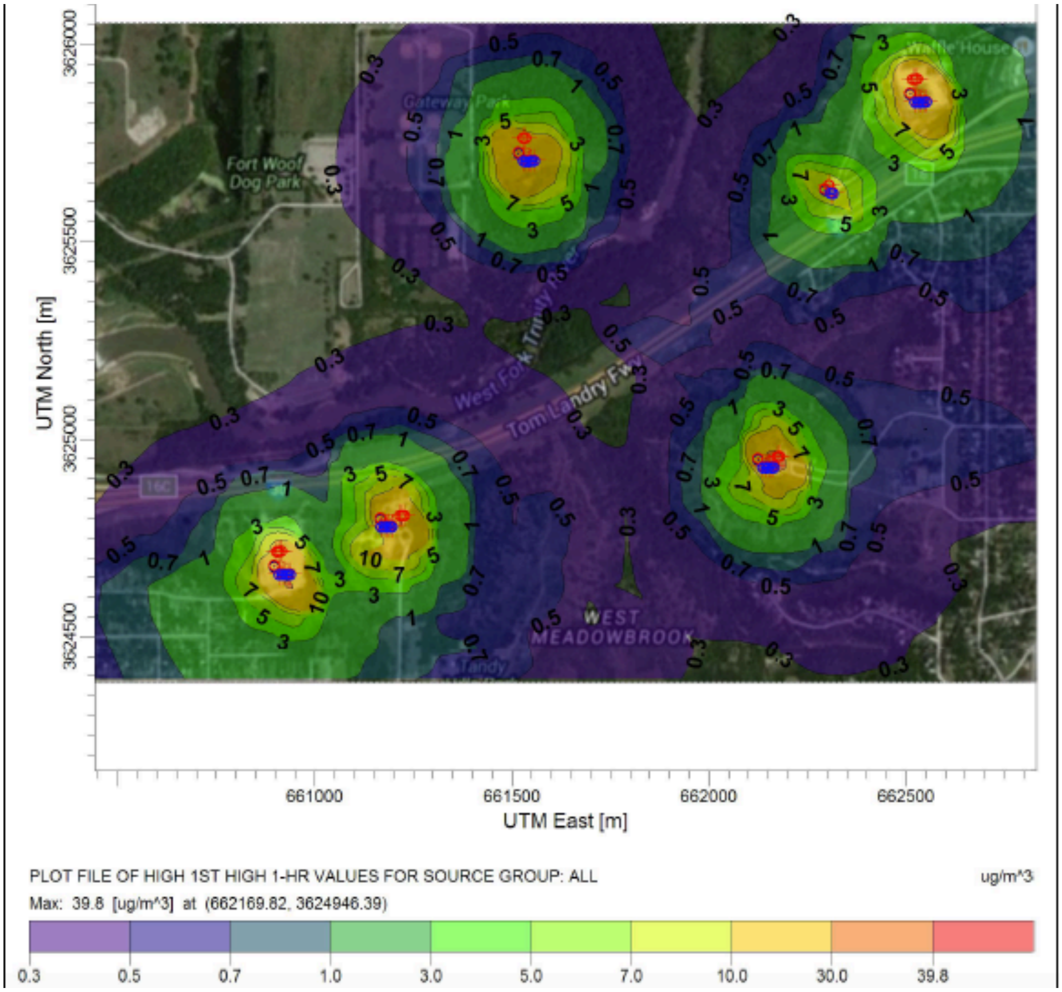


Figure 4-12: Benzene concentrations for inclined terrain, high emission rate

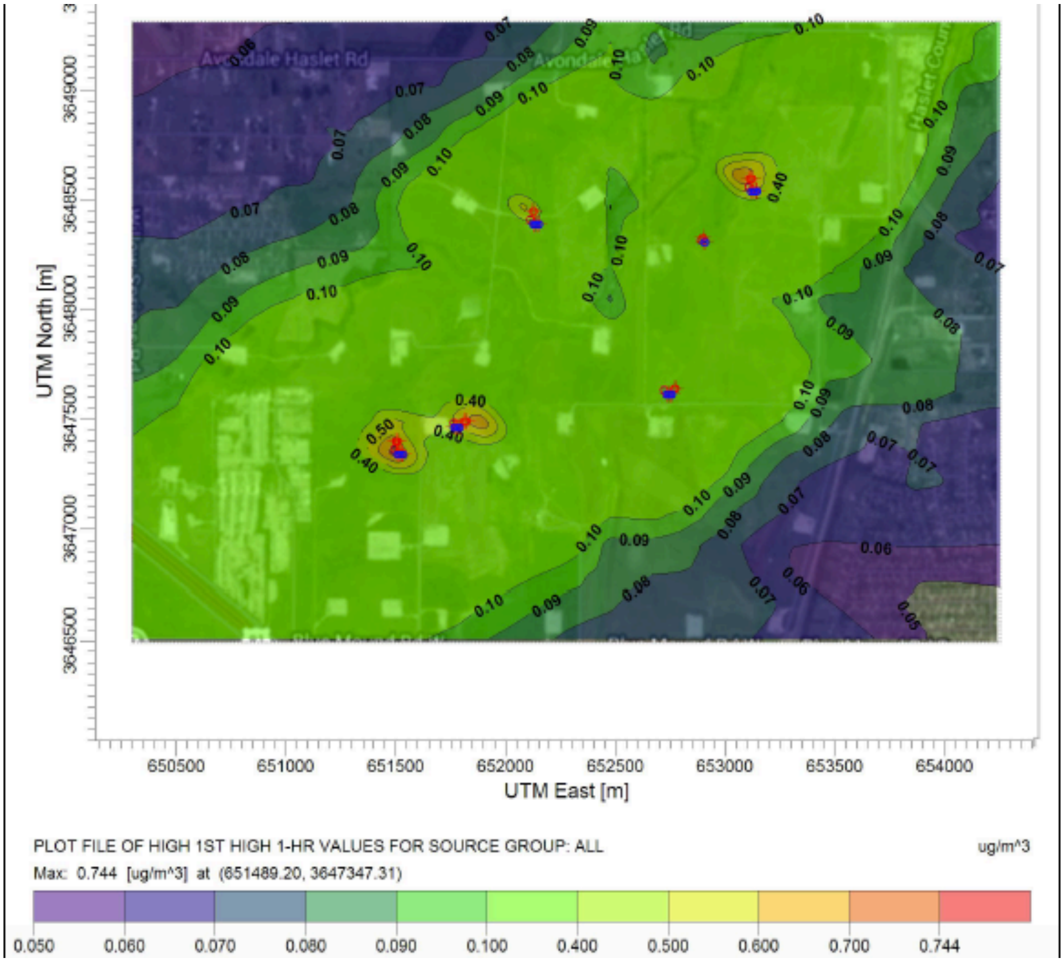


Figure 4-13: PM concentrations for flat terrain, high emission rate

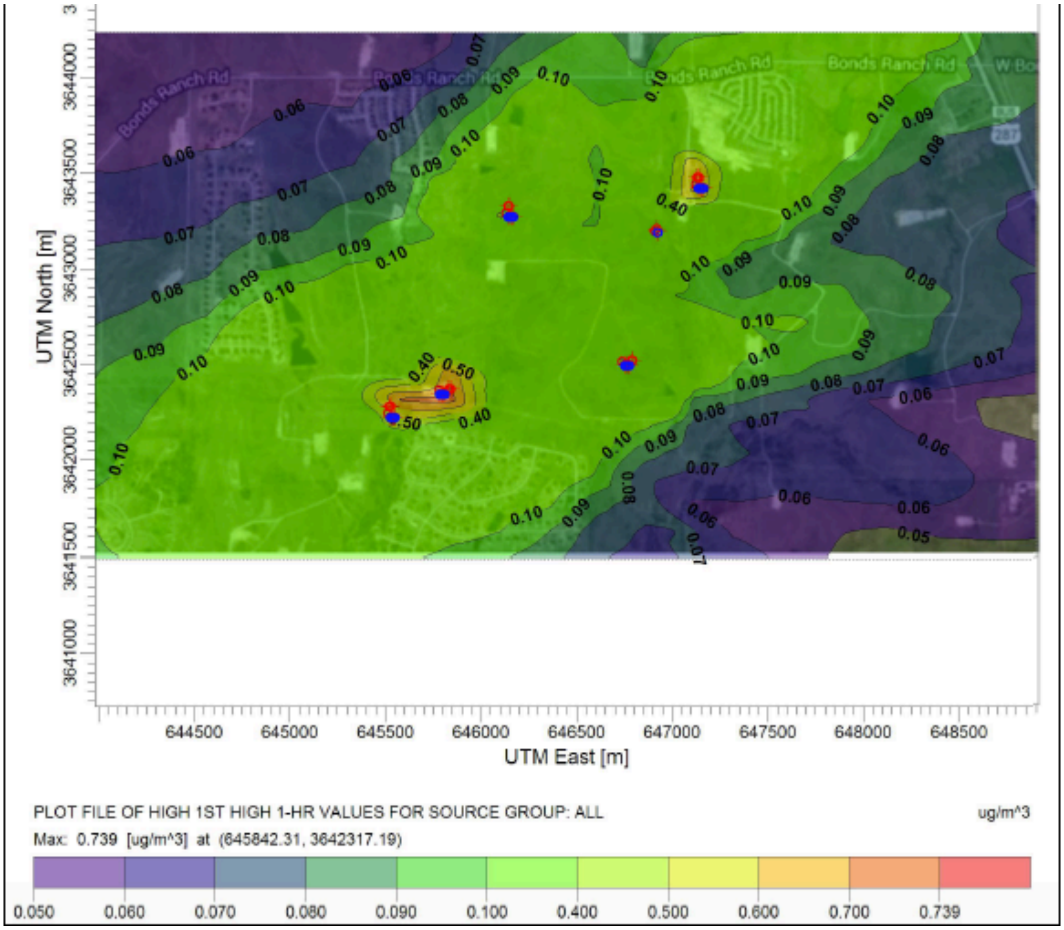


Figure 4-14: PM concentrations for moderate terrain, high emission rate

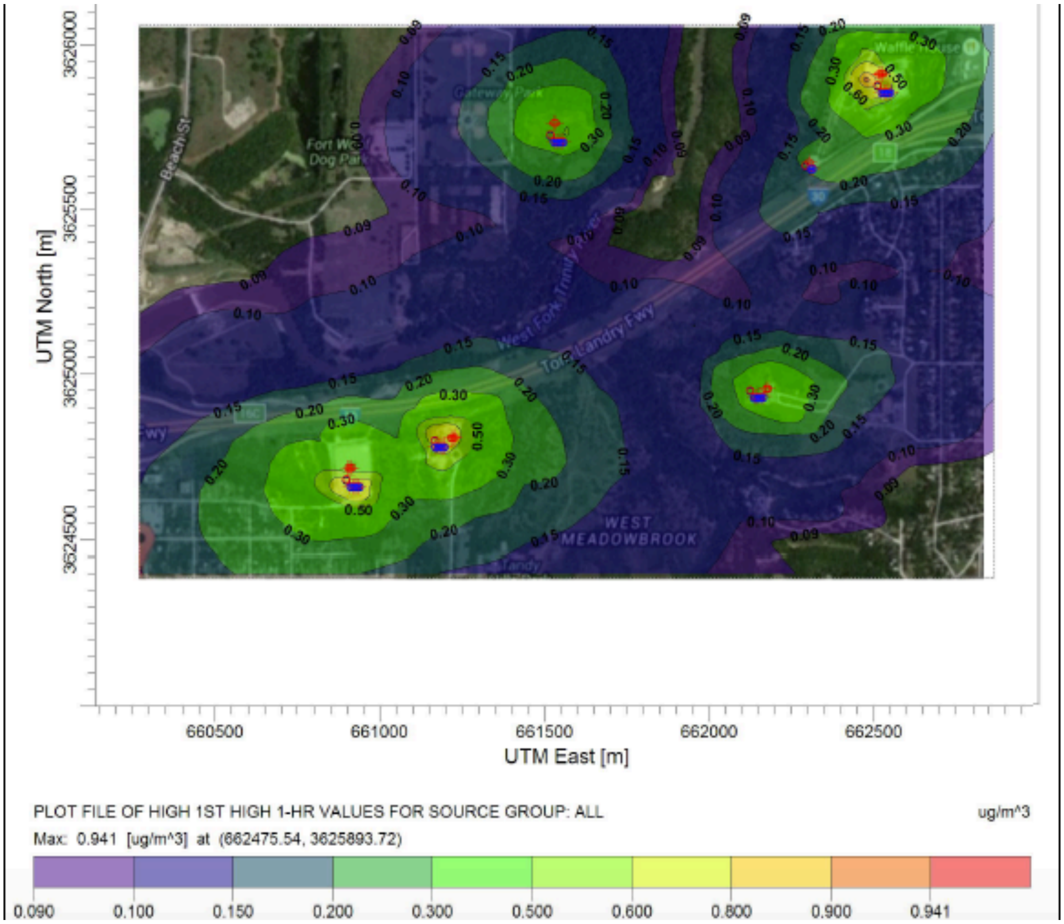


Figure 4-15: PM concentrations for inclined terrain, high emission rate

In scenario 4, based on above Figure 4-1 to 4-15, it can be concluded that the inclined terrain area has higher concentrations compared to moderate and flat terrains, for the same emission rates and well pads. However, it should be mentioned that the maximum concentration for inclined terrain is close to flat terrain value in all cases, and the moderate terrain has the lowest concentration compared to inclined and flat areas. For the inclined area, the east, south and southeast of the area has the highest elevation compared to the other parts of this area, and the northwest and west parts are almost flat compared to east and south. Two of the emission sources are located at northwest and almost west part of area. Therefore, this large elevation difference could be the reason that the pollutant with low heights (like fugitive and storage tanks) cannot disperse from the lowest part to the other parts of the area, as the other parts are high. As a result there would be accumulation of pollutant at lower elevated areas and a higher value.

For PM, NO_x and CO, as critical pollutants emitted from compressor engines (with the highest release height compared to other sources), the maximum concentrations are located at the well pads which are at the almost the highest points in all terrain types. However, for methane and benzene, which are emitted mainly from fugitive and storage tanks, the maximum concentrations are located at the well pads which are located almost at the lower points in all terrain types.

In order to compare the output results for these additional runs of same well pads with same emissions in all three terrain types, Table 4-3 is present as following, which shows the one-hour concentrations, respectively, of all 5 pollutants for all 3 terrains, for the cases with identical high emission rates and identical well pad arrangements.

Table 4-3: Maximum hourly-modeled pollutant concentrations for scenario 4

Pollutant	**1-hour NAAQS or Short-Term ESL** $\mu g/m^3$	**Maximum concentration** $(\boldsymbol{\mu g/m^3})$		
		Inclined terrain	**Moderate terrain**	**Flat terrain**
Benzene	170	39.8	17.3	23.8
CH_4	-	26,900	12,612	18,409
NO_x	188	12.3	10.34	10.45
PM	150	0.94	0.73	0.75
CO	$40x10^3$	77	72.1	73.5

*For all terrains, high emission rates were modeled.

Based on above output results of Scenarios 1, 2, and 3, there is not any concern about the impact of emissions from multiple gas well pads, and there is not any exceeding from standard level in all three scenarios.

However, about scenario 4, it was expected to see maximum concentrations for al pollutants in flat terrain, but inclined terrain has the maximum values for all pollutants in compared to flat and moderate terrain. The reason could be that the vertical elevation change per 100 feet horizontal distance in inclined terrain is 30 feet, which is much more than moderate and flat terrains (as 10 and 0.94 feet respectively for moderate and flat terrains); this large elevation difference may prevent pollutants from dispersing to the other parts of the area, as discussed previously.

The low emission rates for all terrain types were modeled in order to range of maximum pollutant concentrations when sources emit the lower rate and compare those with the maximum concentrations at high emission rates, to see the difference value. And the output results are presented at Appendix B. Based on presented results on Tables 4-1 and 4-2, the gap difference between the concentration from low and high emission rates are for benzene, in all case in which the maximum concentrations from high emissions are more than 300 times of maximum concentrations from low emissions. For methane in all cases, the maximum concentrations from high emission rates are almost 10 to 13 times of contraptions from low emission rates. For the rest of pollutants, the maximum concentrations from high emissions are 2 to 4 times of maximum concentrations from low emissions.

Also, by modeling the low emission rates, there would be extra output result for IDW equation evaluation, for finding exponent value.

4.2 Inverse Distance Weighting method and dispersion modeling

4.2.1 The IDW equation set up:

The Inverse Distance Weighting equation is used for interpolating of the data as followings:

$$\bar{P}_j = \frac{\sum_{i=1}^{n_j} \frac{1}{d_{ij}^{\alpha}} P_{ij}}{\sum_{k=1}^{n_j} \frac{1}{d_{kj}^{\alpha}}}$$

P_{ij} is weighted by inverse of distance given the mean pollution $\bar{P}_j$ at reference point j.

Ten different reference points from different terrain conditions at high emission rates were selected randomly (named X, Y, Z) by considering just a related source of emission and deleting the other sources. The model has the exact pollutant concentration at the reference points. Around the reference points, various other points (ten or more points) were chosen and the concentration for each point and its distance from the selected point were obtained from AERMOD output. Then, above IDW equation was used, for reference points with different α values as 1, 2, 2.5, 3 and 4, in order to compare the IDW output with the exact value from AERMOD at the reference points. Figures 4-16 to 4-21 show the locations of the ten different reference points.

Figure 4-16: Selected points for IDW from inclined terrain area with high CO emission rate

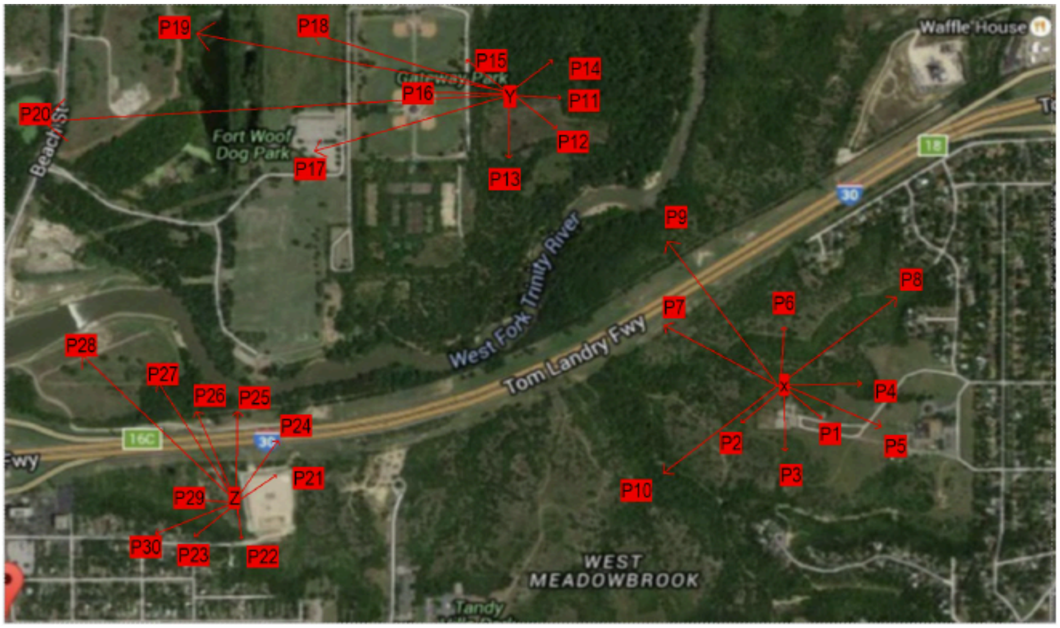


Figure 4-17: Selected points for IDW from inclined terrain area with high PM emission rate

Figure 4-18: Selected points for IDW from flat terrain area with high PM emission rate

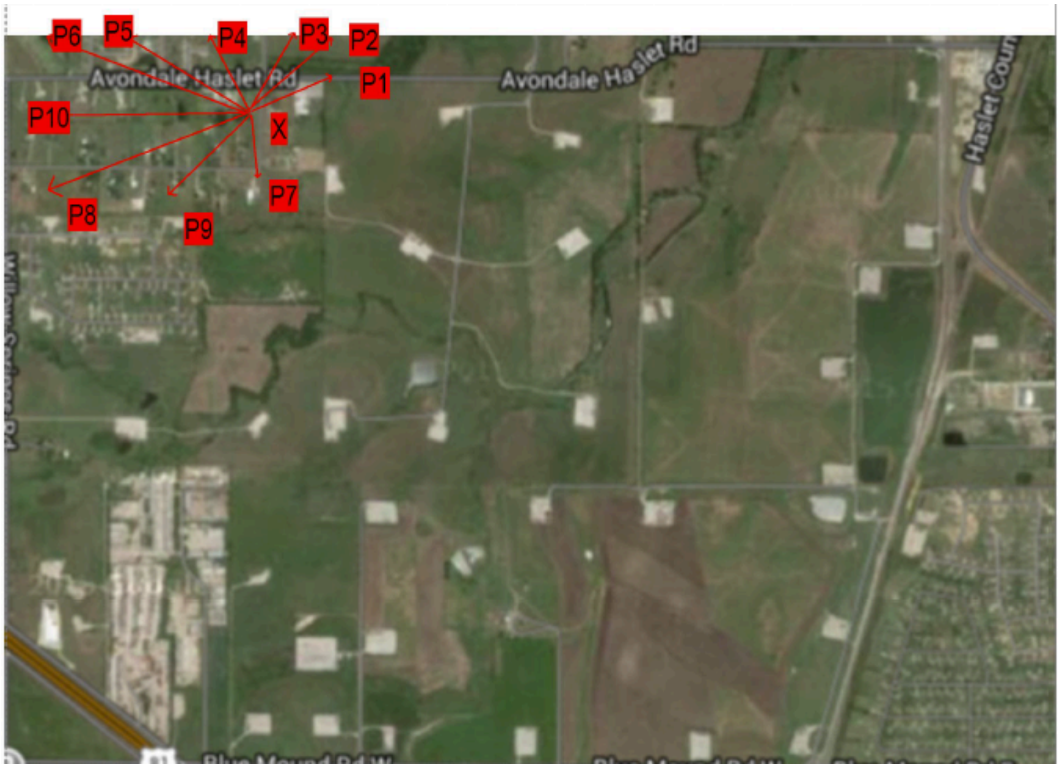


Figure 4-19: Selected points for IDW from flat terrain area with high CO emission rate

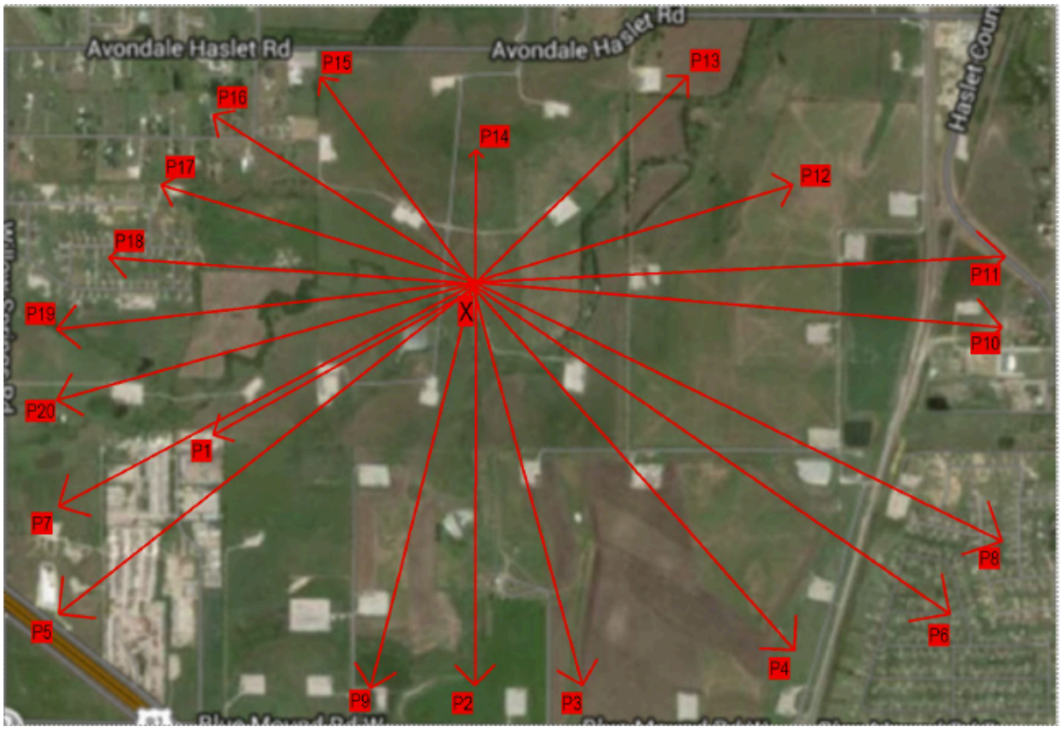


Figure 4-20: Selected points for IDW from flat terrain area with high NOx emission rate

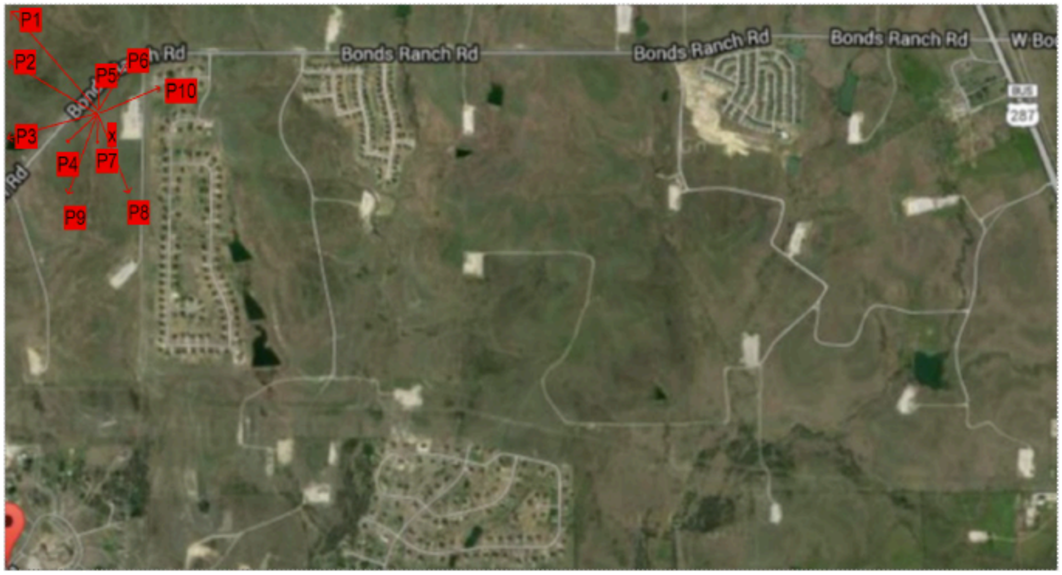


Figure 4-21: Selected points for IDW from moderate terrain area with high PM emission

4.2.2 Results from comparison between IDW equation and dispersion modeling output:

As discussed in Chapter 2, the IDW can be a very useful method to estimate the pollution concentration at a specific location very fast by knowing at least one pollutant concentration and the location from the location of interested pollutant. The major uncertainty about the IDW equation is determining the power value in equation, α. Based on dispersion modeling results from forty different runs, there are plenty good sources of information to have data for finding the most proper value of α. For this purpose, ten different points (name X or Y or Z) were randomly chosen out of results of forty runs. After calculating IDW output with various α values, and comparing them with AERMOD output at those reference points, for five and six points, there result was the same. Therefore the number of reference points decided to be ten, because there was not a significant change in result.

The procedure of finding proper exponent was that, first a reference point (name X or Y or Z) was selected from an area; then different numbers of other points around the reference point were randomly chosen. By having the distances of each around point from the selected reference point (X or Y or Z), the IDW was calculated by various value of α as 1, 2, 2.5, 3 and 4. The output of IDW from each exponent was compared with the expected concentration at reference point (which was taken from AERMOD output). The comparisons between data are presented as Tables 4-4 to 4-9.

Table 4-4: Inclined terrain, high CO emission rate (IDW comparison)

	Point ID#	Concentration ($\mu g/m^3$)	Distance from selected point (m)	IDW output, Alpha=1 ($\mu g/m^3$)	IDW output, Alpha=2 ($\mu g/m^3$)	IDW output, Alpha=2.5 ($\mu g/m^3$)	IDW output, Alpha=3 ($\mu g/m^3$)	IDW output, Alpha=4 ($\mu g/m^3$)	Model output at point X, Y, Z ($\mu g/m^3$)
Point X	1	19.2	158.9	30.52	34.56	36.37	37.97	40.51	36.5
	2	13.1	248.9						
	3	18.6	192.2						
	4	15.2	246.0						
	5	47.3	80.8						
	6	41.0	91.5						
	7	37.4	123.6						
	8	26.4	124.6						
	9	21.0	185.4						
	10	25.6	180.7						
Point Y	11	31.5	124.2	20.22	24.96	26.54	27.59	28.64	25.04
	12	29.1	79.3						
	13	15.9	185.2						
	14	11.3	245.9						
	15	10.0	497.4						
	16	10.3	412.9						
	17	13.1	409.9						
	18	10.6	569.8						
	19	11.7	254.0						
	20	9.1	366.0						
Point Z	21	19.9	189.1	20.89	22.61	23.32	27.02	24.89	28.81
	22	23.7	249.1						
	23	22.0	371.3						
	24	13.9	247.0						
	25	11.3	367.9						
	26	10.0	406.9						
	27	8.9	611.8						
	28	26.9	206.6						
	29	17.6	447.7						
	30	26.8	126.4						
	31	27.0	256.8						

Table 4-5: Inclined terrain, high PM emission rate (IDW comparison)

	Point ID #	Concentration (μg/m^3)	Distance from selected point (m)	IDW output, Alpha=1 (μg/m^3)	IDW output, Alpha=2 (μg/m^3)	IDW output, Alpha= 2.5 (μg/m^3)	IDW output, Alpha=3 (μg/m^3)	IDW output, Alpha= 4 (μg/m^3)	Model output at point X, Y, Z (μg/m^3)
Point X	1	0.38	129.9	0.232	0.259	0.269	0.277	0.290	0.4
	2	0.3	129.0						
	3	0.32	153.0						
	4	0.2	193.0						
	5	0.24	210.0						
	6	0.12	157.0						
	7	0.11	324.0						
	8	0.09	373.0						
	9	0.08	486.0						
	10	0.1	374.0						
Point Y	11	0.37	105.0	0.274	0.301	0.308	0.312	0.319	0.47
	12	0.41	121.0						
	13	0.31	158.0						
	14	0.26	125.0						
	15	0.21	124.0						
	16	0.18	189.0						
	17	0.1	501.0						
	18	0.09	502.7						
	19	0.07	781.0						
	20	0.06	1144.0						
Point Z	21	0.47	124.0	0.365	0.416	0.434	0.448	0.467	0.57
	22	0.54	80.0						
	23	0.41	124.5						
	24	0.27	186.0						
	25	0.18	235.0						
	26	0.15	256.0						
	27	0.13	368.0						
	28	0.11	545.5						
	29	0.38	94.0						
	30	0.3	204.0						

Table 4-6: Flat terrain, high PM emission rate (IDW comparison)

	Point ID#	Concentration ($\mu g/m^3$)	Distance from selected point (m)	IDW output, Alpha=1 ($\mu g/m^3$)	IDW output, Alpha=2 ($\mu g/m^3$)	IDW output, Alpha=2.5 ($\mu g/m^3$)	IDW output, Alpha=3 ($\mu g/m^3$)	IDW output, Alpha=4 ($\mu g/m^3$)	Model output at point X, Y, Z ($\mu g/m^3$)
Point X	1	0.21	340.7	0.20	0.21	0.220	0.224	0.23	0.25
	2	0.19	411.2						
	3	0.17	523.6						
	4	0.14	768.4						
	5	0.13	844.4						
	6	0.15	580.9						
	7	0.16	282.4						
	8	0.26	203.0						
	9	0.23	146.0						
	10	0.18	318.3						

Table 4-7: Flat terrain, high CO emission rate (IDW comparison)

	Point ID#	Concentration ($\mu g/m^3$)	Distance from selected point (m)	IDW output, Alpha=1 ($\mu g/m^3$)	IDW output, Alpha=2 ($\mu g/m^3$)	IDW output, Alpha=2.5 ($\mu g/m^3$)	IDW output, Alpha=3 ($\mu g/m^3$)	IDW output, Alpha=4 ($\mu g/m^3$)	Model output at point X, Y, Z ($\mu g/m^3$)
Point X	1	19.3	328.3	16.85	17.53	17.78	18.00	18.32	20
	2	18.0	405.8						
	3	18.4	317.2						
	4	16.8	314.1						
	5	14.5	529.7						
	6	13.0	801.3						
	7	19.1	226.9						
	8	13.0	801.3						
	9	14.0	416.0						
	10	13.5	754.0						

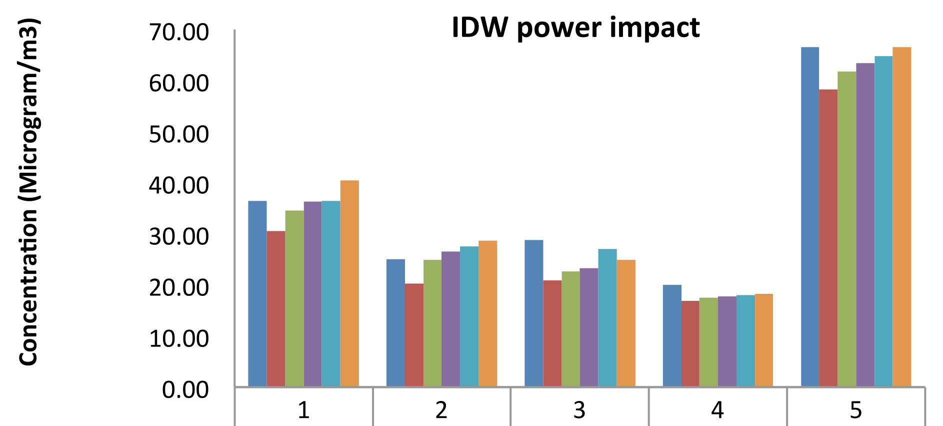
Table 4-8: Flat terrain, high NO_x emission rate (IDW comparison)

	Point ID#	Concentration (μg/m^3)	Distance from selected point (m)	IDW output, Alpha=1 (μg/m^3)	IDW output, Alpha=2 (μg/m^3)	IDW output, Alpha=2.5 (μg/m^3)	IDW output, Alpha=3 (μg/m^3)	IDW output, Alpha=4 (μg/m^3)	Model output at point X, Y, Z (μg/m^3)
Point X	1	2.9	1117.5	2.38	2.43	2.46	2.49	2.55	2.69
	2	2.0	1470.7						
	3	1.9	1529.8						
	4	1.9	1787.9						
	5	2.1	1977.7						
	6	2.0	2141.9						
	7	2.1	1766.9						
	8	2.8	2175.0						
	9	3.6	1527.0						
	10	1.9	1968.9						

Table 4-9: Moderate terrain, high PM emission rate (IDW comparison)

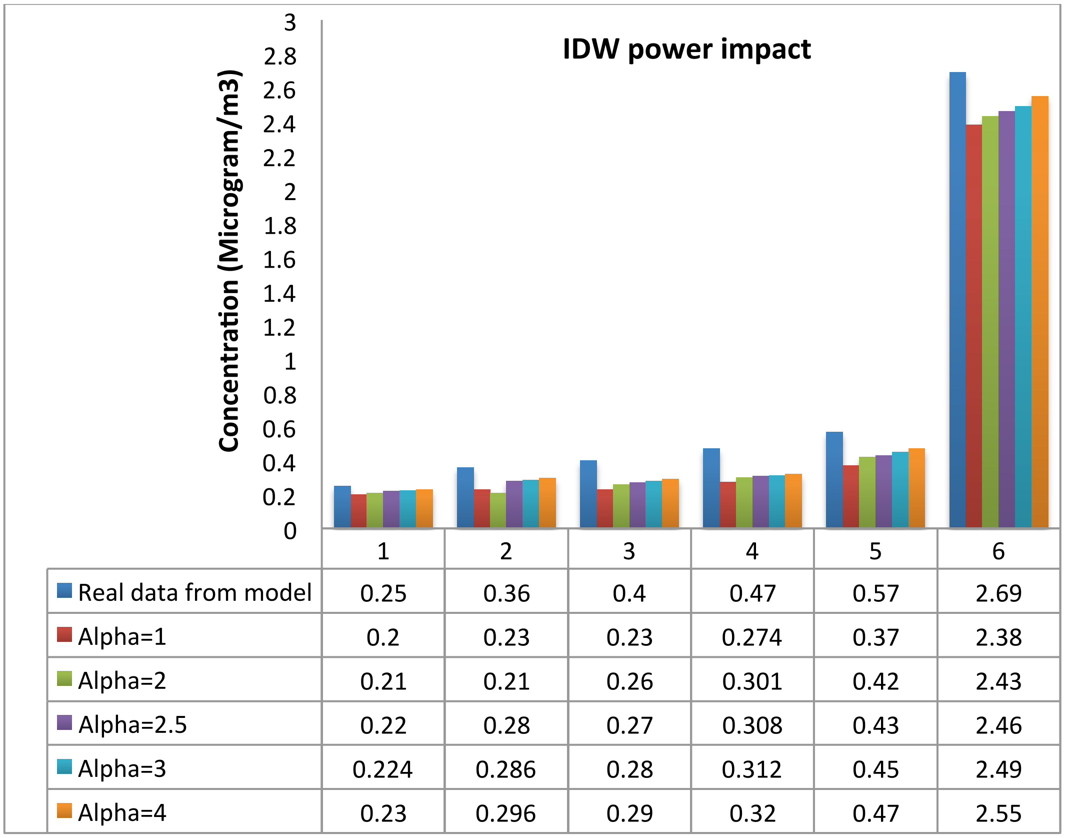
	Point ID#	Concentration (μg/m^3)	Distance from selected point (m)	IDW output, Alpha=1 (μg/m^3)	IDW output, Alpha=2 (μg/m^3)	IDW output, Alpha=2.5 (μg/m^3)	IDW output, Alpha=3 (μg/m^3)	IDW output, Alpha=4 (μg/m^3)	Model output at point X, Y, Z (μg/m^3)
Point X	1	0.11	681.1	0.229	0.265	0.277	0.2857	0.2960	0.360
	2	0.14	520.8						
	3	0.13	463.2						
	4	0.25	201.2						
	5	0.31	127.0						
	6	0.17	306.8						
	7	0.3	136.0						
	8	0.13	424.0						
	9	0.11	422.0						
	10	0.23	328.0						

Based on Tables 4-4 to 4-9 data, the comparison between expected concentration at points X or Y or Z and IDW equation with different α values are presented as Figures 4-22 and 4-23.



	1	2	3	4	5
Real data from model	36.50	25.04	28.81	20.00	66.57
Alpha=1	30.52	20.22	20.89	16.85	58.29
Alpha=2	34.56	24.96	22.61	17.53	61.83
Alpha=2.5	36.37	26.54	23.32	17.78	63.44
Alpha=3	36.50	27.59	27.02	18.00	64.78
Alpha=4	40.51	28.64	24.89	18.32	66.53

Figure 4-22: Comparison the IDW output with expected concentration (for five groups)



	1	2	3	4	5	6
🟦 Real data from model	0.25	0.36	0.4	0.47	0.57	2.69
🟥 Alpha=1	0.2	0.23	0.23	0.274	0.37	2.38
🟩 Alpha=2	0.21	0.21	0.26	0.301	0.42	2.43
🟪 Alpha=2.5	0.22	0.28	0.27	0.308	0.43	2.46
🟦 Alpha=3	0.224	0.286	0.28	0.312	0.45	2.49
🟧 Alpha=4	0.23	0.296	0.29	0.32	0.47	2.55

Figure 4-23: Comparison the IDW output with expected concentration (for the rest six groups)

Based on above curves and comparisons, the value of $\alpha = 4$ in eight cases from total ten above cases makes the IDW output closer to the expected value from dispersion modeling rather than the other values. The value of $\alpha = 1$ makes the least pollutant concentration in all conditions. However, the $\alpha = 3\, and\, 4$ have the closest pollutant concentrations to expected values. By increasing the value of exponent α, almost in all cases, the IDW output did not change a lot and the output would be constant over increasing the component. This means the most proper value of exponent can be considered as 4. Figure 4-24 is the curve for one of the points, which shows the impact on α increase on IDW function. The exponent was increased up to 100 and the output was very close to the value from exponent 4.

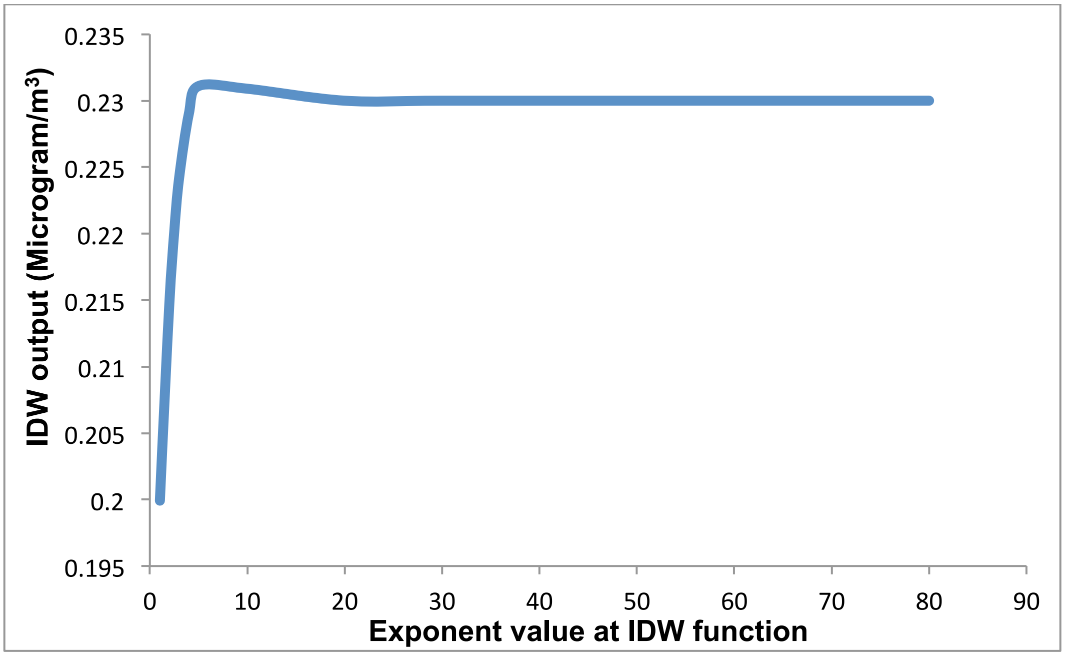


Figure 4-24: Curve for impact of exponent increase on IDW function

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

This study was done for evaluating the impact of multiple well pads working at the production process at different terrain types in the pollution dispersion program from EPA, AERMOD version 9.0.0. Four different scenarios were defined and evaluated. In Scenario 1, 2, and 3 were defined in order to evaluate the impacts of multiple gas well pads emissions, and scenario 4 was considered in order to evaluate the impact of terrain type on dispersion of pollutants. Three terrain types were considered as flat, moderate and inclined. For scenario 1, a flat terrain with twenty one well pads, for scenario 2 a moderate terrain twenty well pads, for scenario3 a inclined terrain area six well pads, and for scenario 4 six well pads in flat, moderate and inclined terrains were modeled with same arrangement and emission rates in each terrain type. In all scenarios, in each well pad one fugitive area source, one group of wellheads, along with storage tanks and compressor engines simultaneously were modeled. The groups of well pads were molded in three different terrain areas, including flat, moderate, and inclined areas, with maximum and minimum emission rates for five different pollutants (VOCs component (benzene), CH_4, CO, NO_x and PM).

Based on model output results, in scenarios 1, 2 and 3 the concentrations of all pollutants were not concerning, because the maximum concentrations in all cases have the lower levels of concentration compared to the National Ambient Air Quality Standards

(NAAQS) established by the United States Environmental Protection Agency under authority of the Clean Air Act (42 U.S.C. 7401 et seq.). Also, the model output concentration of benzene at maximum and minimum emission rates, in all three different terrain conditions are lower than the State of Texas ESLs for benzene, both hourly (short-term) and annually (long-term effect).

Additionally, based on scenario 4, ten other models were done, by considering same numbers of well pad arrangements and emission rates in inclined, flat and moderate terrain areas for all five different pollutants (VOCs component, PM, CH_4, NO_x and CO) with high emission rate, in order to compare the impact of the elevation difference on the dispersion of pollutants. Based on the model outputs, inclined and flat terrains have higher concentrations compared to moderate terrain area. In general, inclined has the highest values of hourly and annually concentrations, due to the inclined terrain limiting pollutant dispersion. For critical pollutants, including PM, NOx, and CO, which are emitted from compressor engines, the maximum concentrations were located at almost highest elevation of area. For methane and benzene, which are emitted mostly from wellheads, fugitive and storage tanks, the maximum concentrations were located at lower elevations.

The other goal of this study was to use the dispersion output data from dispersion model, and put the data in Inverse Distance Weighting equation with different values of exponent α, in order to compare the IDW output with the expected value from AERMOD. The exponent value in the IDW has always been a critical topic, as there is not a fixed recommended value for α, in IDW equation. In this study, based on the model output, ten different reference points were evaluated and tried with different values of α as 1, 2, 2.5, 3 and 4. The IDW results were compared with expected value at those points from AERMOD output. In all cases the IDW with $\alpha = 4$ gives a closer concentration value to the expected concentration. As a conclusion, for air pollution evaluations using IDW equation, it is recommended to use $\alpha = 4$. However, the α value was determined from only three different terrain conditions, which means this recommended value might not be so accurate for other terrain types. Therefore, further investigation from other terrain conditions can be helpful to support this conclusion.

5.2 Recommendations

To have more accurate evaluation and study, it is recommended to consider and model buildings all over the modeled area, in order to include the impact of building down wash.

It is also recommended to evaluate more varied terrain areas, and other regions rather than City of Fort Worth area.

It would be also helpful to consider the on-road, of-road and passing vehicle emissions, and other possible source of pollution in the model based on site characteristics and conditions to have more accurate output.

Appendix A

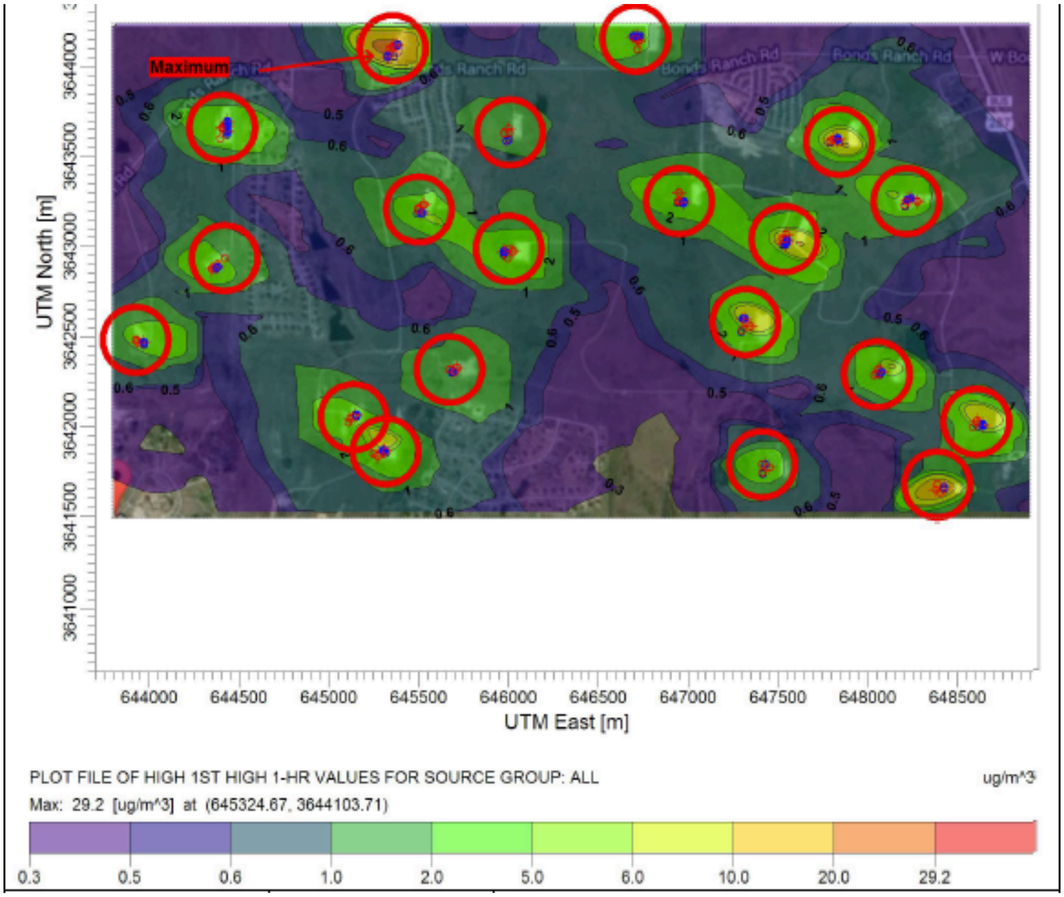
Compressor engine VOC emission factors (EPA, AP-42 list, Chapter 5)

Pollutant	Emission Factors (Lb/Million Btus)	Pollutant	Emission Factors (Lb/Million Btus)
1,1,2,2-Tetrachloroethane	6.63E-05	Methylene chloride	1.47E-04
1,1,2-Trichloroethane	5.27E-05	Ethane	1.05E-01
1,1-Dichloroethane	3.91E-05	Chloroethane	1.87E-06
1,2,3-Trimethylbenzene	3.54E-05	Ethylbenzene	1.08E-04
1,2,4-Trimethylbenzene	1.11E-04	Ethylene dibromide	7.34E-05
1,3,5-Trimethylbenzene	3.38E-05	Ethylene dichloride	4.22E-05
1,3-Butadiene	8.20E-04	Fluoranthene	1.11E-06
1,3-Dichloropropene	4.38E-05	Fluorene	5.67E-06
2,2,4-Trimethylpentane	8.46E-04	Formaldehyde	5.52E-02
2-Methyl Naphthalene	3.32E-05	Indeno(1,2,3-cd) pyrene	9.93E-09
Acenaphthene	1.33E-06	Isobutane	3.75E-03
Acenaphthylene	5.53E-06	Isobutyraldehyde	4.37E-04
Acetaldehyde	8.36E-03	Isomers of xylene	2.68E-04
Acrolein	7.78E-03	Methyl alcohol	3.06E-03
Anthracene	7.18E-07	Methylcyclohexane	1.23E-03
Benzene	1.94E-03	Naphthalene	9.71E-05
Benzo (a) anthracene	3.36E-07	n-Butane	4.75E-03
Benzo (a) pyrene	5.68E-09	Hexane	1.11E-03
Benzo (b) fluoranthene	1.66E-07	N-Nonane	1.10E-04
Benzo (e) pyrene	4.15E-07	N-Octane	3.51E-04
Benzo (g,h,i) perylene	4.14E-07	N-Pentane	2.60E-03
Benzo (k) fluoranthene	4.26E-09	Perylene	4.97E-09
Biphenyl	2.12E-04	Phenanthrene	1.04E-05
Carbon tetrachloride	6.07E-05	Phenol	4.21E-05
Chlorobenzene	4.44E-05	Polycyclic Aromatic Hydrocarbons (PAH)	1.41E-04
Chloroform	4.71E-05	Propane	4.19E-02
Chrysene	6.93E-07	Propylene dichloride	4.46E-05
Cyclohexane	3.08E-04	Pyrene	1.36E-06
Cyclopentane	2.27E-04	Styrene	5.48E-05
Toluene	9.63E-04	Vinyl chloride	2.47E-05

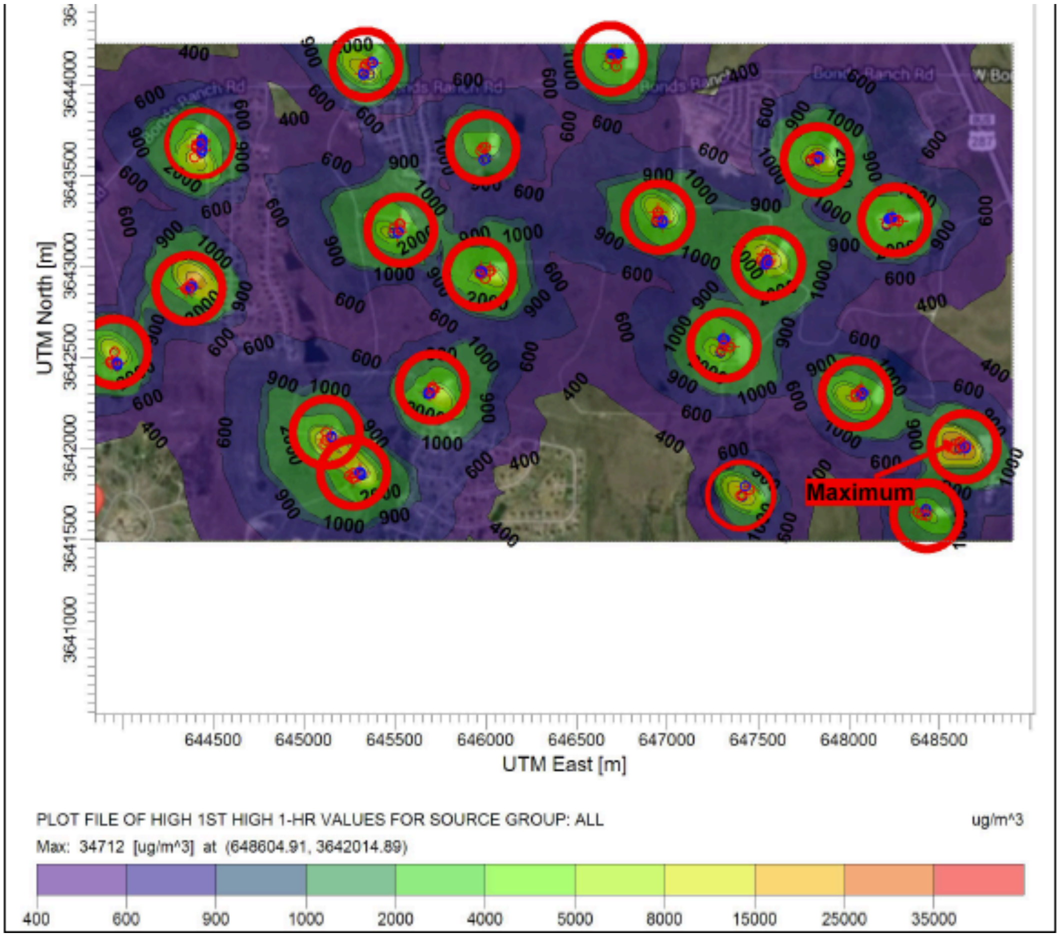
Appendix B

Output Results from AERMOD

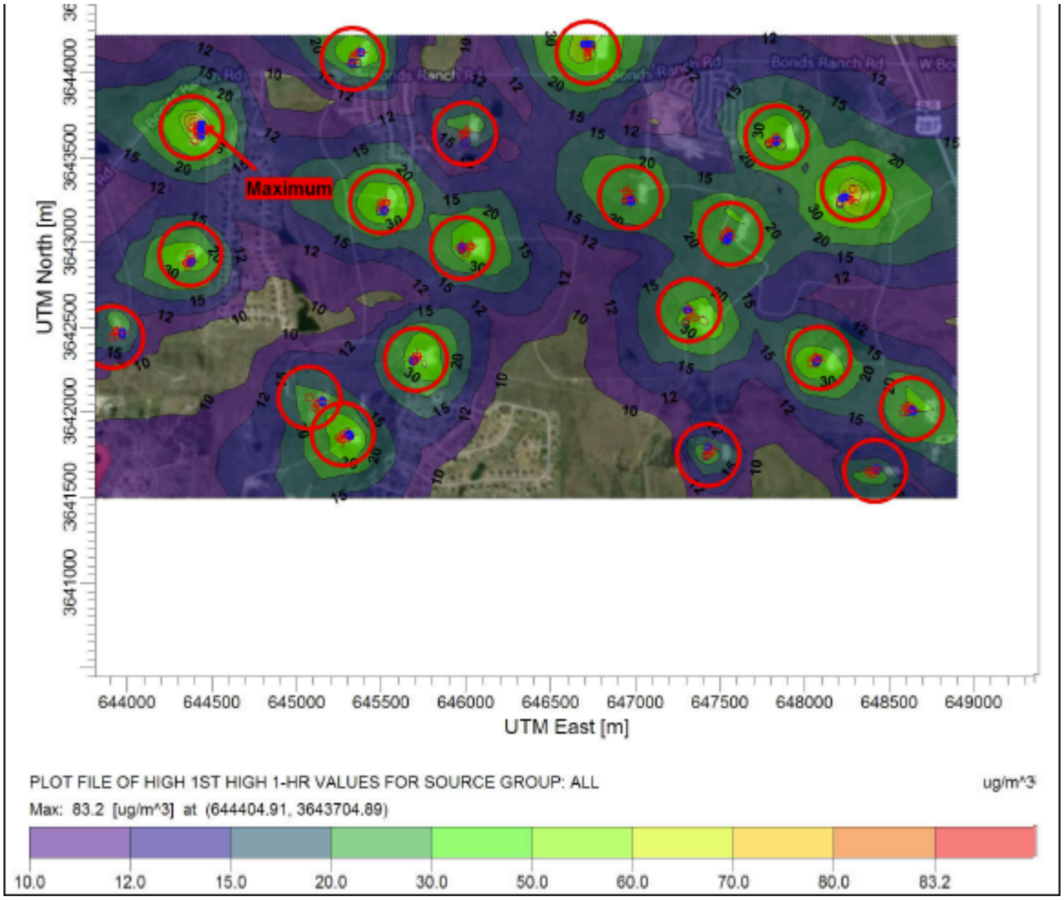
1- Moderate terrain and high benzene emissions (hourly):



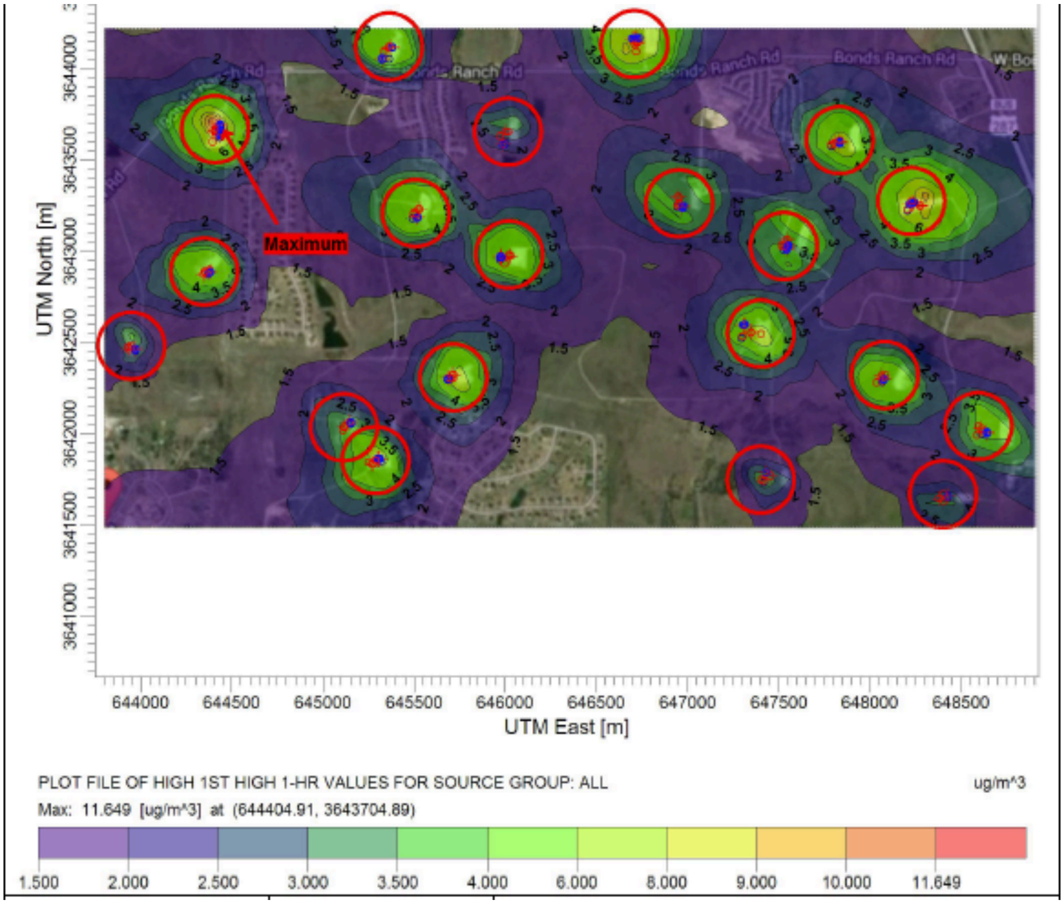
2- Moderate terrain and high CH_4 emissions (hourly):



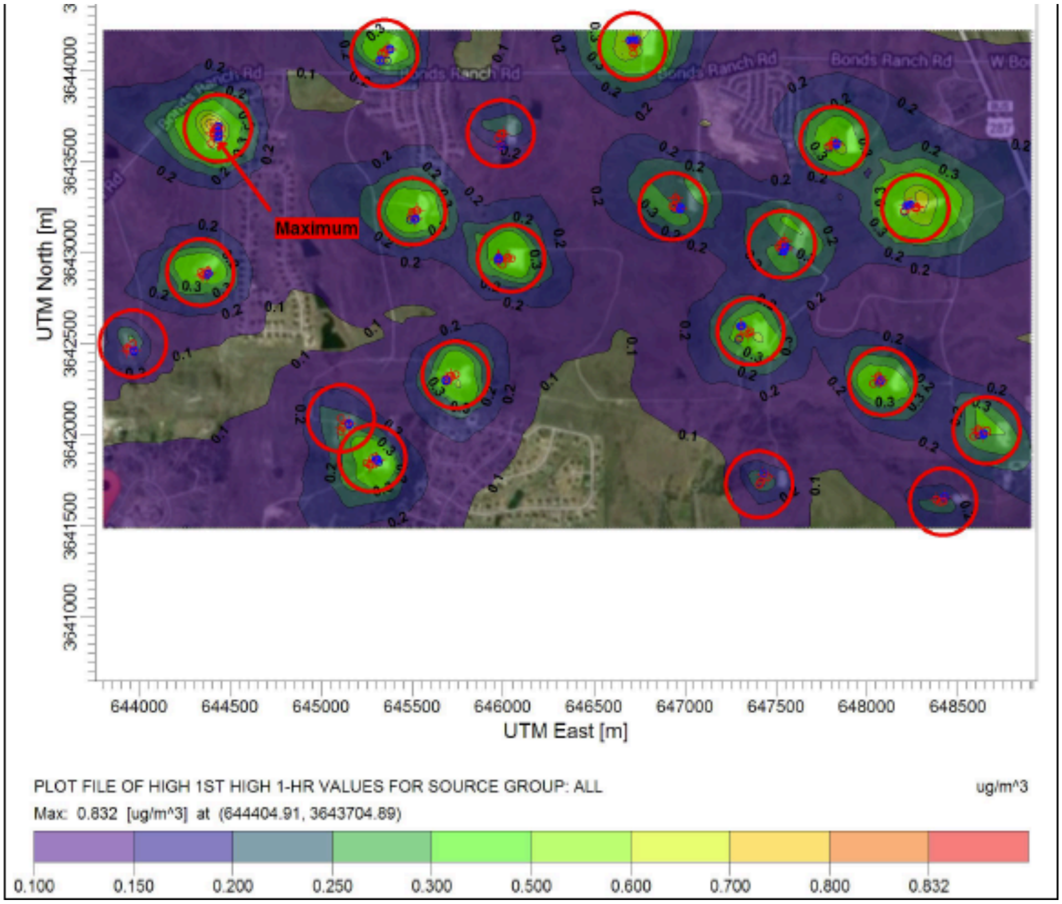
3- Moderate terrain and high CO emissions (hourly):



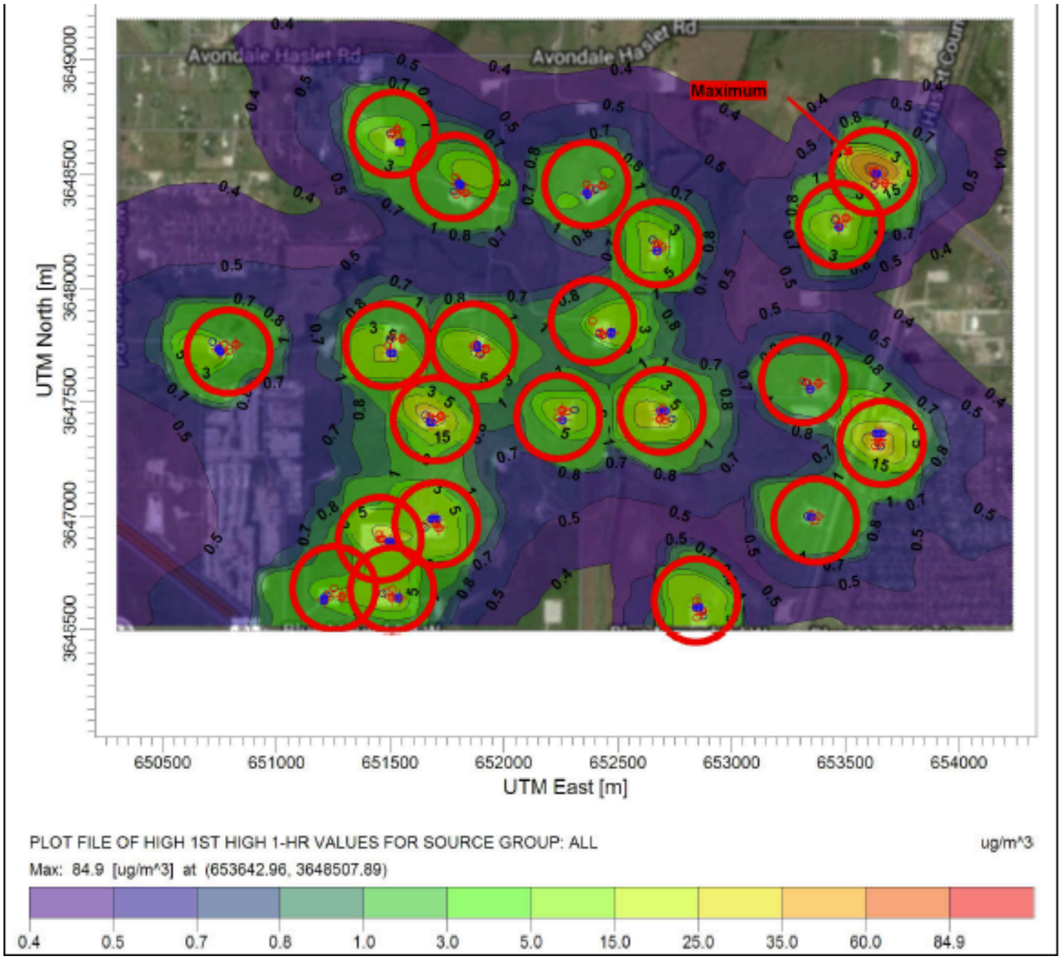
4- Moderate terrain and high NOx emissions (hourly):



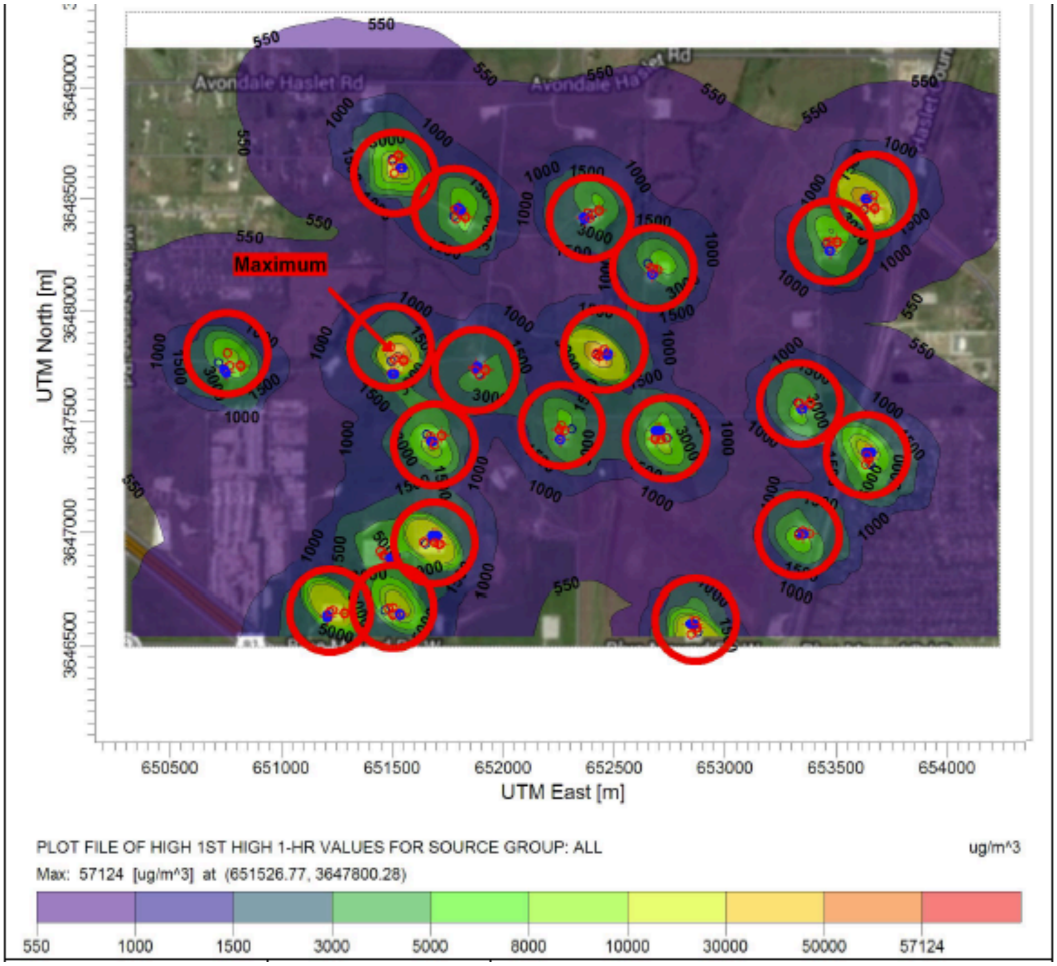
5- Moderate terrain and high PM emissions (hourly):



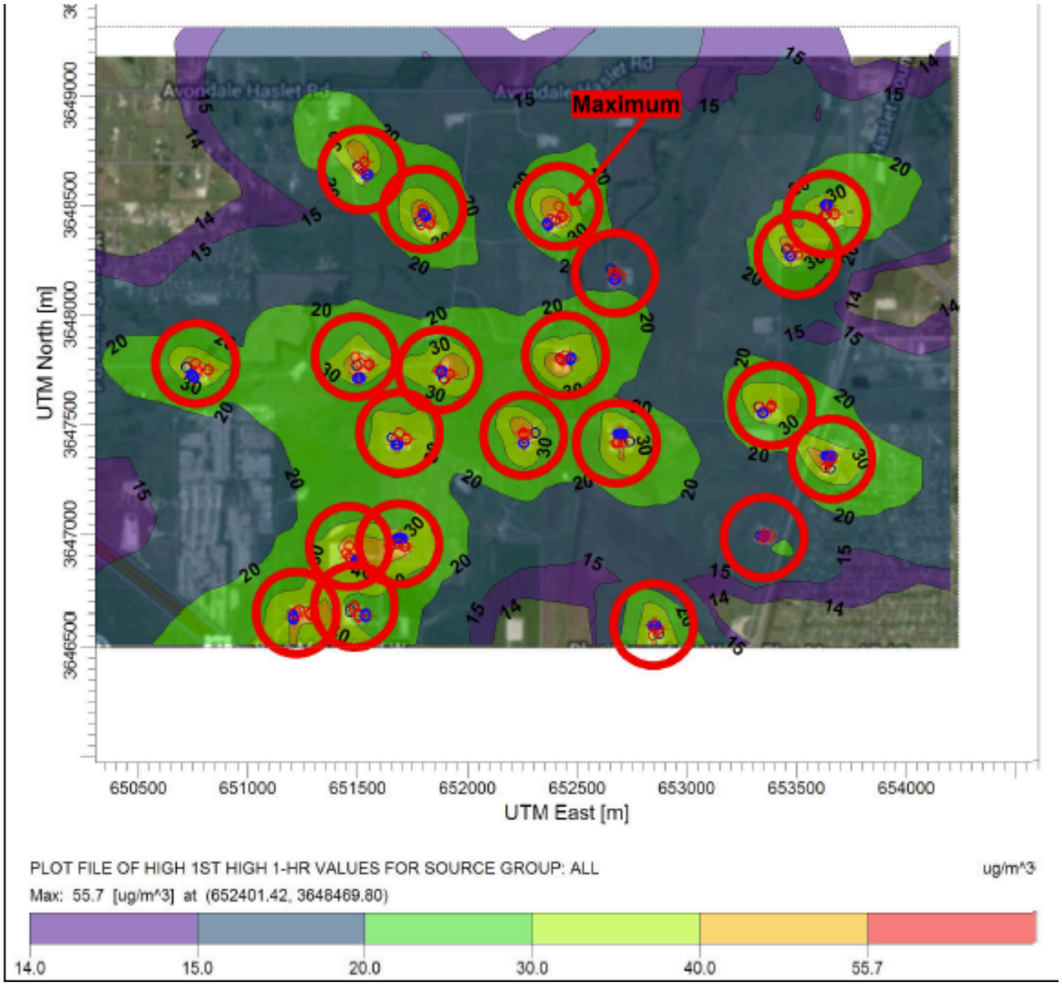
6- Flat terrain and high benzene emissions (hourly):



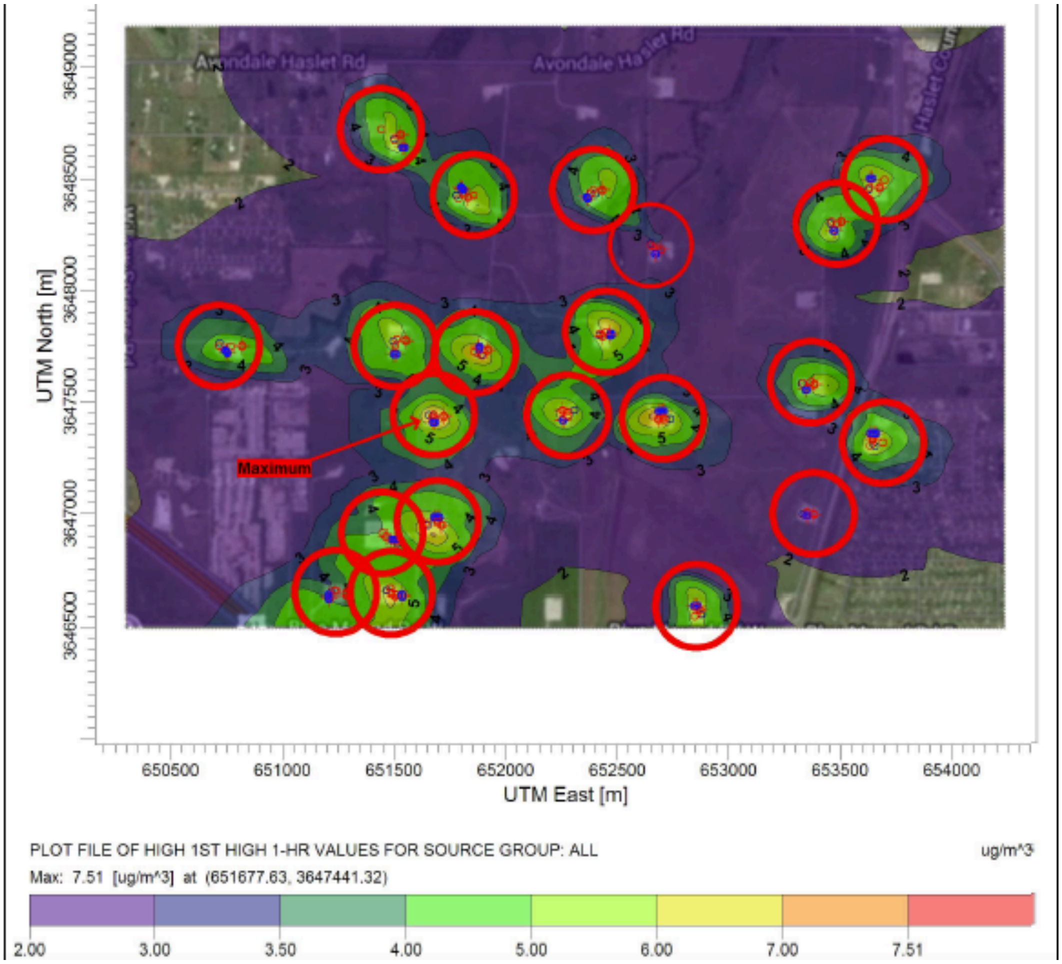
7- Flat terrain and high CH_4 emissions (hourly):



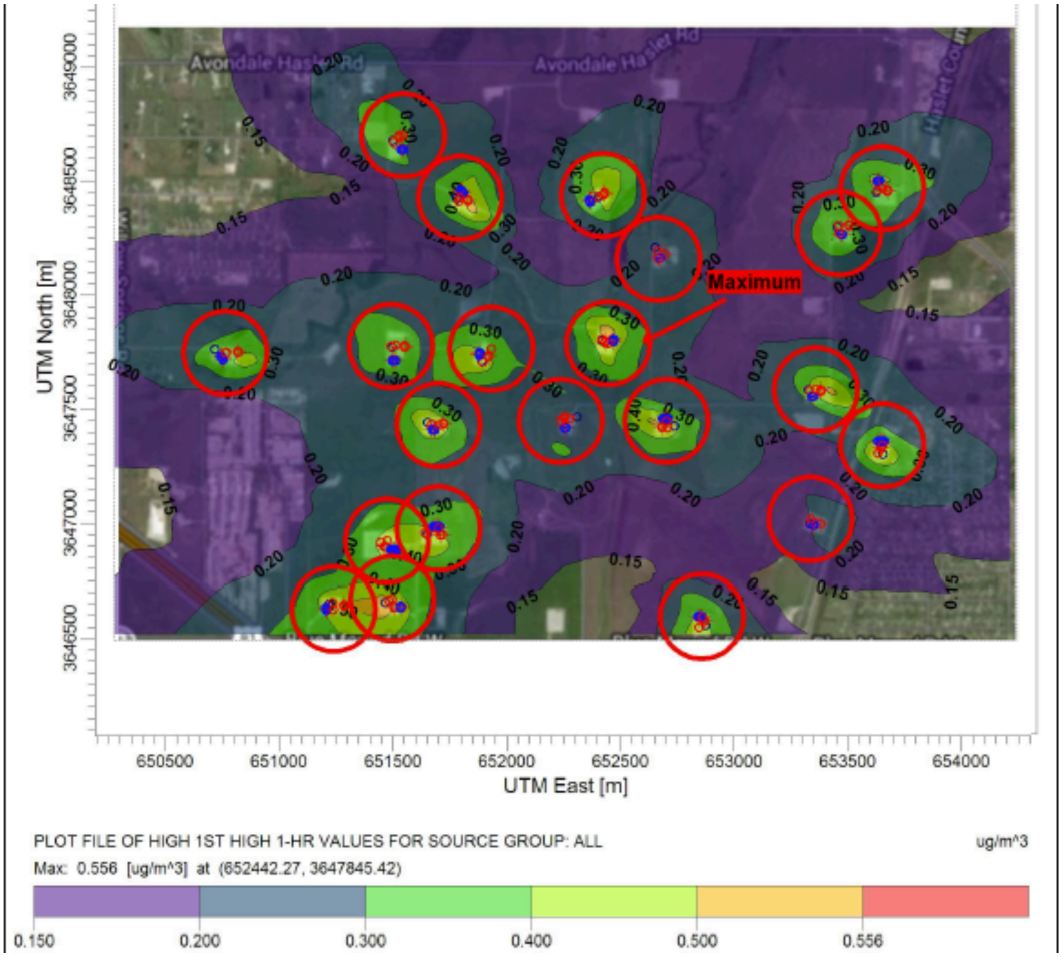
8- Flat terrain and high CO emissions (hourly):



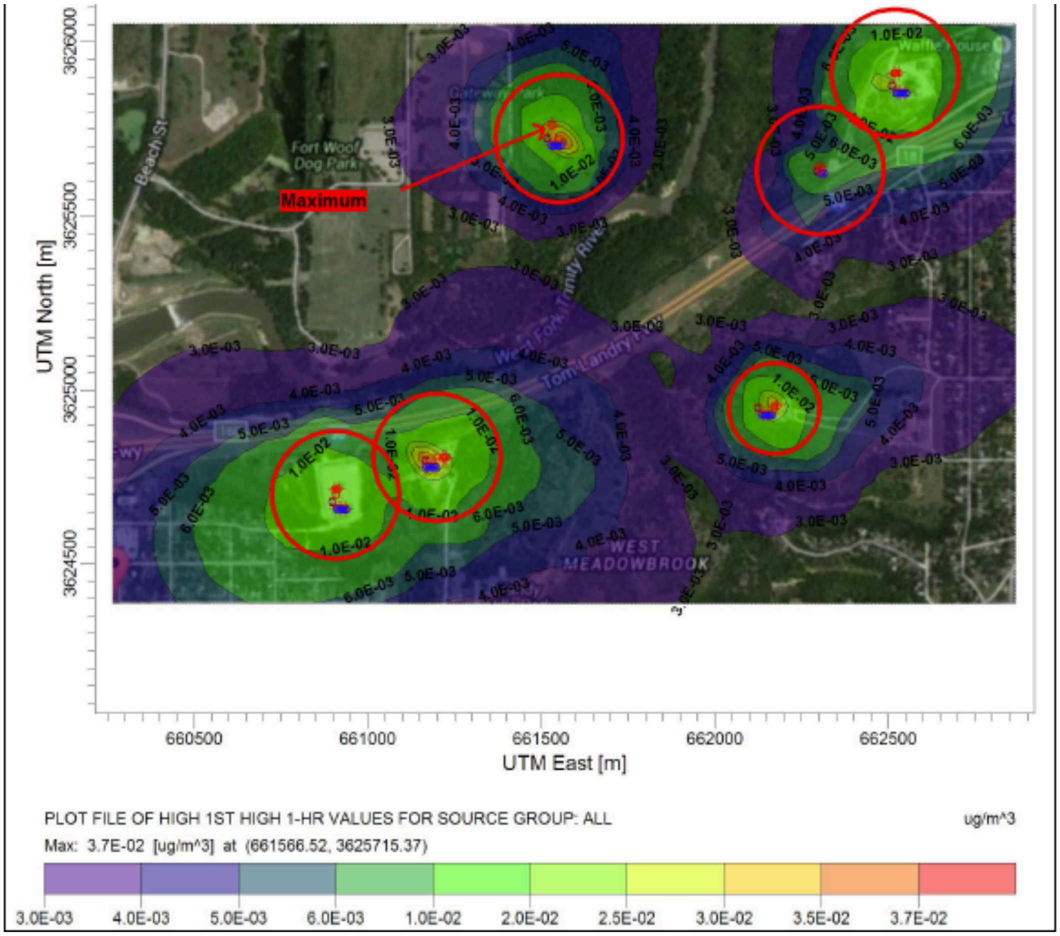
9- Flat terrain and high NOx emissions (hourly):



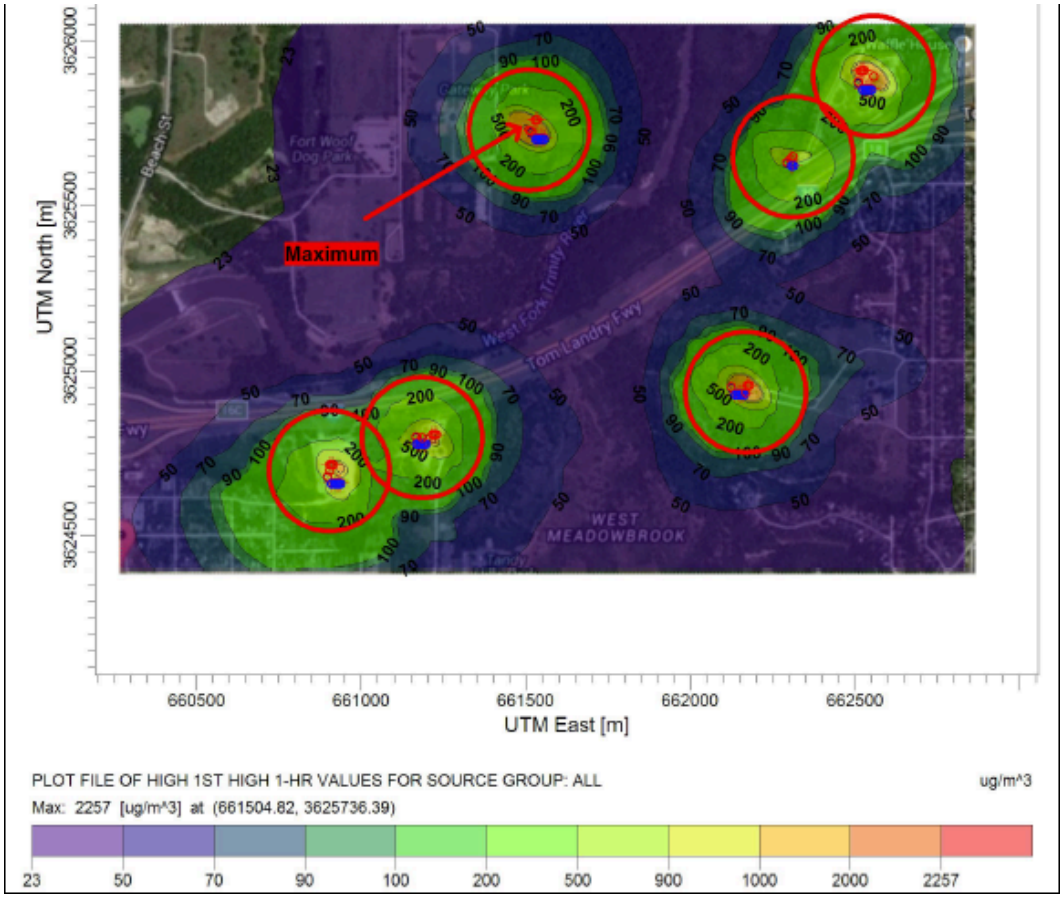
10- Flat terrain and high PM emissions (hourly):



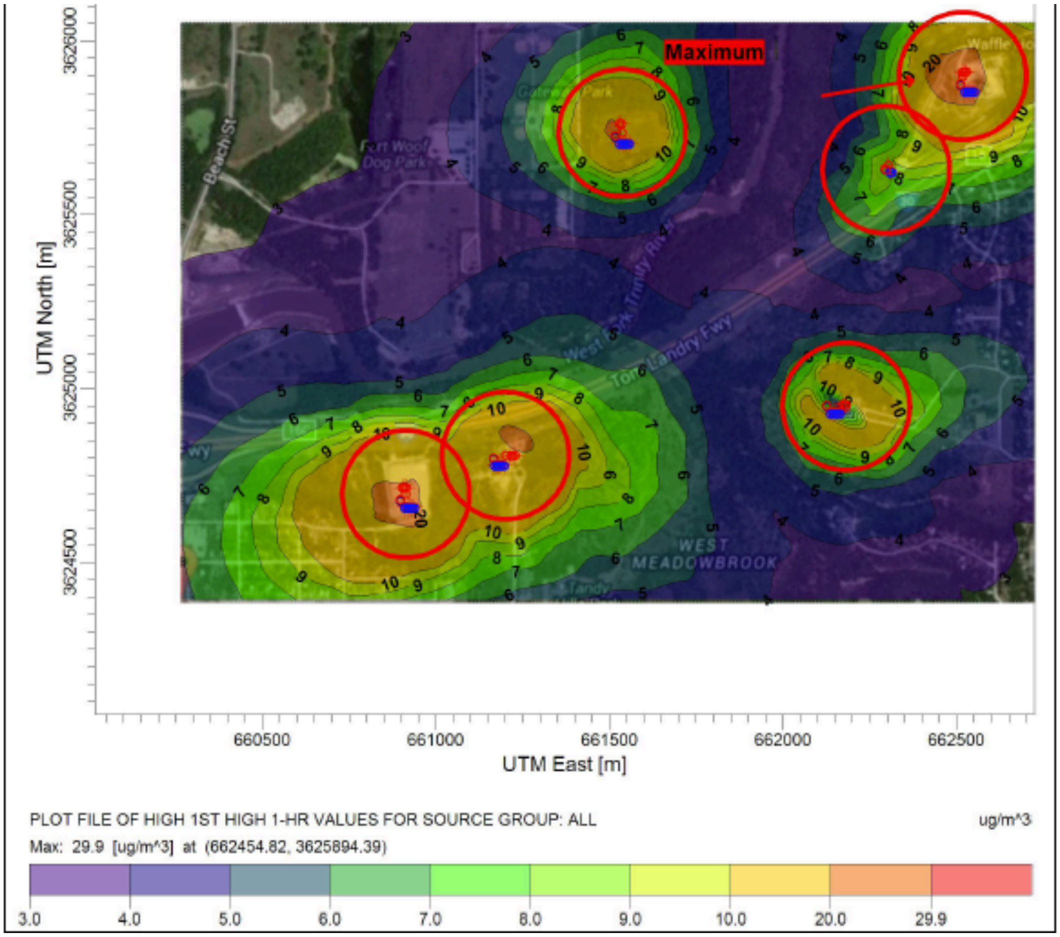
11- inclined terrain and low benzene emission (hourly):



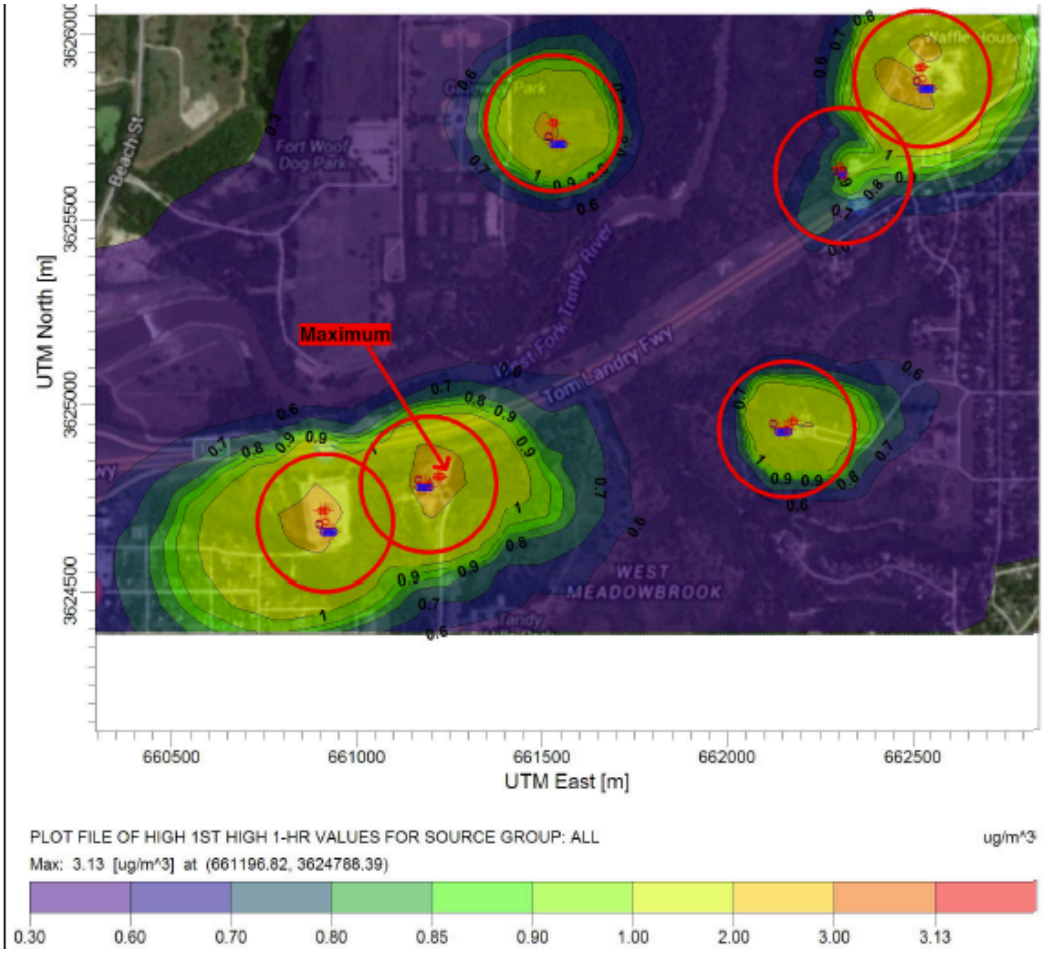
12- inclined terrain and low CH_4 emission (hourly):



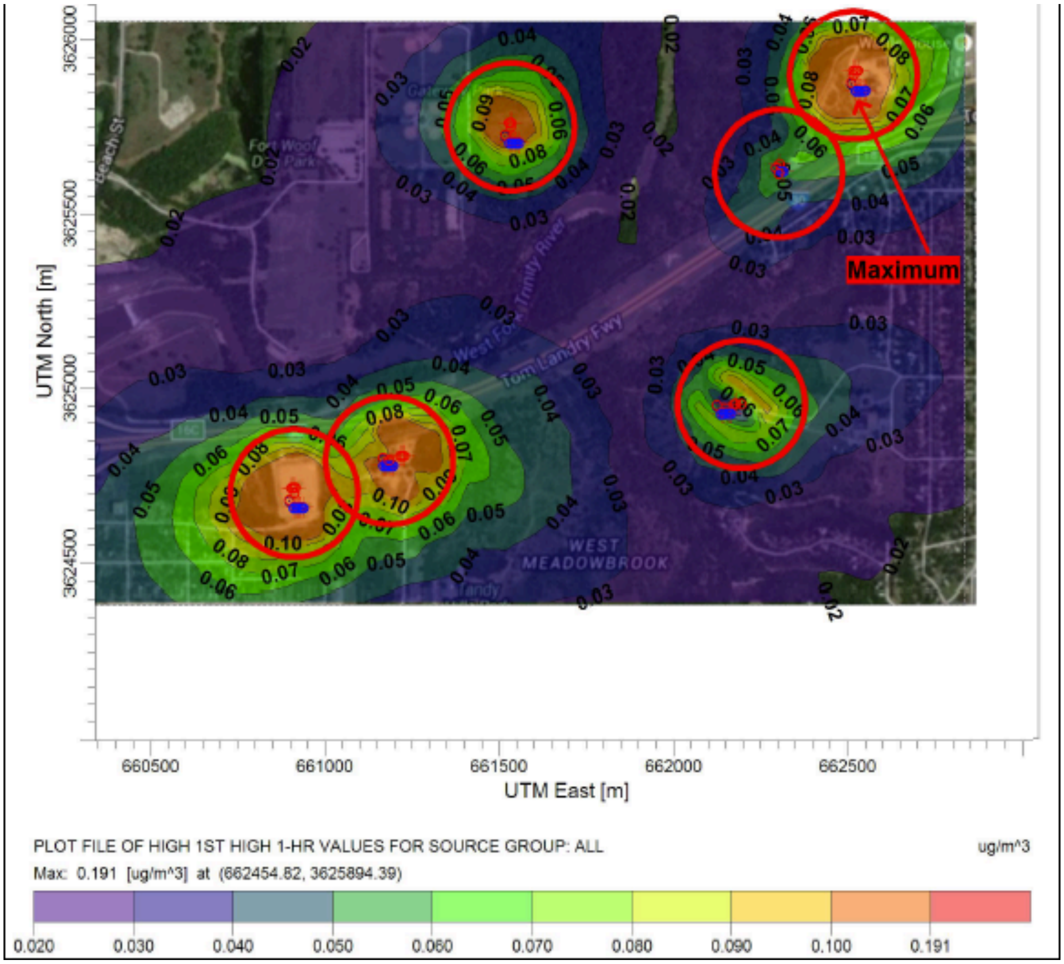
13- Inclined terrain and low CO emission (hourly):



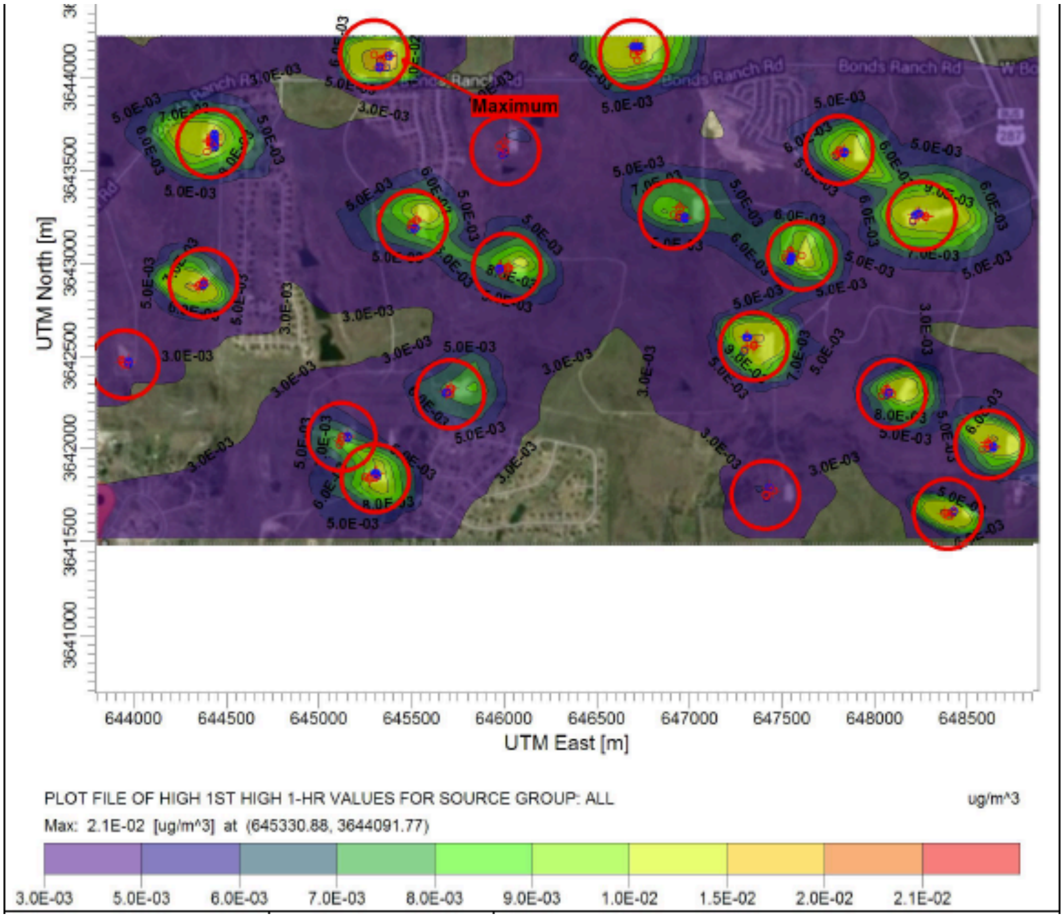
14- Inclined terrain and low NOx emission (hourly):



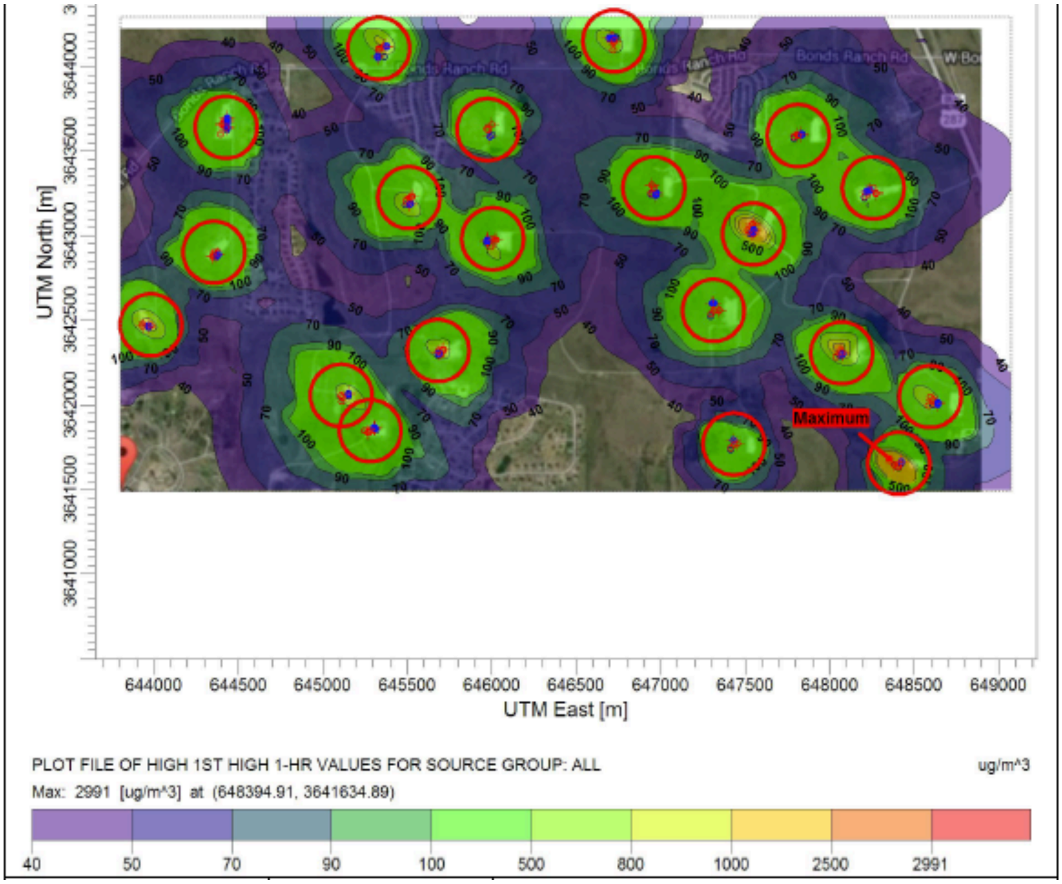
15- inclined terrain and low PM emission (hourly):



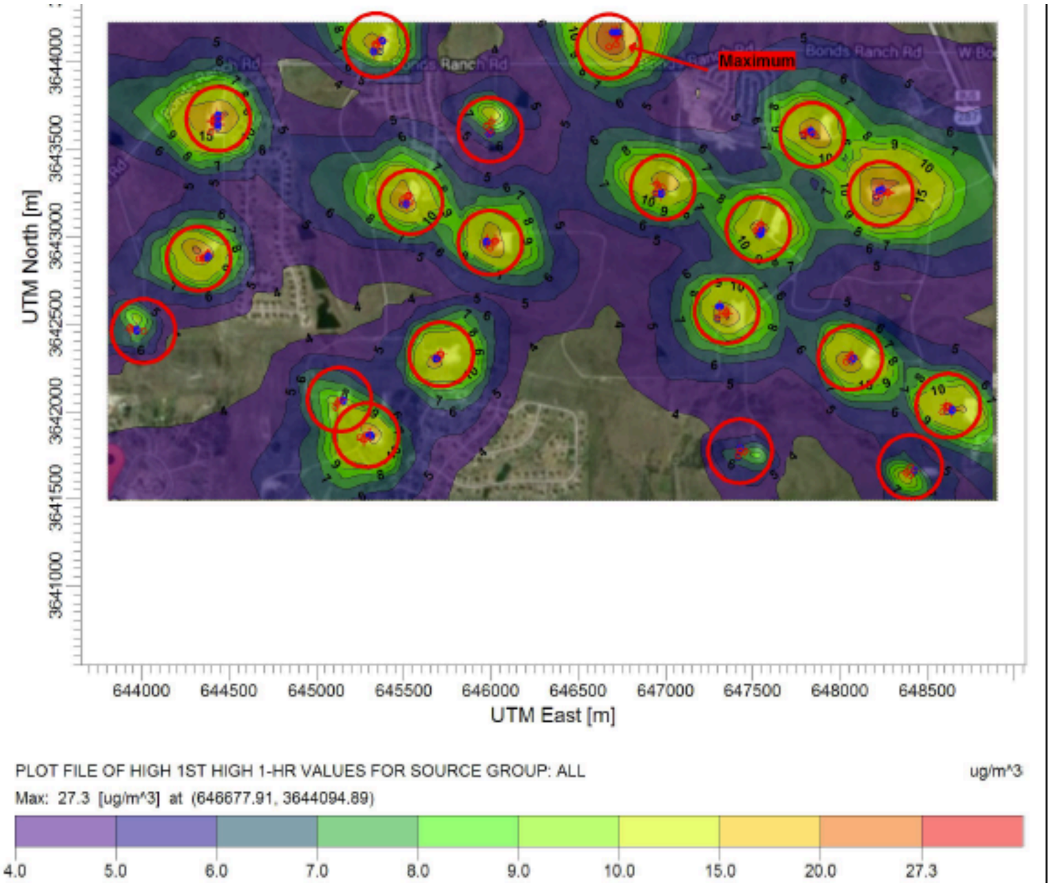
16- Moderate terrain and low benzene emission (hourly):



17- Moderate terrain and low CH_4 emission (hourly):



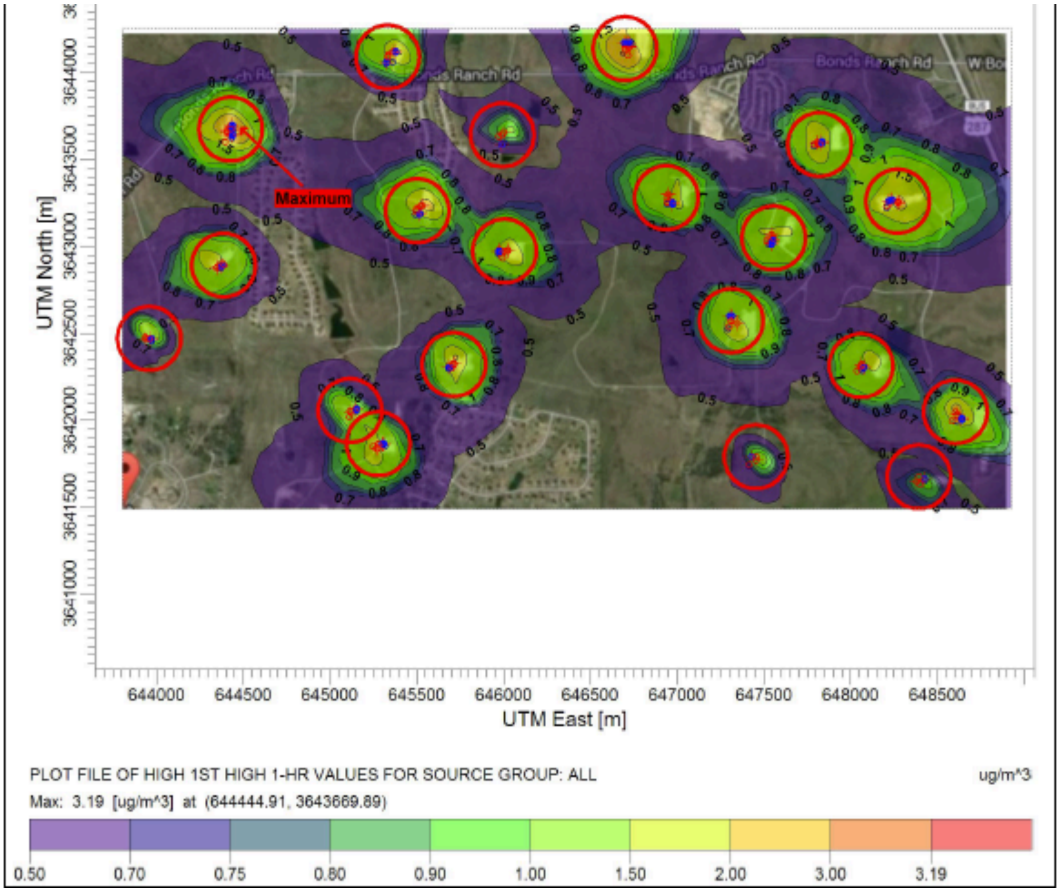
18- Moderate terrain and low CO emission (hourly):



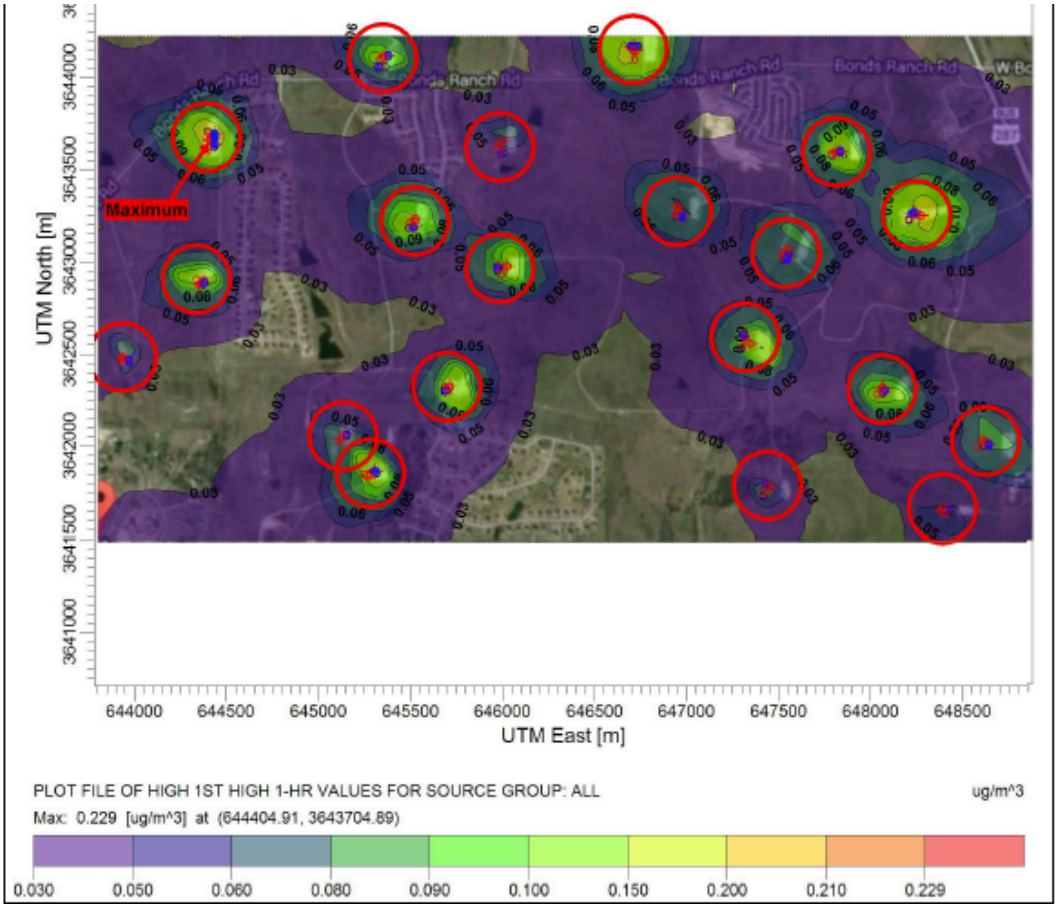
PLOT FILE OF HIGH 1ST HIGH 1-HR VALUES FOR SOURCE GROUP: ALL

Max: 27.3 [ug/m^3] at (646677.91, 3644094.89)

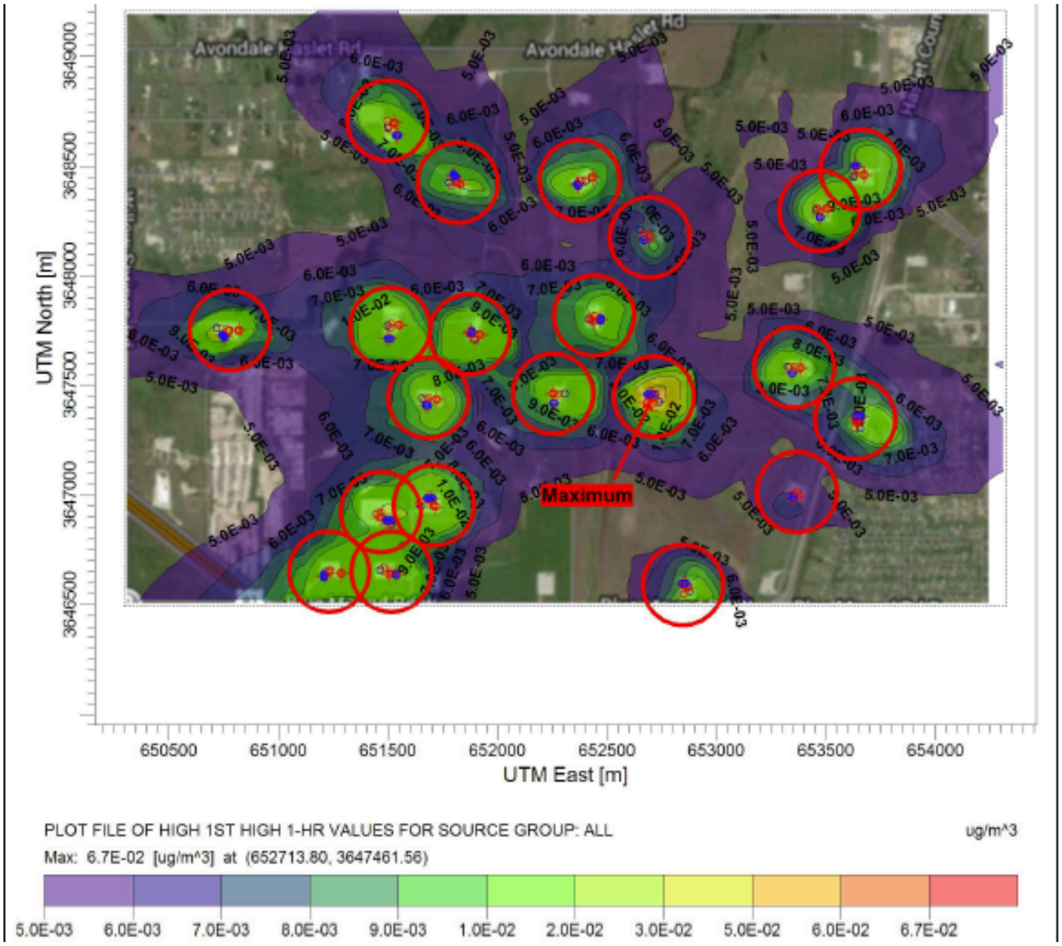
19- Moderate terrain and low NOx emission (hourly):



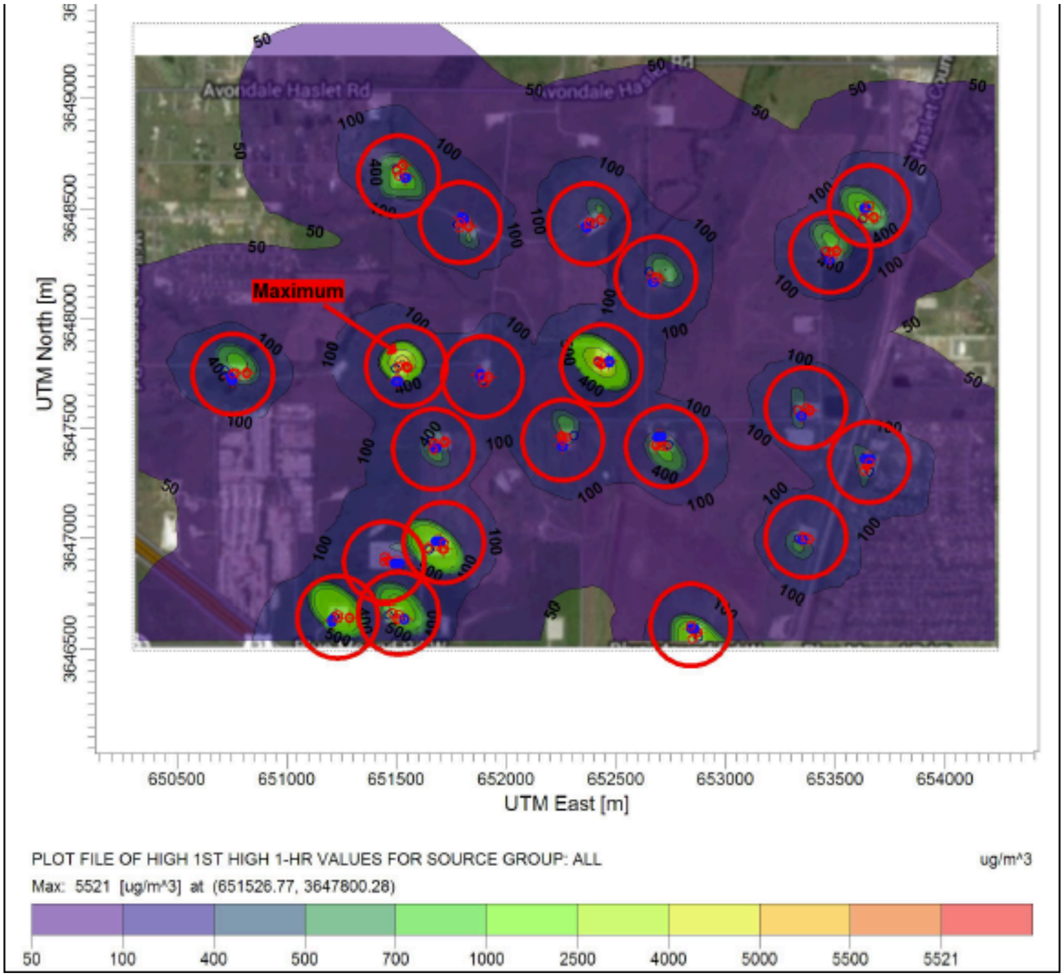
20- Moderate terrain and low PM emission (hourly):



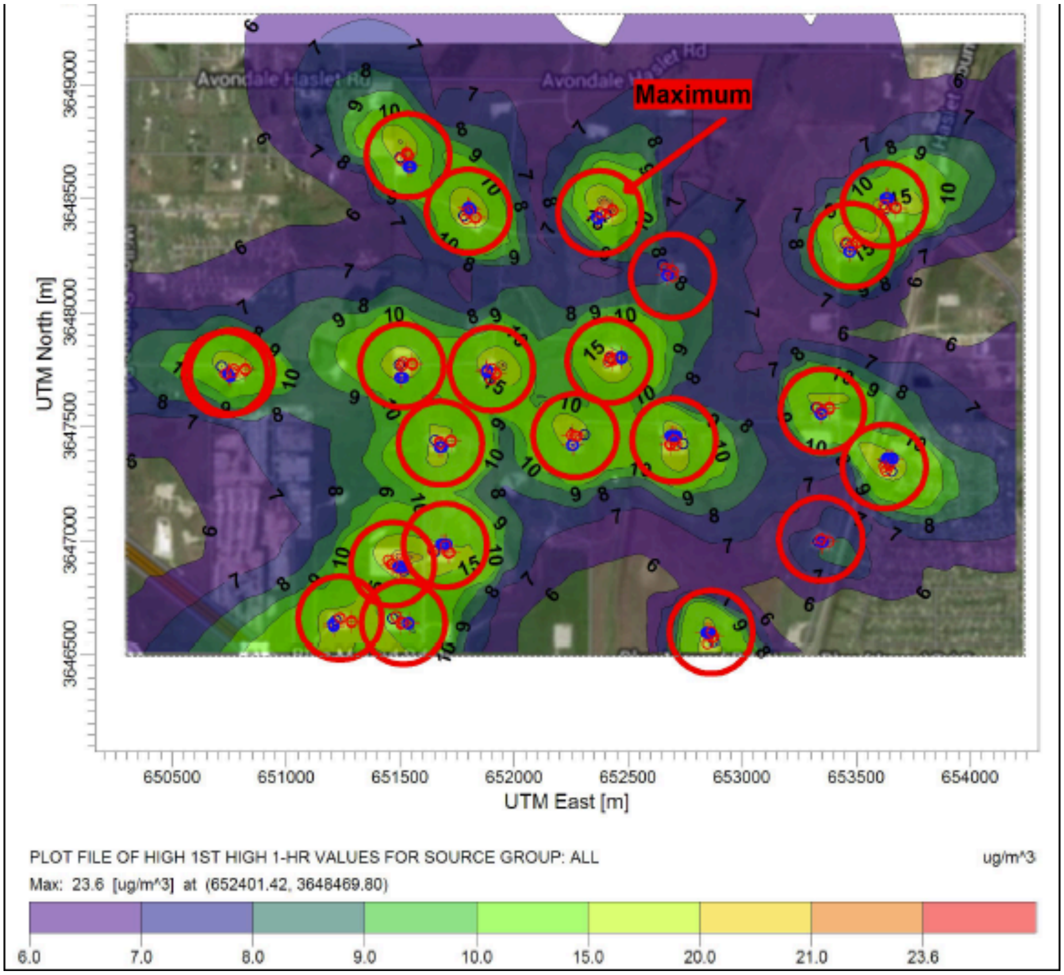
21- Flat terrain and low benzene emission (hourly):



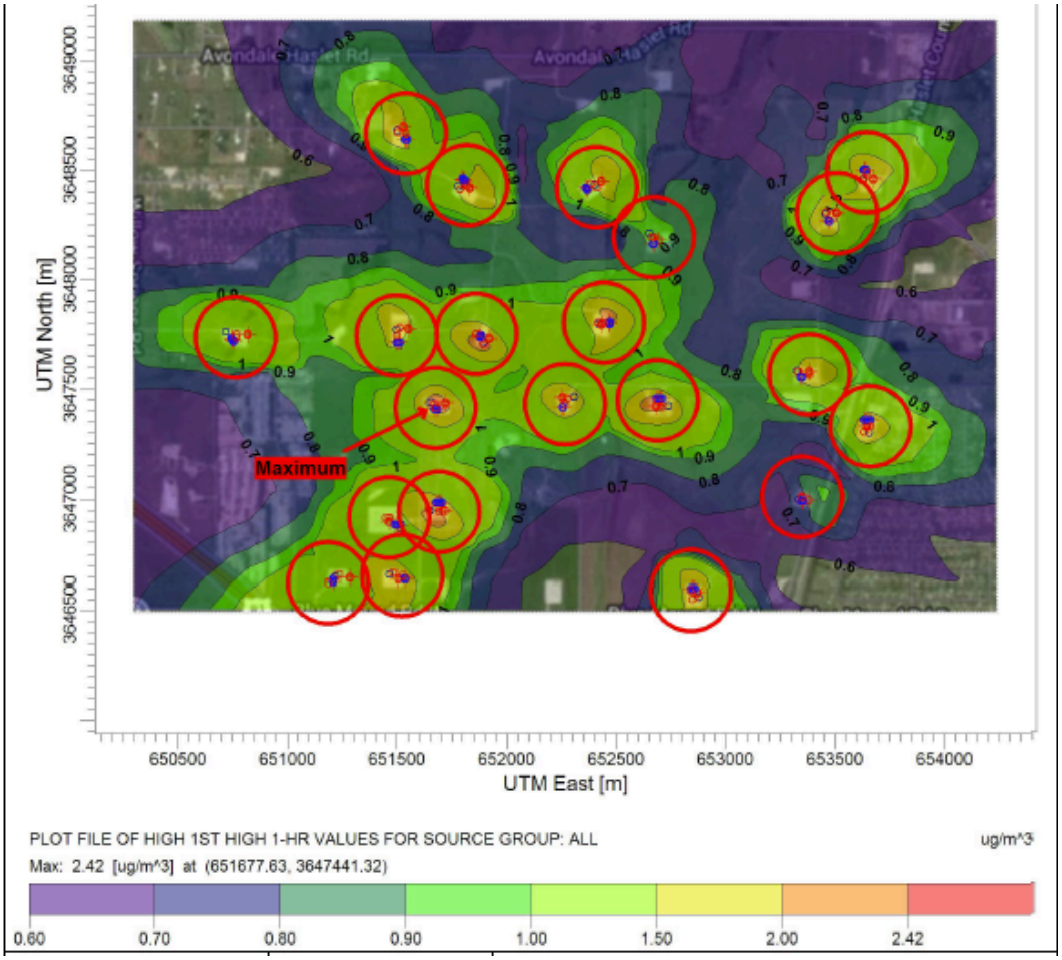
22- Flat terrain and low CH_4 emission (hourly):



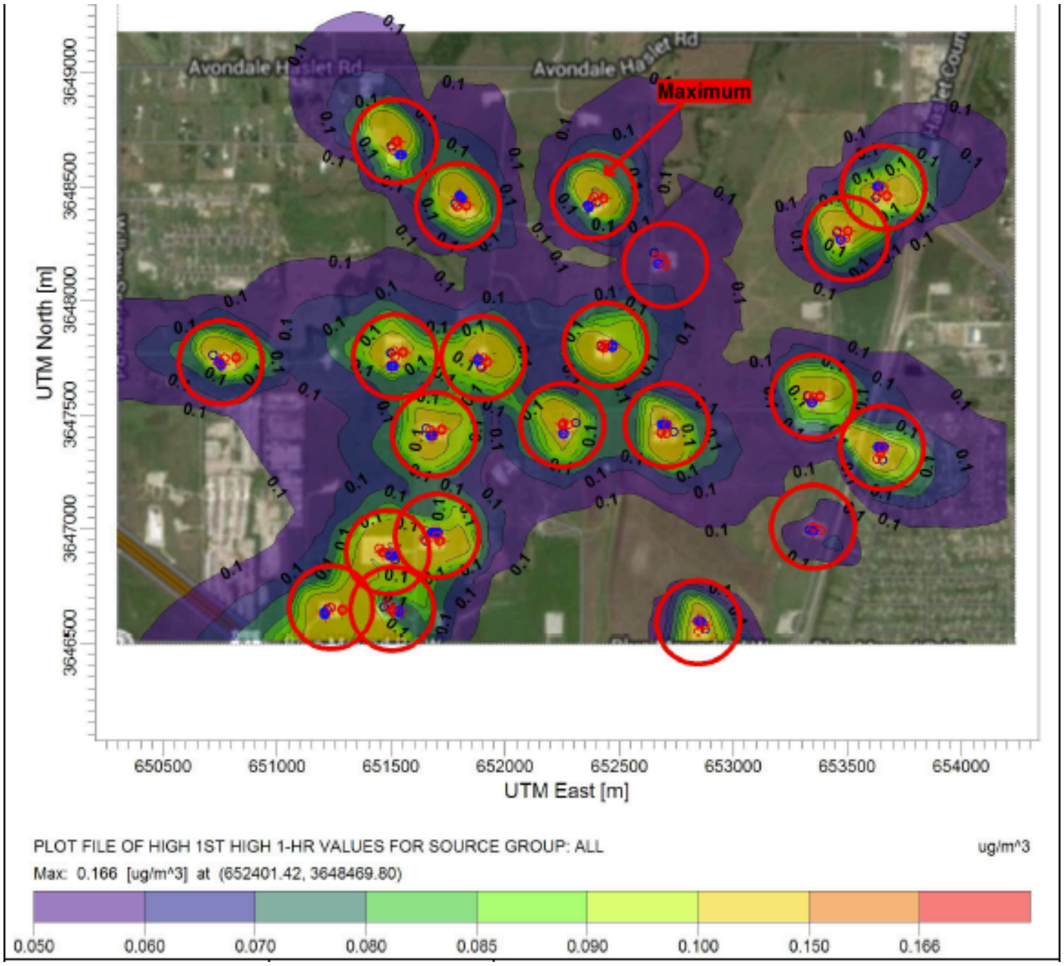
23- Flat terrain and low CO emission (hourly):



24- Flat terrain and low NOx emission (hourly):



25- Flat terrain and low PM emission (hourly):



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