

**UCGE Reports
Number 20352**

Department of Geomatics Engineering

**Estimating Intake Fraction by loose-coupling an air
dispersion model and a geospatial information system
(GIS)**

(URL: <http://www.geomatics.ucalgary.ca/graduatetheses>)

by

Scott Fraser

Date

May 8, 2012



UNIVERSITY OF CALGARY

Estimating Intake Fraction by loose-coupling an air dispersion model and a geospatial
information system (GIS)

by

Scott Fraser

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

DEPARTMENT OF GEOMATICS ENGINEERING

CALGARY, ALBERTA

AUGUST, 2011

© Scott Fraser 2011

Abstract

This thesis describes an air quality decision support system that integrates the CALPUFF air dispersion model with the ArcGIS Geospatial Information System (GIS) through a loose-coupling technique. This system uses simple receptor level exposure modeling and outputs from CALPUFF to estimate the relative impacts on human populations from multiple air pollution sources by calculating Intake Fractions (iF), defined as the fraction of pollutant emitted by a pollution source that is inhaled by a population. The relative Intake Fraction contribution from each point pollution source is calculated and the sources are ranked from the highest Intake Fraction contribution to the lowest. This system is unique when compared to existing systems because it focuses on screening options by estimating relative pollutant exposure contributions for individual sources. The capabilities of the system were demonstrated using meteorological and emission data in central Alberta.

Table of Contents

Abstract.....	iii
Table of Contents.....	iv
List of Figures	vi
List of Tables	ix
List of Symbols and Abbreviations.....	x
Chapter 1: Introduction	1
1.1 Pollution Exposure Modeling.....	3
1.1.1 Proximity Models.....	3
1.1.2 Hybrid Models.....	4
1.1.3 Human Inhalation Models	4
1.1.4 Biomarkers.....	5
1.1.5 Air Dispersion Models.....	5
1.1.5.1 Geospatial Information Systems (GIS)	7
1.1.5.2 Loose-Coupling an Air Dispersion Model and a GIS.....	8
1.1.5.3 Intake Fraction.....	10
1.2 Air Quality Decision Support Systems.....	12
1.3 Objective	17
1.4 Organization of the Thesis	19
Chapter 2: Methodology.....	20
2.1 Study area	20
2.2 CALPUFF	21

2.3 Datasets	23
2.4 ArcGIS.....	28
2.5 Loose-Coupling CALPUFF with ArcGIS	28
2.5.1 Import Tool.....	29
2.5.2 Analyze Tool	30
2.5.3 Report Tool.....	32
Chapter 3: Results.....	34
3.1 Cumulative Intake Fraction.....	34
3.1.1 Cumulative Maximum and Average Ground Level PM2.5 Concentrations	35
3.1.2 Average Cumulative PM2.5 Intake Fraction for Total Population	39
3.2 Contributing Source Intake Fraction.....	42
3.2.1 Individual Contributing Source Average Ground Level PM2.5 Concentrations	43
3.2.2 Contributing Source PM2.5 Intake Fraction for Total Population	55
3.2.3 Contributing Source PM2.5 Intake Fraction Contributions for Total Population	67
3.3 Contributing Source Intake Fraction for Sub-Populations.....	70
3.3.1 Contributing Source PM2.5 Intake Fraction for Children and Seniors.....	71
3.3.2 Contributing Source PM2.5 Intake Fraction Contributions for Children and Seniors	93
Chapter 4: Conclusion.....	98
References	101

List of Figures

Figure 1.1 Comparison of a Puff Model and a Plume Model in Steady and Non-Steady State Scenarios.....	6
Figure 1.2: Definition of GIS (Macguire, 1991)	7
Figure 1.3 AirQUIS Cycle Diagram.....	14
Figure 2.1 Study Area.....	21
Figure 2.2 Air Quality Decision Support Toolbar	29
Figure 2.3 Import Tool Flow Chart	30
Figure 2.4 Loose-Coupling Implementation Process	33
Figure 3.1.1 Import Tool - User Dialog (Cumulative Intake Fraction Configuration)	36
Figure 3.1.2 Import Tool – PM2.5 Emission Source Locations	36
Figure 3.1.3 Import Tool – Cumulative Maximum PM2.5 Concentration	37
Figure 3.1.4 Import Tool – Cumulative Average PM2.5 Concentration	38
Figure 3.1.5 Analyze Tool - User Dialog (Cumulative Intake Fraction Configuration)	40
Figure 3.1.6 Analyze Tool –Cumulative Average PM2.5 Intake Fraction for Total Population.....	41
Figure 3.2.1 Import Tool - User Dialog (Total Contributing Source Intake Fraction Configuration).....	44
Figure 3.2.2 Import Tool – Average PM2.5 Concentration from Point Source P1	45

Figure 3.2.3 Import Tool – Average PM2.5 Concentration from Point Source P2	46
Figure 3.2.4 Import Tool – Average PM2.5 Concentration from Point Source P3	47
Figure 3.2.5 Import Tool – Average PM2.5 Concentration from Point Source P4	48
Figure 3.2.6 Import Tool – Average PM2.5 Concentration from Point Source P5	49
Figure 3.2.7 Import Tool – Average PM2.5 Concentration from Point Source P6	50
Figure 3.2.8 Import Tool – Average PM2.5 Concentration from Point Source P7	51
Figure 3.2.9 Import Tool – Average PM2.5 Concentration from Point Source P8	52
Figure 3.2.10 Import Tool – Average PM2.5 Concentration from Point Source P9	53
Figure 3.2.11 Analyze Tool - User Dialog (Total Population Contributing Source Intake Fraction Configuration).....	56
Figure 3.2.12 Analyze Tool – P1 Total Population Average Intake Fraction.....	57
Figure 3.2.13 Analyze Tool – P2 Total Population Average Intake Fraction.....	58
Figure 3.2.14 Analyze Tool – P3 Total Population Average Intake Fraction.....	59
Figure 3.2.15 Analyze Tool – P4 Total Population Average Intake Fraction.....	60
Figure 3.2.16 Analyze Tool – P5 Total Population Average Intake Fraction.....	61
Figure 3.2.17 Analyze Tool – P6 Total Population Average Intake Fraction.....	62
Figure 3.2.18 Analyze Tool – P7 Total Population Average Intake Fraction.....	63
Figure 3.2.19 Analyze Tool – P8 Total Population Average Intake Fraction.....	64

Figure 3.2.20 Analyze Tool – P9 Total Population Average Intake Fraction.....	65
Figure 3.2.21 Report Tool – User Dialog (Total Population Contributing Source Intake Fraction Configuration).....	68
Figure 3.2.22 Report Tool – Point Sources Ranked based on Intake Fraction Contribution for Total Population	68
Figure 3.3.1 Analyze Tool - User Dialog (Children Contributing Source Intake Fraction Configuration).....	72
Figure 3.3.2 Analyze Tool - User Dialog (Seniors Contributing Source Intake Fraction Configuration)	73
Figure 3.3.3 Analyze Tool – P1 Children Population Average Intake Fraction	74
Figure 3.3.4 Analyze Tool – P1 Seniors Population Average Intake Fraction	75
Figure 3.3.5 Analyze Tool – P2 Children Population Average Intake Fraction	76
Figure 3.3.6 Analyze Tool – P2 Seniors Population Average Intake Fraction	77
Figure 3.3.7 Analyze Tool – P3 Children Population Average Intake Fraction	78
Figure 3.3.8 Analyze Tool – P3 Seniors Population Average Intake Fraction	79
Figure 3.3.9 Analyze Tool – P4 Children Population Average Intake Fraction	80
Figure 3.3.10 Analyze Tool – P4 Seniors Population Average Intake Fraction	81
Figure 3.3.11 Analyze Tool – P5 Children Population Average Intake Fraction	82
Figure 3.3.12 Analyze Tool – P5 Seniors Population Average Intake Fraction	83

Figure 3.3.13 Analyze Tool – P6 Children Population Average Intake Fraction	84
Figure 3.3.14 Analyze Tool – P6 Seniors Population Average Intake Fraction	85
Figure 3.3.15 Analyze Tool – P7 Children Population Average Intake Fraction	86
Figure 3.3.16 Analyze Tool – P7 Seniors Population Average Intake Fraction	87
Figure 3.3.17 Analyze Tool – P8 Children Population Average Intake Fraction	88
Figure 3.3.18 Analyze Tool – P8 Seniors Population Average Intake Fraction	89
Figure 3.3.19 Analyze Tool – P9 Children Population Average Intake Fraction	90
Figure 3.3.20 Analyze Tool – P9 Seniors Population Average Intake Fraction	91
Figure 3.3.21 Report Tool – User Dialog (Children Contributing Source Intake Fraction Configuration)	94
Figure 3.3.22 Report Tool – User Dialog (Senior Contributing Source Intake Fraction Configuration)	94
Figure 3.3.23 Report Tool – Point Sources Ranked on Intake Fraction Contribution to Children	95
Figure 3.3.24 Report Tool – Point Sources Ranked on Intake Fraction Contribution to Seniors	96

List of Tables

Table 2.1 Description of the data used in the study.....	24
Table 3.2.1 Highest Average Ground Level Pollutant Concentration.....	54
Table 3.2.2 Point Source Intake Fraction Contributions to Total Population.....	69
Table 3.3.1 Average PM _{2.5} Intake Fraction Contributions for Children and Seniors	93
Table 3.3.2 Point Source Intake Fraction Contributions to Children.....	95
Table 3.3.3 Point Source Intake Fraction Contributions to Seniors.....	96

List of Symbols and Abbreviations

iF.....Intake Fraction

DA.....Dissemination Area

GIS.....Geospatial Information System

AAAQO.....Alberta Ambient Air Quality Objectives

P.....Population

C.....Ground Level Pollutant Concentration

Q.....Emission

Chapter 1: Introduction

Air quality policy is an important societal consideration because proper air pollution regulation is critical to the well being of a population. Alberta Environment has expressed a commitment to air quality beyond ensuring that emissions are in compliance with the maximum acceptable levels defined in the Alberta Ambient Air Quality Objectives (AAAQO). This is apparent in the primary goal of the Government of Alberta's current Clean Air Strategy (1991), which is to "Implement a comprehensive air quality management system in Alberta that allows for identification of problems, prioritization of issues, allocation of resources, development of action plans and is based on full multi-stakeholder involvement." The document goes on to explain that "the identification and definition of air quality issues or problems should: describe emission types, amounts, and dispersion characteristics; assess or predict effects of emissions; and assess the probability and significance of the effects of emissions on health, socio-economics and the biophysical environment." The report also acknowledges that "criteria should include: human health effects, biophysical impacts, economic impacts, urgency, and regulatory compliance." Interpretation of these statements leads to the conclusion that the Government of Alberta is committed to the implementation of an air quality decision making process that optimizes air quality in terms of several criteria, not just compliance with AAAQO.

Presently, Alberta Environment continues to ensure compliance with AAAQO through extensive ambient air quality monitoring and mandatory industry submissions, including continuous emission reports and standardized air dispersion modeling results. If the AAAQO are exceeded, an air quality management plan is developed for the area. The development of these plans is a complex decision making process and the intended result of their implementation is to reduce emissions in such a way that AAAQO are no longer exceeded. This pass/fail approach gives a finite weight to the negative human health effects that can result from air pollution. No consideration is given to human health effects that occur in areas where AAAQO are not exceeded. This deficiency must be addressed if Alberta Environment intends to achieve its goal of assessing the probability and significance of the effects of air pollution emissions on human health.

Recently, air quality policy makers with goals similar to those expressed in the Government of Alberta's Clean Air Strategy have turned to technology, and more specifically air quality decision support systems, to support their decision-making process. These systems typically specialize in estimating probabilities and significance of human health effects as a result of air pollution emissions, called pollution exposure modeling.

1.1 Pollution Exposure Modeling

The World Health Organization (WHO) (2000) defines exposure modeling as a “logical or empirical construct which allows estimation of individual or population exposure parameters from available input data”. The first studies examining the association between human health and air pollution were undertaken as early as the 1950s. Since then numerous air pollution exposure studies have been completed using several distinct categories of methods. A review of these studies is provided by Zou et al. (2009). This review outlines and critically evaluates the five categories of exposure methods, briefly describes past studies that used each method, and provides suggestions for future research.

1.1.1 Proximity Models

Proximity modeling is the simplest approach to pollution exposure. As the name suggests, pollution exposure is based solely on the receptor’s proximity to the pollution source. Orr et al. (2002) successfully used proximity modeling to suggest an increased risk of chromosomal anomalies in offspring of women who lived near hazardous waste sites. This method can be conducted using a GIS alone (Nuckols et al., 2004). The simplicity of this method is enticing, but the lack of consideration for parameters influencing the dispersion process of the pollutants trivializes the results (Zou et al. 2009).

1.1.2 Hybrid Models

Hybrid models typically integrate two or more models and/or monitoring data in an effort to combine their strengths (Zou et al. 2009). Isakov et al. (2009) used a hybrid model that combined a regional-scale air quality model (CMAQ), a local-scale air quality model (AERMOD) with two exposure models (HAPEM and SHEDS) to provide detailed estimates of human pollution exposure. However, key limitations such as the difficulty of integrating multiple dispersion and exposure models at varying scales and the unavailability of detailed personal and regional monitoring data make this method ambitious, but impractical (Zou et al, 2009).

1.1.3 Human Inhalation Models

These models quantify chemical inhalation from contact with air pollutants. They require parameters describing human interaction with air pollution and chemical and environmental conditions. These models attempt to link adverse health outcomes and air pollution. Burke et al. (2001) developed the Stochastic Human Exposure and Dose Simulation (SHEDS) and used it to simulate daily average particulate matter exposures indoors, outdoors, and in vehicles. This model focused on estimating the contribution of the ambient concentration in each microenvironment to the average daily exposure based on human activity. An important limitation with the human inhalation method is that it requires human time-activity measurements, which are difficult or impossible to obtain (Zou et al. 2009).

1.1.4 Biomarkers

Biomarkers can be described as indicators of interaction between an environment agent (pollution) and a biological organism (human). In the case of interaction with air pollution, the biomarkers are the inherent response ability of the person (susceptibility) and the negative health effects that result. Fanou et al. (2006) used the urinal excretion of benzene as a biomarker to demonstrate a higher benzene exposure in cities compared to rural areas. This approach could be considered the reverse of the other methods. The principle is that if a population can be studied to determine a specific response to air pollution while considering susceptibility, exposure can be estimated (Zou et al. 2009).

1.1.5 Air Dispersion Models

Air dispersion models generally produce estimates of ground level pollutant concentrations by incorporating emission and meteorological data with numerical processing. Lopez et al. (2005) used the CALPUFF air dispersion model to estimate health impacts from power plant emissions in Mexico. This method is rapidly gaining popularity and promises to be influential in the improvement of human intake models (Zou et al. 2009).

The accuracy of the model is dependent on the validity of the formulas used in the numerical processing to approximate dispersion characteristics, as well as the accuracy and spatio-temporal resolution of the emission and meteorological data. Improvements

in computing power and dispersion theory have resulted in an increase in the sophistication of these numerical methods. For example, relatively simple Gaussian plume air dispersion models that can only simulate steady state conditions are being replaced by more complex Gaussian puff air dispersion models that are capable of modeling steady and non-steady state conditions. This is illustrated in Figure 1.1. The top scenario represents a steady state condition, in which the wind speed and direction are constant, and the lower scenario represents a non-steady state condition, in which the wind speed and direction have changed during the model run. In the lower scenario, the puff represents more accurate substance transport modeling than the plume.

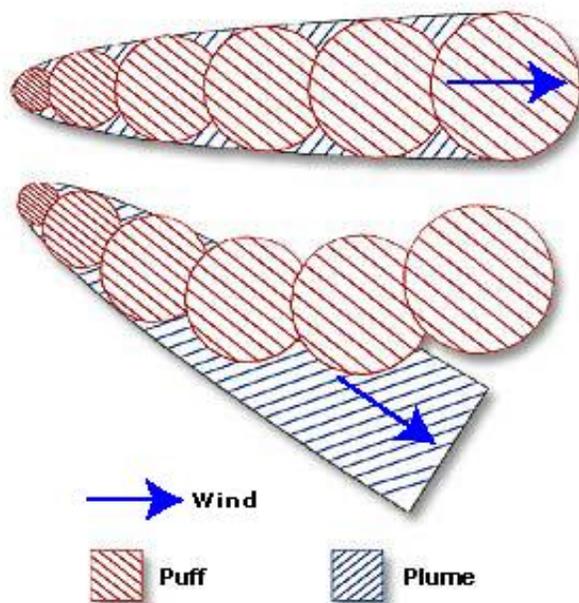


Figure 1.1 Comparison of a Puff Model and a Plume Model in Steady and Non-Steady State Scenarios

Air dispersion models produce ground level pollutant concentrations that can be integrated within a Geospatial Information System (GIS) to reflect individual exposure by combining air pollution concentration data with residence location.

1.1.5.1 Geospatial Information Systems (GIS)

GIS have become the most common tool for analyzing spatial data. They are commonly defined as geographically oriented computer systems (Macguire, 1991), but they are much more powerful than this definition implies. GIS represent a relationship between computer cartography, database management, computer aided design, and remote sensing, as illustrated in Figure 1.2. This relationship allows for powerful analytical capabilities including spatial relation of data and intuitive data visualizations.

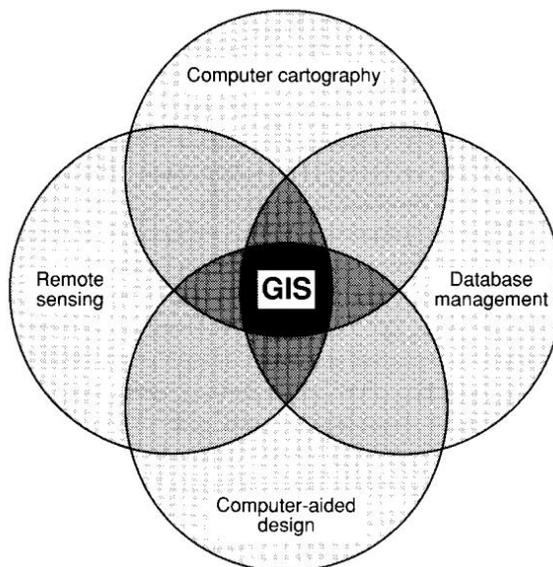


Figure 1.2: Definition of GIS (Macguire, 1991)

Since the results from air dispersion models are spatial, they lend themselves very well to GIS. As a result, many air dispersion models include a rudimentary GIS in their software. These are useful for viewing wind vector fields, terrain, and air pollution concentration distributions. However, these simple GIS interfaces do not allow users to overlay external data (such as population density) for analysis or perform even mildly complex spatial calculations. More usefully, some air dispersion models facilitate the conversion of their output to data formats readily accepted by popular GIS platforms. Integrating GIS with air dispersion models have made it possible to reflect individual exposure to air pollutants more accurately by combining residence location with air pollution concentration data (Zou et al., 2009). This technique, called loose-coupling, is now commonly used for detailed air quality analysis.

1.1.5.2 Loose-Coupling an Air Dispersion Model and a GIS

Loose-coupling describes any mechanism used to integrate two systems that were designed separately (Maantay et al., 2009). The mechanism itself can range from an action as simple as manually converting the outputs from one system into a data format that can be input into the other system, to as complex as a custom-developed software that incorporates both of the systems as modules.

The most common loose-coupling technique employed in air quality decision support is to use a complex air dispersion model (such as CALPUFF) to estimate spatially explicit ground level pollutant concentration distributions, import them into a GIS (such as

ArcMap), and overlay them with population distributions to estimate population exposure.

An application of this technique is provided by Maantay et al. (2009) to study air pollution and asthma in the Bronx, New York City. This study focused on the spatial coincidence between outdoor air pollution and asthma hospitalization rates. These authors loose-coupled two systems: an air dispersion model (AERMOD) and a GIS (ArcGIS). Spatial data were preprocessed in ArcGIS and converted into formats required by AERMOD, then imported into AERMOD. AERMOD was then run and the outputs were converted to GIS for postprocessing and analysis (Maantay et al. 2009).

More recently, Zhou et al. (2009) also integrated AERMOD with ArcGIS. This study aimed at identifying the population exposure contribution from different pollution source types (namely vehicle and industrial). Though not mentioned explicitly, a loose-coupling approach was used. The outputs from AERMOD were converted and imported into ArcGIS where they were interpolated and overlaid with population density. ArcGIS was then used to estimate the population exposure before estimating the source type contribution.

Elbir (2004) loosely-coupled CALPUFF and ArcGIS, if only to a limited degree, to accurately model the air pollution concentrations in the city of Izmir, Turkey. The results were converted and displayed in ArcMap where pollution concentrations were

compared with air quality standards, visually inspected, and separated into source type contributions.

A major limitation with this type of loose-coupling technique is its lack of scalability, both spatially and temporally. Any air quality study conducted using this technique is limited to a small area and/or a short run time simply because it would require an unreasonable amount of time and effort otherwise. This technique is also not scalable in terms of data availability. The general assumption is made that complete datasets are available. If this is not true, and it seldom is, the resulting pollution exposure estimates will be inaccurate. A relative exposure estimate, such as Intake Fraction, can provide the most meaningful results from these types of datasets.

1.1.5.3 Intake Fraction

Originally, air dispersion models were designed for regulation purposes and this is still their primary use. When run for these purposes, the outputs from these models are ground level pollutant concentrations that are compared with acceptable concentrations, which are determined somewhat arbitrarily by air quality regulators. Generally, acceptable air quality standards are a compromise between health and economy. Even if all air quality standards were met, there will still be negative human health impacts from air pollution. A more useful system would enable modelers to rank air pollution sources based on their estimated danger to the public. A useful measure for this ranking is the fraction of the mass released into the environment from a

particular pollution source that is absorbed by the population, or Intake Fraction (iF) (Bennett et al., 2002).

In their study to estimate population exposure to power plant emissions in Beijing using CALPUFF, Zhou et al. (2002) used Intake Fraction to overcome a lack of data in their study area. According to the authors “the main advantage of Intake Fraction is in its ability to model limited sources (where data are available) and extrapolate to other sources”. Basically, there was not enough emission data available in their study area to model pollutant concentrations without drastic underestimation. Using Intake Fraction, this study was able to provide meaningful recommendations despite a lack of data. This is an example of the flexibility of Intake Fraction as an exposure measure.

Around the same time, Li and Hao (2003) conducted a similar study in which they used Intake Fraction to assess population exposure to air pollution in Hunan province of China. They also used a regression analysis to explore the relationships between Intake Fractions and emission and receptor variables. They discovered that the Intake Fraction was related to the stack height and aggregate populations. Though these discoveries cannot be assumed to be universal, they illustrate the versatility of Intake Fraction as a measure of pollution exposure.

More recently, Carella and Mudu (2009) completed a study to critically evaluate Intake Fraction as an exposure measure. The authors confirmed the advantages of using Intake Fraction when working with limited data and for quick calculation and use. The

study also indicated that Intake Fraction is a consistent measure of exposure. The major disadvantage was described as the difficulty of validating measurements of Intake Fraction. The study concludes by suggesting that Intake Fraction is a representative measure of pollution exposure, but could provide a more complete indication of exposure if it was better understood or used as a first step in a more general risk-characterization program.

Rather than relying on complete datasets for accurate results, Intake Fraction gives optimal results for the available data. For instance, if an air dispersion model is used to model ground level concentrations in an area with several air pollution sources and no data are available for one or more of the sources in that area, it would be impossible to accurately model ground level pollutant concentrations. If the Intake Fraction is used instead, meaningful results will be obtained for all of the sources that were included in the modeling. This technique is useful in areas where complete datasets do not exist.

1.2 Air Quality Decision Support Systems

Presently, computer-based decision support systems for air quality are in use by regulators, industry, and government. As described by Elbir (2004) “the basic idea of decision support systems is to improve the decision making process for policy makers by providing a professional tool to assist air quality planning.” Until recently, these decision support systems were concentrated in European nations. Some examples are Austria’s AirWare (2009), Norway’s AirQUIS (2009), and Sweden’s EnviMan (2009).

These systems are all very similar in their design and intended use. They focus on modeling current air quality and, in some cases, forecasting it. Generally, each of these systems have three main purposes: (i) estimating current air quality and comparing the results with air quality standards, (ii) forecasting air quality to provide warnings, and (iii) estimating the results of proposed air quality regulation. Since the success of these systems is dependent on accurately modeling air dispersion, any results are very heavily dependent on the quality and completeness of input data. This means that meaningful results will only be obtained if complete and accurate data are used in the air dispersion model.

These systems suffer from several common weaknesses. They generally apply simple air dispersion models, have low spatial resolutions and they only consider simple exposure (Elgbir, 2004). But more importantly, they are all designed to be operated as part of an air quality decision cycle. This cycle involves a crucial step in which the users view the systems results and come to a decision about an abatement strategy before starting the entire process over again (AirQUIS, 2001). This cycle is illustrated in Figure 1.3.

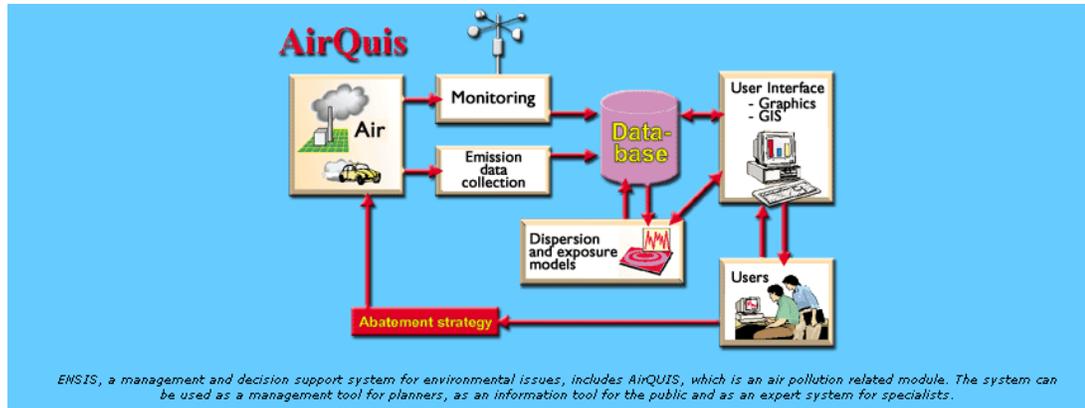


Figure 1.3 AirQUIS Cycle Diagram

More recently, the U.S. Environmental Protection Agency (EPA) has developed an air quality decision support tool, called Benefits Mapping and Analysis Program (BenMAP), which addresses many of the problems experienced by earlier systems (US EPA, 2009). Rather than including a simple air dispersion model, BenMAP allows users to input any gridded air quality data, like ground level concentrations obtained from a sophisticated air dispersion model or air quality data from a monitoring network. The spatial resolution of BenMAP is dependent on the user specifications and can effectively be as fine as the input data. It also allows users to input gridded population and sub-population information, allowing more complex exposure modeling.

The reason the EPA was able to design a tool that did not suffer from limited spatial resolutions and simple air dispersion and exposure modeling is because BenMAP was based on a GIS framework. This allows an unprecedented level of custom analysis. The primary analyses that can be performed include generation of population/community level ambient pollution exposure maps, estimation of health impacts associated to

current air quality levels, estimation of health benefits from improved air quality standards, valuation of health impacts and benefits, and scenario modeling (Fann, 2009).

Although BenMAP is very well suited for the task of evaluating current and proposed air quality conditions, like AirWare, AirQUIS, EnviMan, it functions as a quantitative simulation model, which transforms detailed meteorological and emission observations into estimates of pollution dispersion, population exposure, and even human health impact valuation. In other words, it provides estimates of tangible air quality indicators that can be used to evaluate an input air quality scenario. However, it does not support the entire decision making process.

A decision has two steps: (i) prechoice, defined as screening to determine options, and (ii) choice, defined as selection of the best option (Beach, 1993). Current air quality decision support systems focus on choice, but ignore prechoice. In other words, they focus on evaluating options that have been screened by the user of the tool, but they do not offer any information that can support the screening process. The manner in which the tools do this is by providing only cumulative exposure estimates, rather than individual source exposure contributions, described as the proportion of the total exposure that is due to emissions from an individual source. This results in a system that is useful for evaluating options, but does not aid the user in deciding which options are worth evaluating. To put it simply, this can lead to a decision-maker overlooking a

favorable option or wasting time evaluating several unfavorable options. For example, if an air quality regulator is tasked with reducing pollution exposure of a pollutant released from point emission sources and does not have a clear understanding of the relative exposure contributions of each of these sources, the only logical option would be to reduce emissions from all of the sources equally. An existing air quality decision support system can be used to estimate the results of this option, but it cannot be used to indicate whether it is the best option or even indicate better options. Perhaps there is one particular point emission source that is responsible for the majority of the pollution exposure and regulating or decommissioning this source alone would have better results. This deficiency is easily addressed through the development of a system that focuses on estimating the pollutant exposure contribution from each individual source.

At the time of this paper and to the best of our knowledge there are no air quality decision support systems focusing on estimating the relative exposure contributions of individual air pollution sources. Most air quality decision support systems that are capable of scenario modeling can be leveraged to determine individual air pollution source contributions. However, the procedure for accomplishing this is less than ideal since the system must be run once for each scenario and the results from each run must then be compiled for analysis. This can result in a cyclical process that requires somewhat arbitrary input from the user as seen in the AirQUIS System Cycle in Figure 1.3. This may not seem too inconvenient, but the number of scenarios grows exponentially as pollution sources are added, making this method of contribution

analysis impractical for large areas with numerous air pollution sources. The aim of this thesis is to present an air quality decision support system that addresses this deficiency.

Zou et al. (2009) made several suggestions for future research. Two of these suggestions are directly addressed in this thesis. The first suggestion is to increase the level of integration between exposure models and geographic information technologies (such as GIS). The second suggestion is to consider uncertainty as a critical issue relating to both inaccuracy and inconsistency or variability of monitoring data and model results. Both suggestions are addressed in this thesis by the extensive modification of ArcMap to allow the spatio-temporal analysis of the modeling results generated by CALPUFF and the use of Intake Fraction as a relative pollutant exposure measurement.

1.3 Objective

The main objective of this project is to create an air quality decision support system that could help a regulatory agency such as Alberta Environment in meeting its Clean Air Strategy goals. To overcome the limitations of existing systems, the system must meet three conditions. It must:

- focus on individual air pollution source contributions,
- complement existing scenario-focused decision support systems (such as BenMAP), by supporting option screening, and
- streamline the loose-coupling technique.

The system can be used to help improve overall air quality in Alberta, not just in areas that exceed AAAQO, by identifying the air pollution sources with the highest Intake Fraction contribution. This is done by integrating ground level air pollutant concentrations from CALPUFF with population data using Intake Fraction. These recommendations lead to scenarios that could then be tested using a scenario-focused decision support system (such as BenMAP).

1.4 Organization of the Thesis

The remainder of this thesis is organized as follows. The implementation methods of the air quality decision support system and the procedure for loose-coupling CALPUFF with ArcMap are presented in Chapter 2. Chapter 3 presents a demonstration of the capabilities of the system through example run scenarios. The conclusion and recommendations for future work are presented in Chapter 4.

Chapter 2: Methodology

Achieving the objectives of this project did not endorse the creation of an entirely new air quality decision support system. Instead, it requires a loose-coupling and augmentation of many existing systems and datasets. In this chapter, the details of these systems and datasets are presented, as well as their interactions and the reasons they were selected for use in this project. This is followed by a presentation of the custom software solution that was used for loose-coupling and augmenting them.

2.1 Study area

The study area is a 165 km by 180 km portion of the Parkland Airshed Management Zone (PAMZ) in central Alberta, Canada (Fig. 2). The PAMZ Airshed includes a portion of the Rocky Mountains on its western edge. Due to the unreasonable complexity of modeling air dispersion in mountainous regions with very limited meteorological observations, the study area excludes this portion of the Airshed.

The study area was chosen to illustrate the versatility of the proposed air quality decision support tool. The area includes grassland, deciduous forest, and mixed forest. It also contains both rural and urban areas. Covering approximately 30,000 km², it is also uncharacteristically large when compared to most spatial extents used in air dispersion modeling projects. The total population is 227,280 inhabitants with 67,705 of them residing in Red Deer (the only city in the study area). The majority of the population live in the 18 towns, 14 villages, 4 hamlets, and other rural areas within the study area. The

study area also contains approximately 170 km of the Queen Elizabeth II highway, which is the busiest roadway in Alberta (Government of Alberta Ministry of Transportation, 2009).



Figure 2.1 Study Area

2.2 CALPUFF

CALPUFF is one of the most sophisticated air dispersion models currently in use (Scire, 2009). It includes two main components. The first one is a comprehensive meteorological model called CALMET. CALMET produces 3D wind fields and various other air dispersion parameters required by CALPUFF (such as surface friction velocity, mixing height, and Monin-Obukhov length) from surface meteorological observations, modeled upper air, elevation, and land cover data. The second component is the non-steady-state puff air dispersion model called CALPUFF. CALPUFF produces gridded estimates of ground level pollution concentrations from the air dispersion parameters

produced by CALMET and pollution emission characteristics (including stack height, stack diameter, exit velocity, exit temperature, and emission rate).

CALPUFF is a non-steady-state puff model. This means that the air pollution plume is represented by a series of continuous puffs. This allows CALPUFF to accurately simulate long range pollutant transport in temporally and spatially varying meteorological conditions (Scire, 2009). Since these conditions are present in this project, the CALPUFF air dispersion model was an appropriate choice. Also, CALPUFF is capable of modeling individual pollution source contributions, which is a main objective of this project.

For this project, CALPUFF was run with default settings using the data described in the next section. Air quality monitoring data are available and could be used to calibrate CALPUFF for the study area. However, since several pollution sources are missing, most notably vehicle emissions, a calibration would not make sense. Without modeling vehicle emissions, calibrating the model with air quality measurements would result in an overestimation of the contribution of point source air pollution. Instead, Intake Fraction is used as a relative measure of pollution exposure, limiting the emphasis on the precision of the resulting ground level pollutant concentrations. After running CALPUFF, the resulting gridded ground level pollution concentrations were used as inputs for the GIS analysis.

2.3 Datasets

This project requires a substantial amount of data including meteorology, air pollution emission, and population density. It focuses on the year 2002 due to the relatively high availability of the necessary data. A modelling resolution of 1 km² was selected to accommodate the 1 km² resolution of the land cover dataset as well as reducing the computing time of CALMET, CALPUFF, and ArcMap. Table 1 describes the required datasets in detail.

Table 2.1 Description of the data used in the study

Description	Source	Spatial Resolution	Temporal Resolution	Date
MM5 modeled upper air data	Alberta Environment	12 km	hourly	2002
Surface Meteorological Observation data (Wind, Precipitation, Temperature, Pressure)	National Climate Data and Information Archive, Government of Canada, monitoring stations	6 discrete points	hourly	2002
Digital Elevation Model	USGS, derived from NASA's Shuttle Radar Topography Mission (SRTM)	90 m		2002
Land Cover	USGS North America Land Cover Database	1 km		1992
Pollution Emission (stacks only)	Environment Canada's National Pollutant Release Inventory (NPRI)	13 discrete points	monthly	2002
Population (including Age and Gender)	Census Canada, Dissemination Areas (DA)	416 discrete polygons		2001

CALMET (the meteorological pre-processor for CALPUFF) was designed to accommodate Mesoscale Model 5 (MM5) modeled upper air data so no preprocessing of this dataset was required. The resolution of these data is much coarser than the model grid's 1 km² resolution. Fortunately, upper air wind patterns are not as complex as surface wind patterns. So it is acceptable to assume that the wind does not change drastically over 12 km.

The surface meteorological observation data that were obtained from Alberta Environment required a format conversion from comma-separated value (CSV) into Station for Atmospheric Measurements (SAM). This was done using a conversion program obtained from the USGS website. SAM is a CALMET compatible format. The only problem with this dataset is its poor coverage. Although six stations are adequate to run CALPUFF on relatively flat and consistent terrain, the accuracy of the air dispersion modeling results would improve with more stations.

The Digital Elevation Model (DEM) required only very simple preprocessing. The data were obtained as over 200 tiles that were mosaiked using ArcMap. These data have a much finer resolution than the modeling grid of 1 km. However, since this does not drastically affect the processing speed of CALMET, there was no need to use a coarser DEM.

The land-cover raster map was obtained in a CALMET compatible format and required no preprocessing. Unfortunately, the most current land-cover map that could be obtained was created from aerial imagery captured in 1992. This is a full ten years earlier than would be ideal. It is undeniable that some land-cover changes would have taken place during those ten years. Fortunately, these changes could not have been drastic enough to greatly alter the air dispersion modeling results at such a coarse resolution.

The pollution emission data were obtained as two Access databases. The first database was made up of 22 tables, of which only four were used. The SubsRele table contains the emitted amounts of each pollutant for each polluting facility aggregated monthly. The Stack table contains the emission parameters (stack height, emission velocity, emission temperature, stack diameter) of each stack present in the facility. The ChemList table contains the names of all the pollutants in the SubsRele table. The Facility table contains names and descriptions of polluting facilities. The second database contains four tables and the only relevant table was the GEO_Location table. It contains the geographic coordinates of each of the polluting facilities. The first preprocessing step was to link all of these tables into one table using the NPRI_ID. This ID is unique to each polluting facility. A unique element was created for each pollutant for each pollution stack. For example, if one stack has four pollutant species, four unique elements were created. These elements were populated with all of the data from the five tables mentioned above, including geographic coordinates from the GEO_Location table. These coordinates were then used to geocode the pollution sources onto a map in ArcMap. There are two problems with this dataset that should be mentioned.

First, the stack location is based only on the facility location. This means that if a facility has several stacks they are all geocoded to be located in the center of the facility. This could result in a stack location error of up to 200 m. Given the size of the study area and the model grid of 1 km, this error is tolerable, but not ideal.

Second, the emission quantities are aggregated into months. CALPUFF requires an emission rate in mass per second. To obtain this number, the monthly totals were interpolated into mass per second values based on the operation times of the facility. This forces the assumption to be made that the pollutant is emitted at a constant rate whenever the facility is in operation, which may be incorrect. It is difficult to quantify this error due to the complicated manner in which CALPUFF handles emission rates. Since monthly aggregates are the only data available, there is no choice but to assume a constant emission rate.

The population data were obtained in two files. The first one is a table containing population information based on the unique ID of each census dissemination area in the study area. The second file is a shapefile containing polygon boundaries of the census dissemination areas. A simple join was created between the table and the shapefile based on the unique identifier. Since these data will be used for the GIS analysis and not for the air dispersion modeling, no consideration needed to be given to the CALPUFF compatibility.

Generally, appropriately addressing all of the data problems would have required a significant time investment, more than the resources of this project allowed. However, the objective of this project is to develop a scalable air quality decision support tool, not to accurately model the ambient air quality. Considering this, the data obtained were considered sufficient for this project.

2.4 ArcGIS

ArcGIS is a complete GIS software package. ArcMap 9.2 includes all of the tools required for this project. Using ArcGIS libraries in Microsoft Visual Studio VB.NET 2008, a custom toolbar was developed for ArcMap that contains all of the tools necessary for importing and analyzing the CALPUFF results. The objective of improving and streamlining the loose coupling process was easily achieved through the development of this toolbar in ArcMap. The details of the GIS analysis will be presented through the description of the Import, Analyze, and Report tools in the next section.

2.5 Loose-Coupling CALPUFF with ArcGIS

The implemented loose-coupling technique consisted of using CALPUFF to produce gridded ground level pollution concentrations and using the custom toolbar in ArcMap for post processing, analysis, and reporting. There is no need to use ArcGIS as a preprocessor since CALPUFF has built-in preprocessors for converting and importing input data.

The development of the custom toolbar in ArcMap was the most important step in the loose-coupling process. Currently, loose-coupling an air dispersion model with a GIS involves several intermediate steps that require a detailed understanding of GIS. These steps can include data conversion, joining, mosaicking, merging, geocoding, and symbolization. The custom toolbar in ArcMap eliminates the need for any intermediate steps and opens the analysis procedure to researchers unfamiliar with GIS. This custom

toolbar (illustrated in Figure 2.2) includes three tools (from left to right): Import, Analyze, and Report. These tools are presented in detail. Figure 2.4 illustrates the loose-coupling implementation.



Figure 2.2 Air Quality Decision Support Toolbar

2.5.1 Import Tool

The Import tool reads CALPUFF outputs and creates shapefiles containing pollutant concentration information for use in the Intake Fraction calculations.

The output from CALPUFF contains x, y coordinates and hourly concentration values. So if the model is run for a year, each x, y point will have 8760 concentration values (one for every hour in the year); this number can be multiplied by the number of sources once source contributions are considered. This is too much data to store in a shapefile (since a shapefile can only have a maximum of 255 fields), so concentration statistics (average concentration and/or maximum concentration) were calculated instead. These values were then added to point features that were created based on the x,y coordinates of the center of each cell output from CALPUFF. Each point feature was populated with concentration statistics representing the total pollutant concentration and each contributing pollutant source. Once the point shapefiles were created, their concentration statistic values were averaged based on which census DA they lie within. Then a copy of the DA shapefile was created and populated with these averaged

concentration statistics. The final result is a copy of the DA polygon shapefile populated with average and maximum concentrations. These polygons could then be used in the Analyze Tool to calculate Intake Fractions. The Import Tool procedure is illustrated in Figure 2.3.

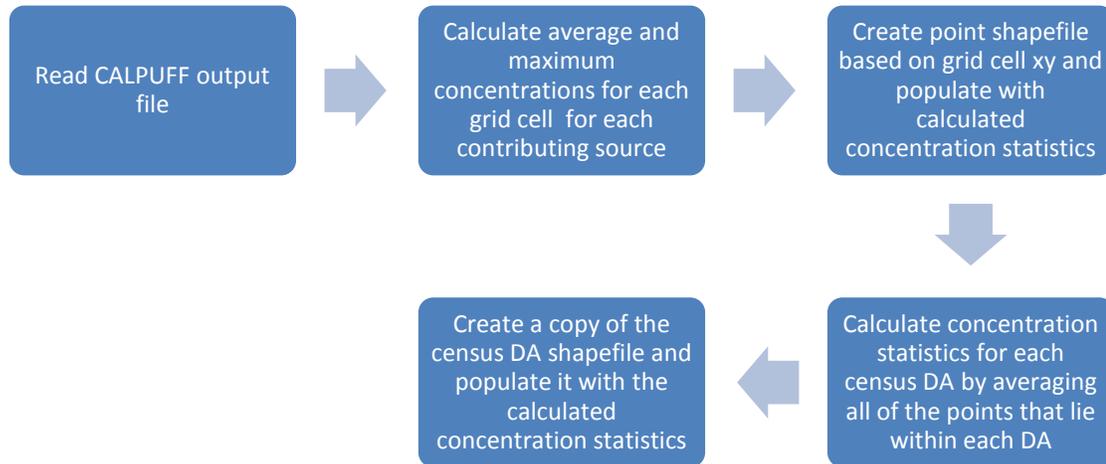


Figure 2.3 Import Tool Flow Chart

2.5.2 Analyze Tool

The Analyze tool is based on the Intake Fraction formula (Equation 1) (Bennett et al., 2002). The user is able to select from several different versions of the Intake Fraction calculation and make specifications depending on the type of calculation selected (ex. sub-population may need to be selected).

$$iF = \frac{P \times C \times BR}{Q} \quad (\text{Equation 1})$$

P = population, *C* = ground level concentration, *BR* = breathing rate, *Q* = emission

The best way to illustrate different versions of the Intake Fraction calculation is to show how various selections alter the variables in the Intake Fraction equation.

The first example is the cumulative Intake Fraction calculation. This represents the fraction of total air pollution emitted that is absorbed by the population in each DA. In this calculation, the population (P) is the total number of people in each DA, the concentration (C) is the total concentration of the pollutant (i.e. all of the contributing sources combined), the breathing rate (BR) is an average person's breathing rate, and the emission (Q) is the total emitted pollutant. Each DA will have one value.

A second version is a sub-population Intake Fraction calculation. This represents the fraction of total air pollution emitted that is absorbed by a sub-population (ex. persons 65 years of age and older) in each DA. In this calculation, the population (P) is the number of people 65 years of age or older in each DA, the concentration (C) is the total concentration of the pollutant (i.e. all of the contributing sources combined), the breathing rate (BR) is the breathing rate of an average person 65 years of age or older, and the emission (Q) is the total emitted pollutant. Each DA will have one value.

A third example is a total contributing source Intake Fraction. This calculation represents the fraction of air pollution from each individual contributing source that is absorbed by the entire population in each DA. In this calculation the population (P) is the total number of people in each DA, the concentration (C) is the concentration of the pollutant from a single contributing source, the breathing rate (BR) is an average person's breathing rate, and the emission (Q) is the pollutant emitted by that single contributing source. Each DA will have several values (one for each contributing source).

The fourth example is a sub-population contributing source Intake Fraction. This calculation represents the fraction of air pollution from each individual contributing source that is absorbed by a sub-population (ex. persons 65 years of age and older) in each DA. In this calculation, the population (P) is the number of people 65 years of age or older in each DA, the concentration (C) is the concentration of the pollutant from a single contributing source, the breathing rate (BR) is the breathing rate of an average person 65 years or age or older, and the emission (Q) is the pollutant emitted by that single contributing source. Each DA will have several values (one for each contributing source).

2.5.3 Report Tool

The report tool is simple, but powerful. It identifies the source contribution Intake Fractions of each of the sources in the model run. This is accomplished by simply summing the contributing source Intake Fractions from each Dissemination Area for each contributing source. This sum is then added to the source point shapefile as an attribute. The sources are then symbolized using a color gradient to allow the user to visually identify the contributing sources with the highest Intake Fractions.

CALMET



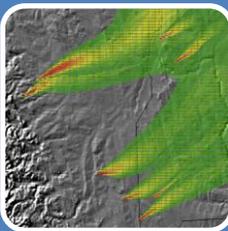
- Input:**
 - 3D terrain (DEM)
 - land use (RASTER)
 - surface station meteorological observations (wind speed/direction, precipitation, pressure)
 - MMS upper air estimates (wind speed/direction)
- Output:**
 - estimated dispersion parameters (ASCII)

CALPUFF



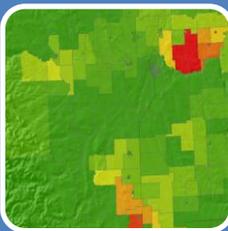
- Input:**
 - estimated dispersion parameters (ASCII)
 - emission characteristics (stack height/diameter, exit velocity/temperature, emission rate)
- Output:**
 - ground level pollutant concentration estimates (ASCII)

Import Tool



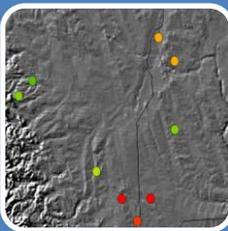
- Input:**
 - ground level pollutant concentration estimates (ASCII)
- Output:**
 - point features with ground level pollutant concentration estimates attributes (shapefile)

Analyze Tool



- Input:**
 - point features with ground level pollutant concentration estimates attributes (shapefile)
 - Polygon features with human population attributes (shapefile)
- Output:**
 - polygon features with Intake Fraction (iF) attributes (shapefile)

Report Tool



- Input:**
 - polygon features with Intake Fraction (iF) attributes (shapefile)
- Output:**
 - pollution source point features with iF contribution attributes (shapefile)

Figure 2.4 Loose-Coupling Implementation Process

Chapter 3: Results

For the purpose of demonstrating the capabilities of the toolbar, ground level pollutant concentrations of Particulate Matter with a diameter of less than or equal to 2.5 microns (PM_{2.5}) were modeled with CALPUFF for the entire study area for the month of June 2002. The resulting 1 km² hourly ground level PM_{2.5} concentration grids were used as inputs for the toolbar.

The remainder of this chapter is divided into three sections. The first section illustrates cumulative Intake Fraction, representing the fraction of the total emitted air pollution that is absorbed by a population. The second section illustrates a contributing source Intake Fraction, representing the fraction of emitted air pollution from each individual contributing source that is absorbed by the total population. The final section illustrates contributing source Intake Fraction for sub-populations, representing the fraction of air pollution from each individual contributing source that is absorbed by a sub-population (ex. persons 65 years of age or older).

3.1 Cumulative Intake Fraction

Cumulative Intake Fraction is an estimate of the fraction of the total pollutant emitted by all modeled sources that is breathed in by people in the study area. This estimate does not indicate individual pollution source contributions. It estimates the cumulative exposure from all pollution point sources.

3.1.1 Cumulative Maximum and Average Ground Level PM2.5 Concentrations

Figure 3.1.1 illustrates the Import Tool's user dialog configured to import the maximum and average PM2.5 concentrations resulting from the emissions of all point sources over the entire modeling period from a CALPUFF output file. Clicking the Import button with the Import Tool user dialog in this configuration results in the creation of three point shapefiles. The first contains point features representing the locations of the sources emitting PM2.5 (illustrated in Figure 3.1.2). The second contains point features representing the centroids of a 1 km² grid with a maximum PM2.5 concentration attribute (illustrated in Figure 3.1.3). The third contains point features representing the centroids of a 1 km² grid with an average PM2.5 concentration attribute (illustrated in Figure 3.1.4). The last 2 shapefiles are symbolized using a natural break renderer with ten classes. Individual pollution source contributions are not imported.

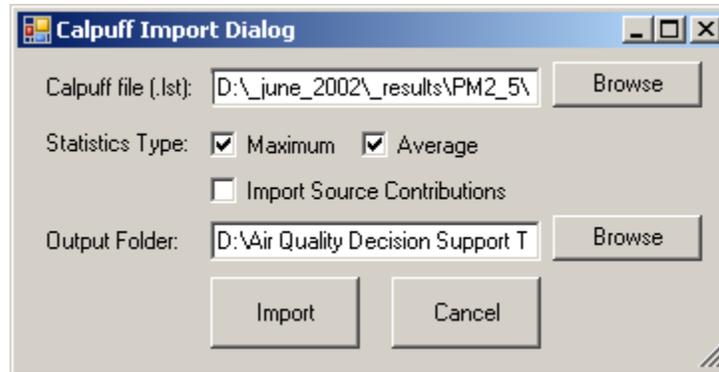


Figure 3.1.1 Import Tool - User Dialog (Cumulative Intake Fraction Configuration)

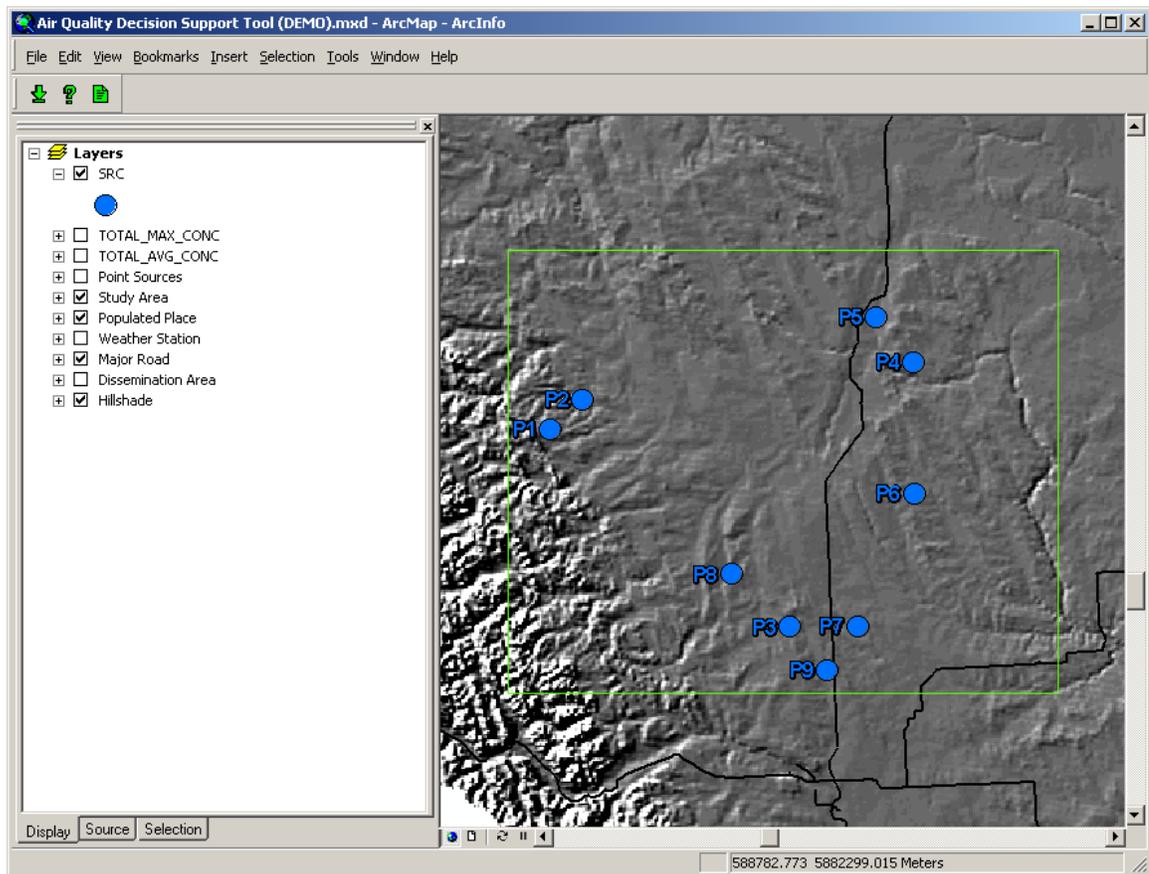


Figure 3.1.2 Import Tool – PM2.5 Emission Source Locations

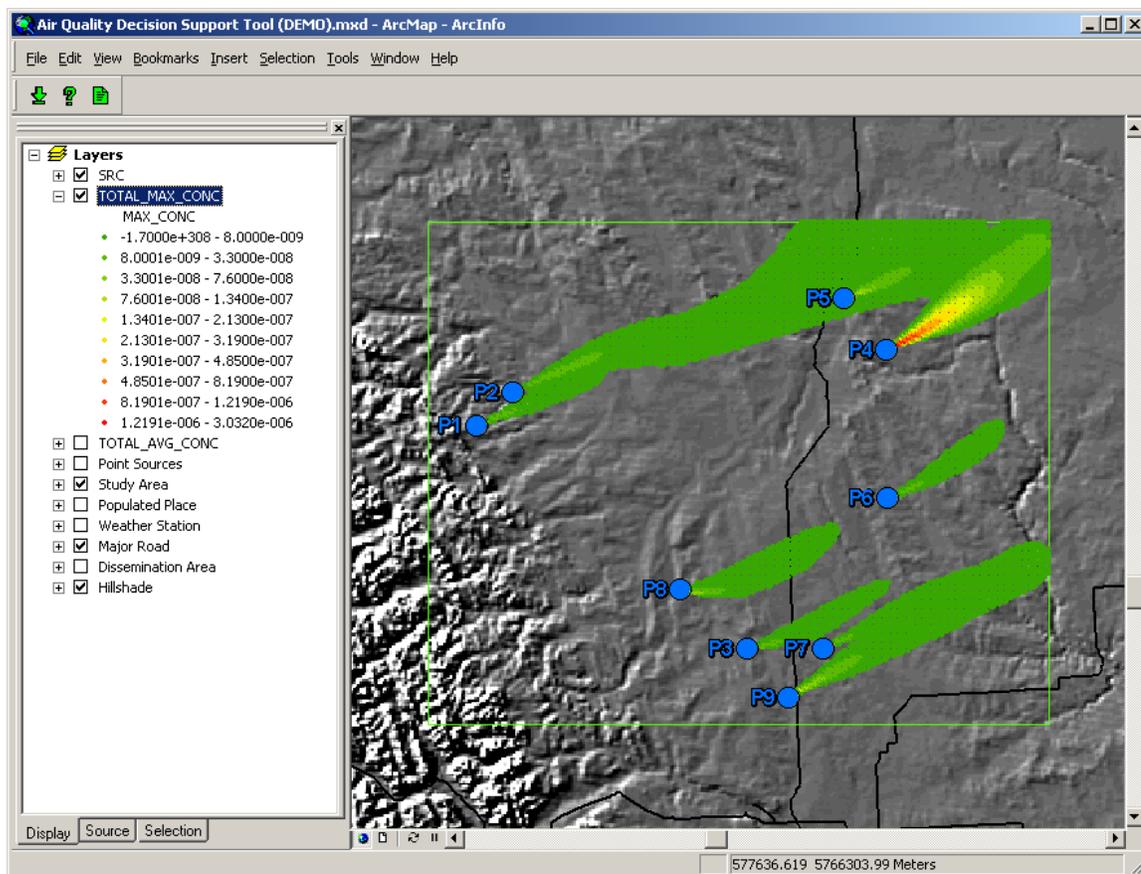


Figure 3.1.3 Import Tool – Cumulative Maximum PM_{2.5} Concentration

Figure 3.1.3 illustrates the Import Tool user interface displaying the cumulative maximum PM_{2.5} concentrations in grams. These values represent the maximum hourly PM_{2.5} concentrations read in from the CALPUFF output file. The symbology classes are defined in the table of contents on the left side of the figure. A color gradient indicates ten classes with relatively high concentrations of PM_{2.5} indicated in red and relatively low PM_{2.5} concentrations in green. In this case red indicates maximum PM_{2.5} concentrations of 1.219×10^{-6} g or higher and green indicates maximum PM_{2.5} concentrations of 8.000×10^{-9} or lower.

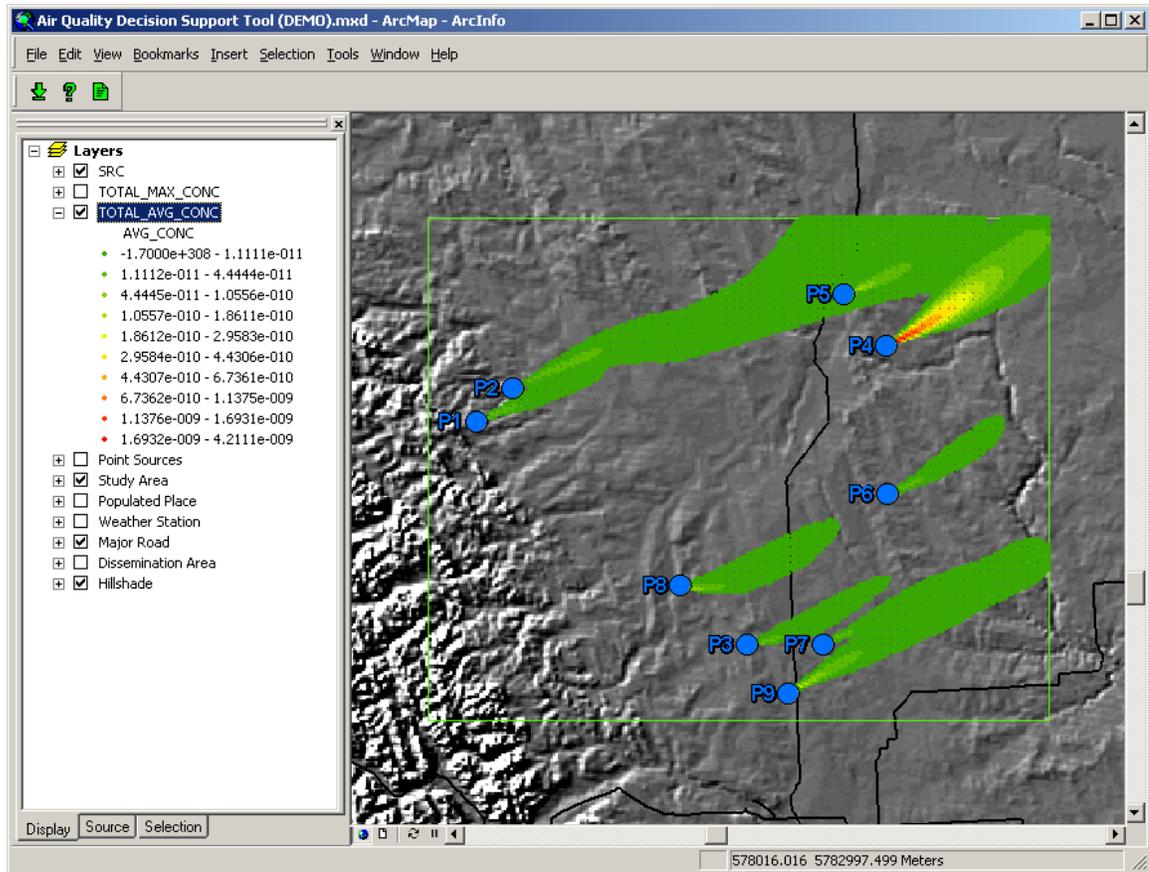


Figure 3.1.4 Import Tool – Cumulative Average PM2.5 Concentration

Figure 3.1.4 illustrates the Import Tool user interface displaying the cumulative average PM2.5 concentrations in grams. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. The symbology classes are defined in the table of contents on the left side of the figure. A color gradient indicates ten classes with relatively high average concentrations of PM2.5 indicated in red and relatively low average PM2.5 concentrations in green. In this case red indicates average PM2.5 concentrations of 1.693×10^{-9} g or higher and green indicates average PM2.5 concentrations of 1.111×10^{-11} or lower.

The differences between the distributions of the features in the maximum and average concentration shapefiles are almost indiscernible. This is due to strong prevailing winds during the modeling period. In light of this, only the average concentration results will be discussed in the remainder of this chapter.

3.1.2 Average Cumulative PM2.5 Intake Fraction for Total Population

Figure 3.1.5 illustrates the Analyze Tool user dialog configured to calculate the cumulative Intake Fraction for average PM2.5 concentrations. Clicking the Analyze button with the Analyze Tool user dialog in this configuration results in the creation of a shapefile containing polygon features representing the Dissemination Areas with an average Intake Fraction attribute (illustrated in Figure 3.1.6). This shapefile is then symbolized using a natural break renderer with ten classes.

The image shows a software dialog box titled "Analyze Dialog". It contains the following elements:

- Dissemination Area Layer:** A dropdown menu with "Dissemination Area" selected.
- Intake Fraction Type:** Two radio buttons: "Maximum" (unselected) and "Average" (selected).
- Analyze Source Contributions:** A checkbox that is currently unchecked.
- Receptors:**
 - Gender:** Three radio buttons: "Everyone" (selected), "Males" (unselected), and "Females" (unselected).
 - Age:** A list of age ranges with checkboxes:
 - All Ages
 - 0 to 5
 - 5 to 9
 - 10 to 14
 - 15 to 19
 - 20 to 24
 - 25 to 29
 - 30 to 34
 - 35 to 39
 - 40 to 44
 - 45 to 49
 - 50 to 54
 - 55 to 59
 - 60 to 64
 - 65 to 69
 - 70 to 74
 - 75 to 79
 - 80 to 84
 - 85 plus

- Output Folder:** A text field containing "D:\Air Quality Decision Support To" and a "Browse" button.
- Buttons:** "Analyze" and "Cancel" buttons at the bottom.

Figure 3.1.5 Analyze Tool - User Dialog (Cumulative Intake Fraction Configuration)

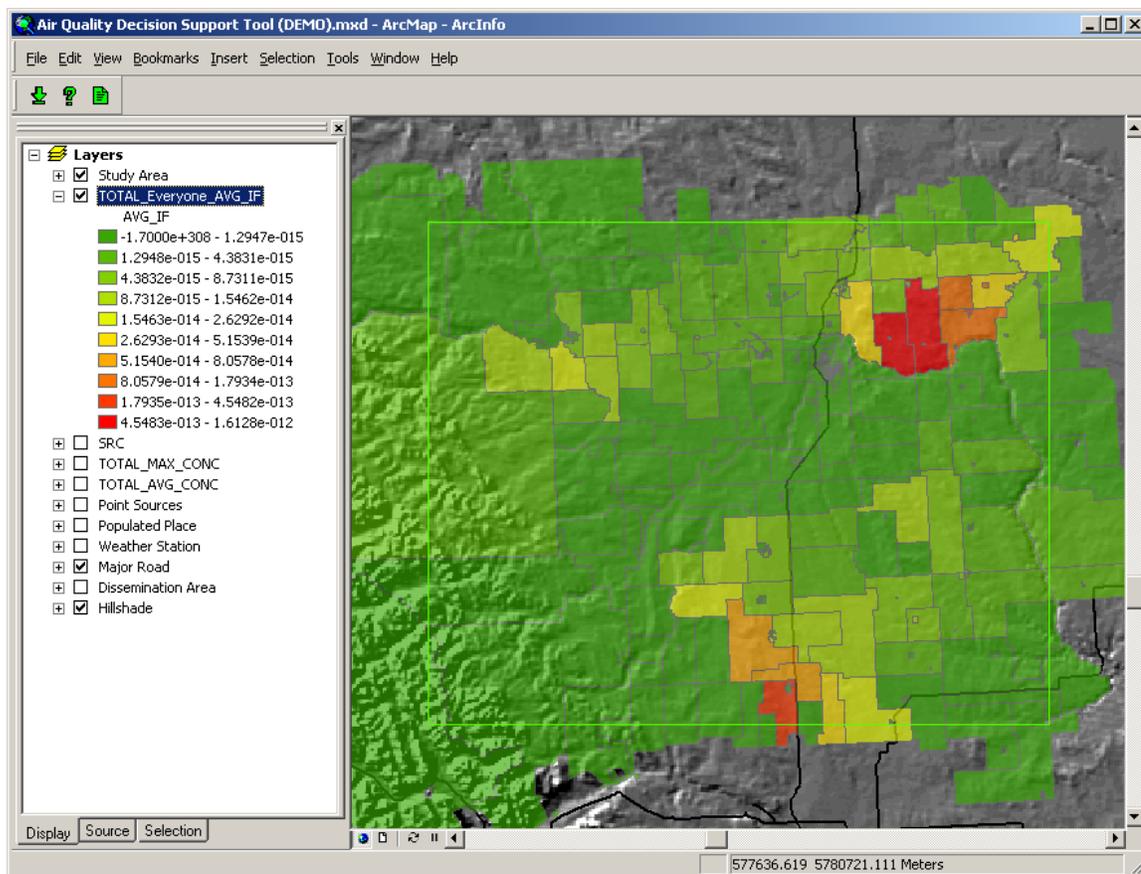


Figure 3.1.6 Analyze Tool –Cumulative Average PM2.5 Intake Fraction for Total Population

Figure 3.1.6 illustrates the Analyze Tool user interface displaying the cumulative average PM2.5 Intake Fraction. These values are obtained using the Intake Equation as calculated with Equation 2. The symbology classes are defined in the table of contents on the left side of the figure. A color gradient indicates ten classes with relatively high average PM2.5 Intake Fractions indicated in red and relatively low average PM2.5 Intake Fractions in green. In this case red indicates average PM2.5 Intake Fractions of 4.548×10^{-13} or higher and green indicates average PM2.5 Intake Fractions of 1.295×10^{-15} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of people in each DA} \times \\ \text{average PM2.5 concentration in each DA} \times \\ \text{average person's breathing rate} \end{array}}{\text{total amount of PM2.5 emitted}} \quad (\text{Equation 2})$$

The results from the Analyze Tool allow the user to visualize the relative cumulative Intake Fraction of the population in each Dissemination Area. For example, approximately 350 times the proportion of the air pollution emitted in the study area is absorbed in the red areas compared to the green areas. Since Intake Fraction is an estimate of the probability of human health effects resulting from the identified emission in each of the Dissemination Areas, these results are useful for identifying the areas that are most sensitive to changes in the emission characteristics of pollution sources in the study area.

Since no individual source contributions were imported in this configuration, the Report Tool cannot be run and is not presented in this section.

3.2 Contributing Source Intake Fraction

Contributing Intake Fraction is an estimate of the fraction of the pollutant emitted by each individual modeled source that is breathed in by the total population in the study area. A separate Intake Fraction calculation is completed for each PM2.5 emitting source.

3.2.1 Individual Contributing Source Average Ground Level PM2.5 Concentrations

Figure 3.2.1 illustrates the Import Tool user dialog configured to import the average ground level pollutant concentrations resulting from each individual PM2.5 emitting source over the entire modeling period from a CALPUFF output file. Clicking the Import button with the Import Tool user dialog in this configuration results in the creation of ten point shapefiles. The first contains point features representing the locations of the sources emitting PM2.5 (same as illustrated in Figure 3.1.2) The other nine shapefiles contain point features representing the centroids of a 1 km² grid with an average PM2.5 concentration attribute. Each shapefile represents the average PM2.5 concentrations that result from the emissions of a single emission source. Since there are nine sources in the study area, there are nine average concentration shapefiles (illustrated in Figures 3.2.2 – 3.2.10). These shapefiles are then symbolized using a natural break renderer with ten classes.

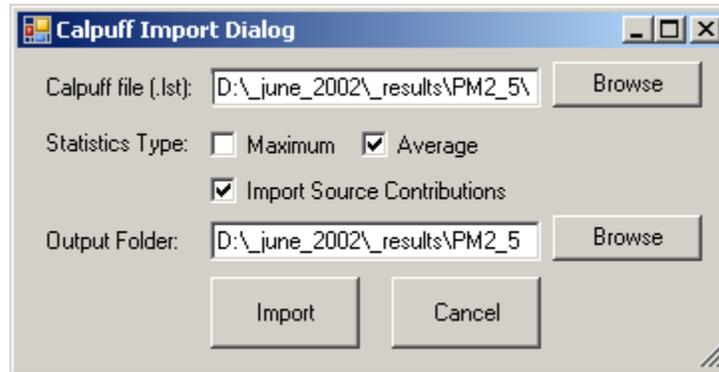


Figure 3.2.1 Import Tool - User Dialog (Total Contributing Source Intake Fraction Configuration)

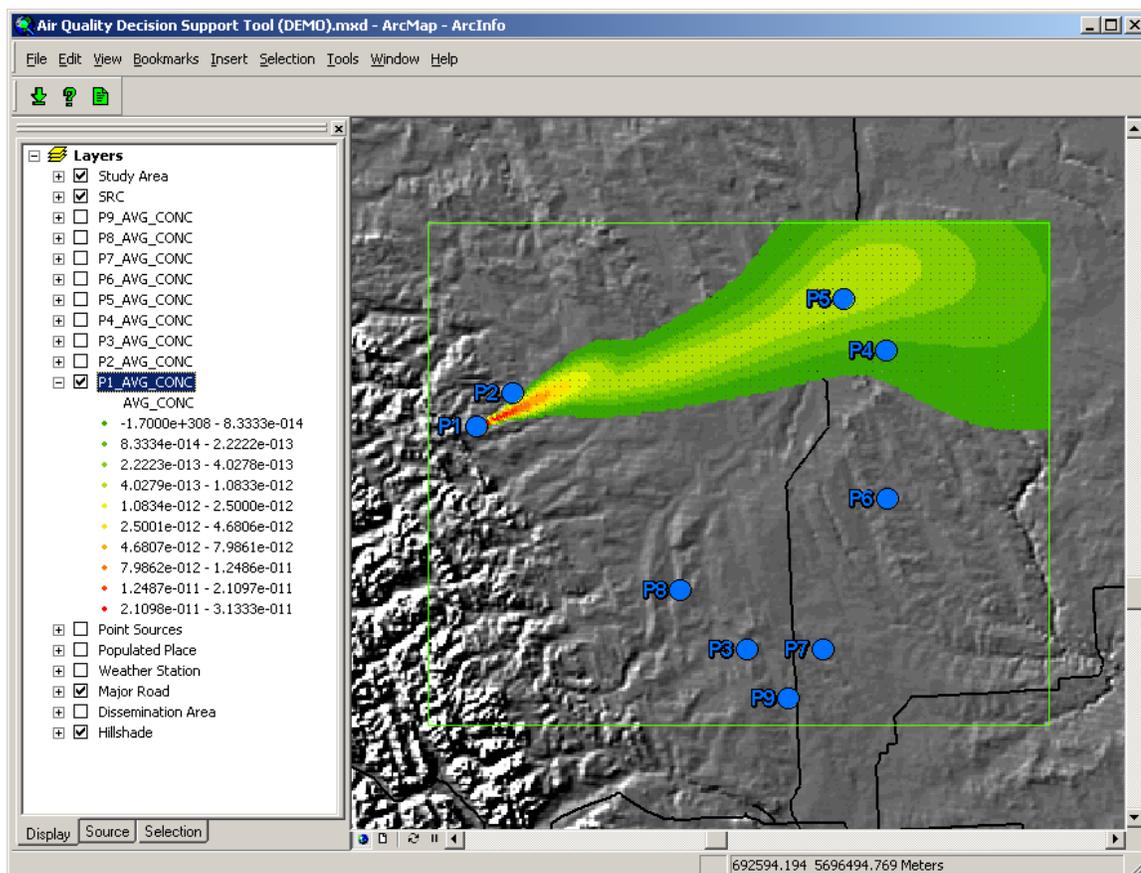


Figure 3.2.2 Import Tool – Average PM2.5 Concentration from Point Source P1

Figure 3.2.2 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P1. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 3.13×10^{-11} g or higher and green indicates average PM2.5 concentrations of 8.33×10^{-14} g or lower.

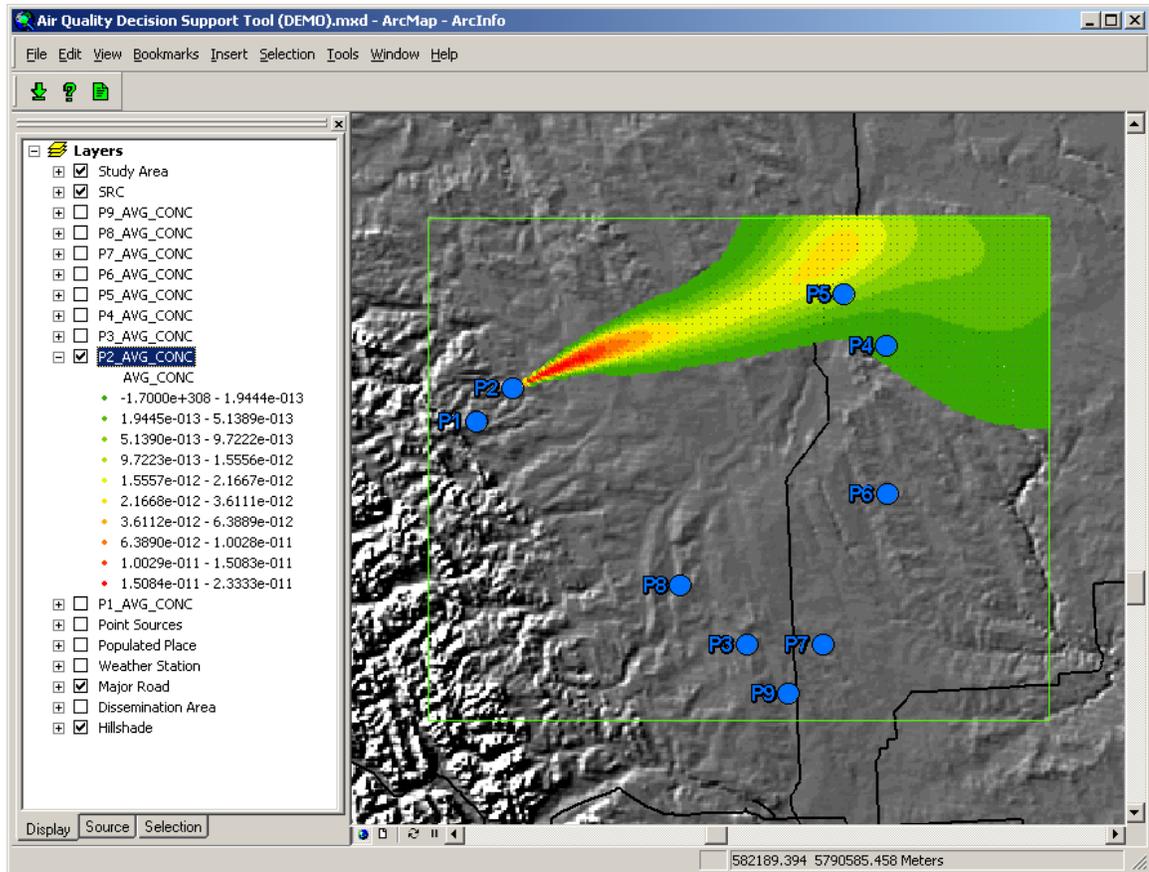


Figure 3.2.3 Import Tool – Average PM2.5 Concentration from Point Source P2

Figure 3.2.3 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P2. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 2.33×10^{-11} g or higher and green indicates average PM2.5 concentrations of 1.94×10^{-13} g or lower.

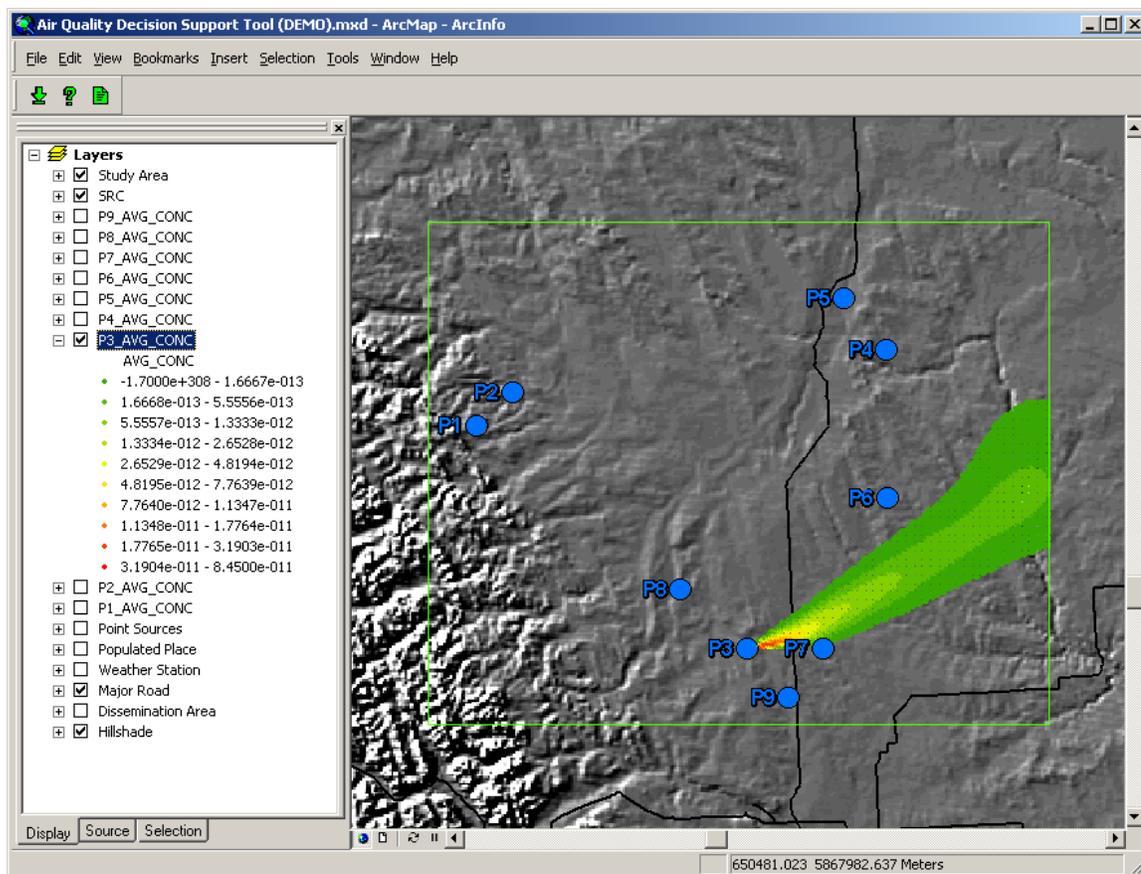


Figure 3.2.4 Import Tool – Average PM2.5 Concentration from Point Source P3

Figure 3.2.4 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P3. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 8.45×10^{-11} g or higher and green indicates average PM2.5 concentrations of 1.67×10^{-13} g or lower.

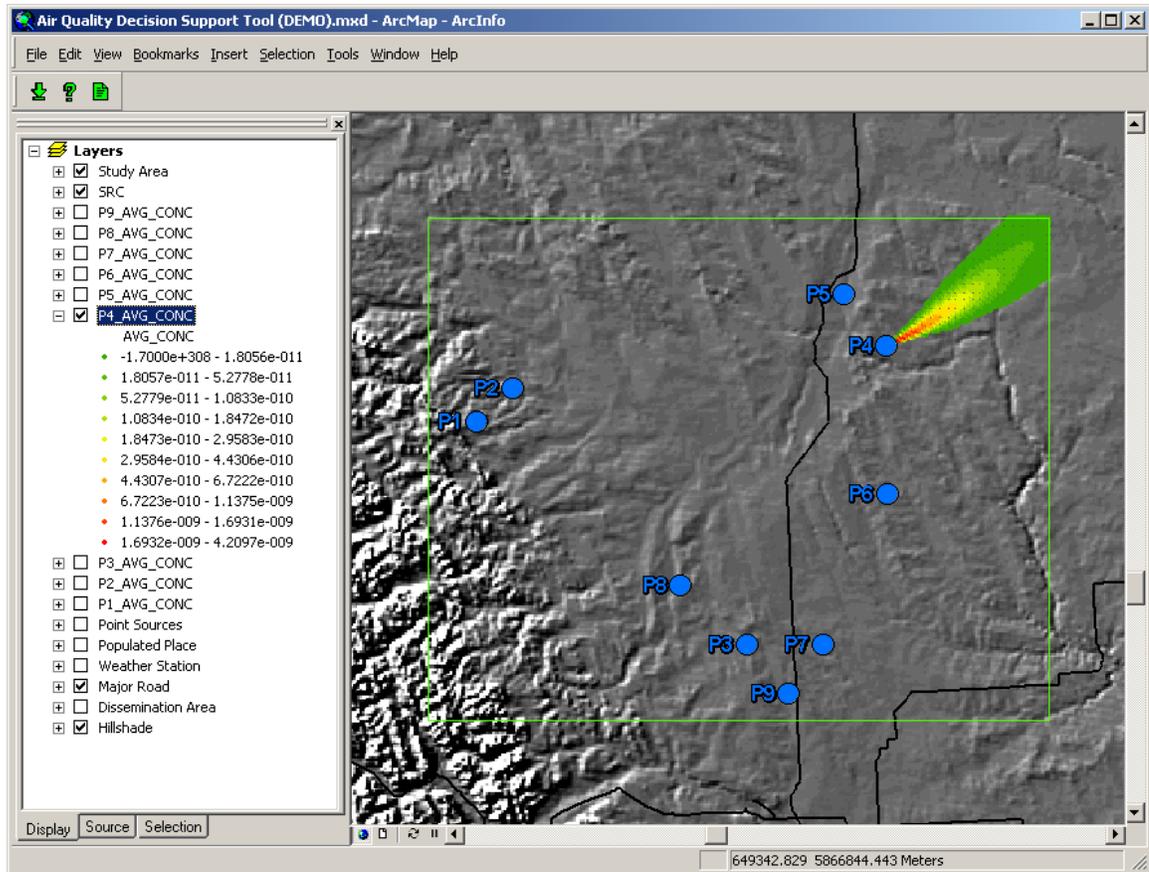


Figure 3.2.5 Import Tool – Average PM2.5 Concentration from Point Source P4

Figure 3.2.5 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P4. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 4.21×10^{-9} g or higher and green indicates average PM2.5 concentrations of 1.81×10^{-11} g or lower.

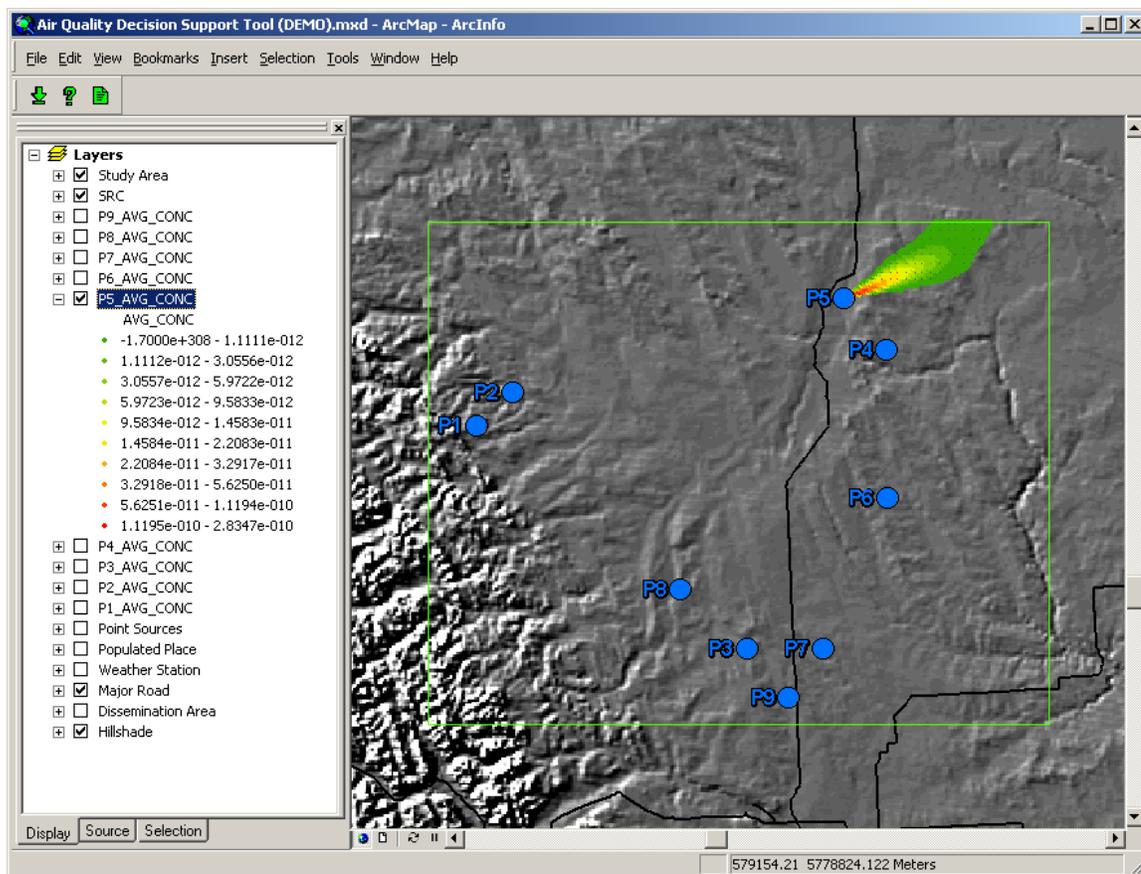


Figure 3.2.6 Import Tool – Average PM2.5 Concentration from Point Source P5

Figure 3.2.6 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P5. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 2.83×10^{-10} g or higher and green indicates average PM2.5 concentrations of 1.11×10^{-12} g or lower.

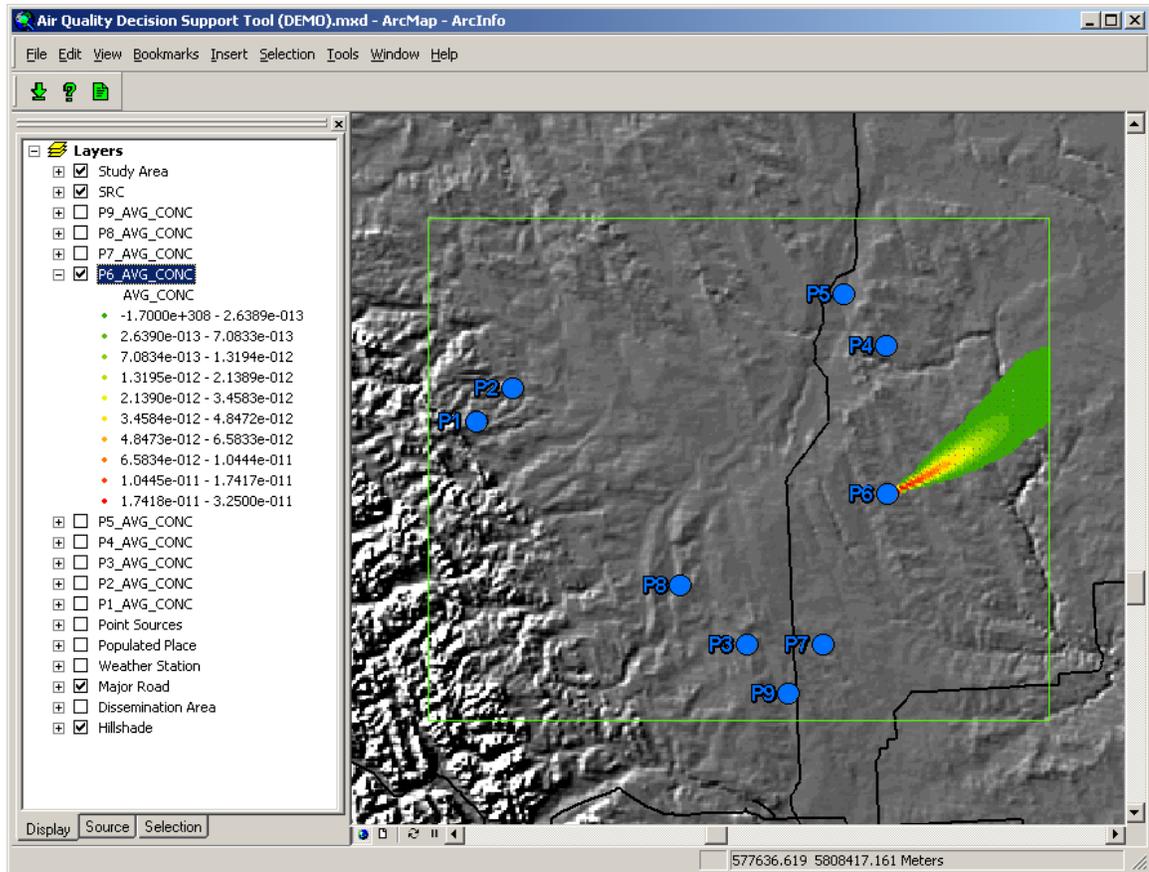


Figure 3.2.7 Import Tool – Average PM2.5 Concentration from Point Source P6

Figure 3.2.7 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P6. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 3.25×10^{-11} g or higher and green indicates average PM2.5 concentrations of 2.64×10^{-13} g or lower.

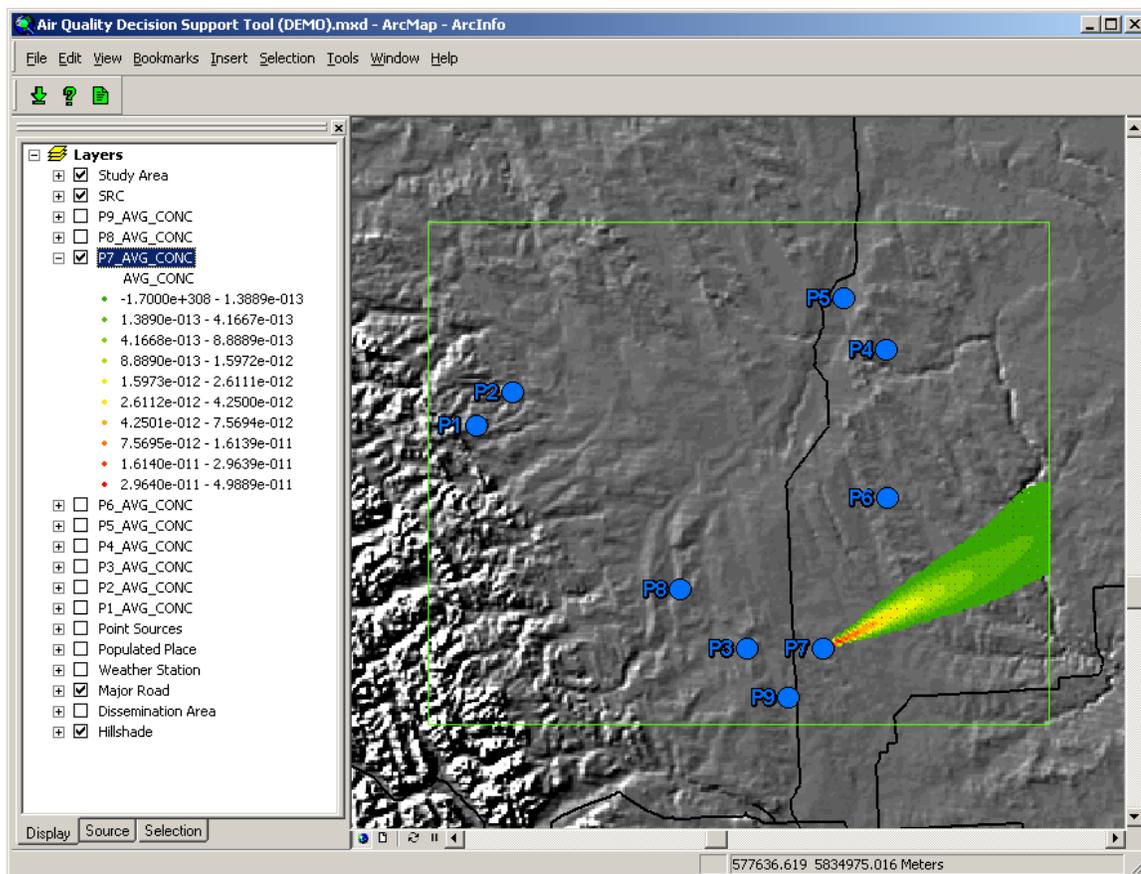


Figure 3.2.8 Import Tool – Average PM2.5 Concentration from Point Source P7

Figure 3.2.8 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P7. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 4.99×10^{-11} g or higher and green indicates average PM2.5 concentrations of 1.39×10^{-13} g or lower.

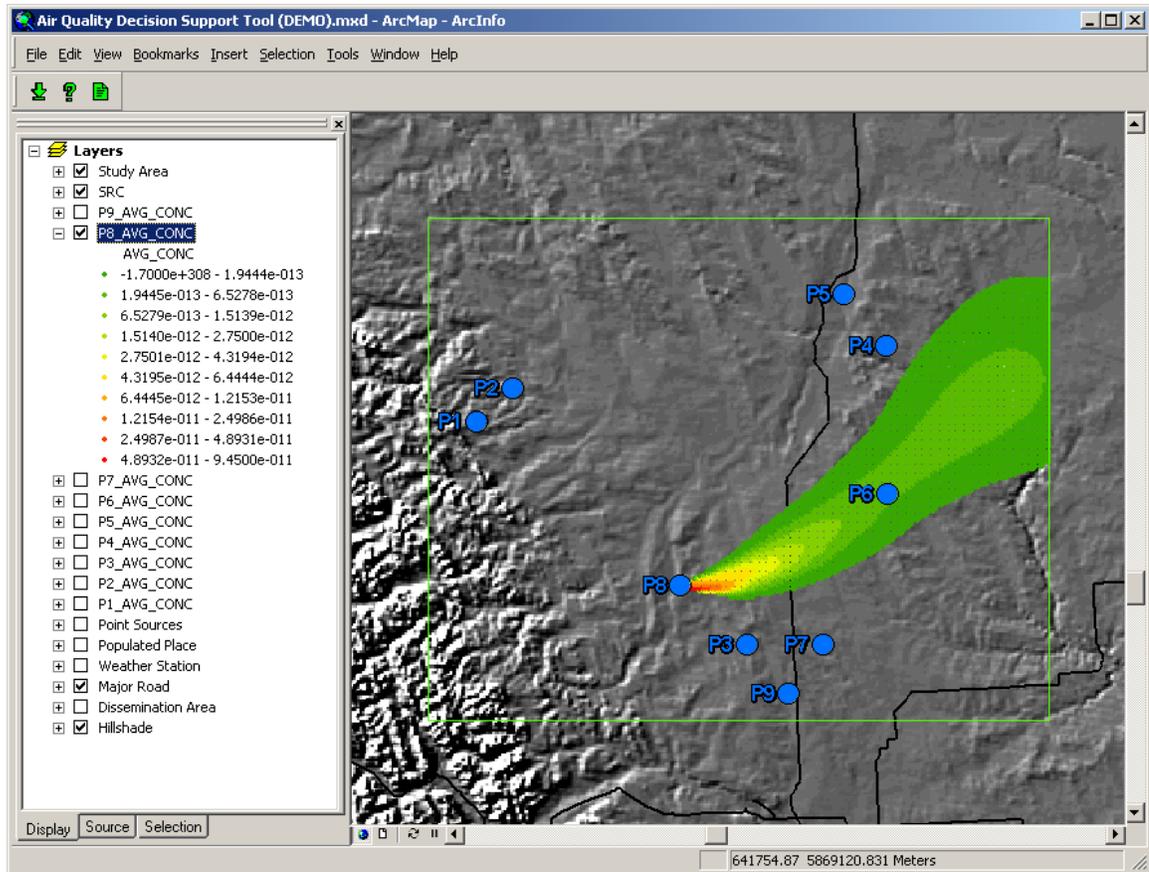


Figure 3.2.9 Import Tool – Average PM2.5 Concentration from Point Source P8

Figure 3.2.9 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P8. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 9.45×10^{-11} g or higher and green indicates average PM2.5 concentrations of 1.94×10^{-13} g or lower.

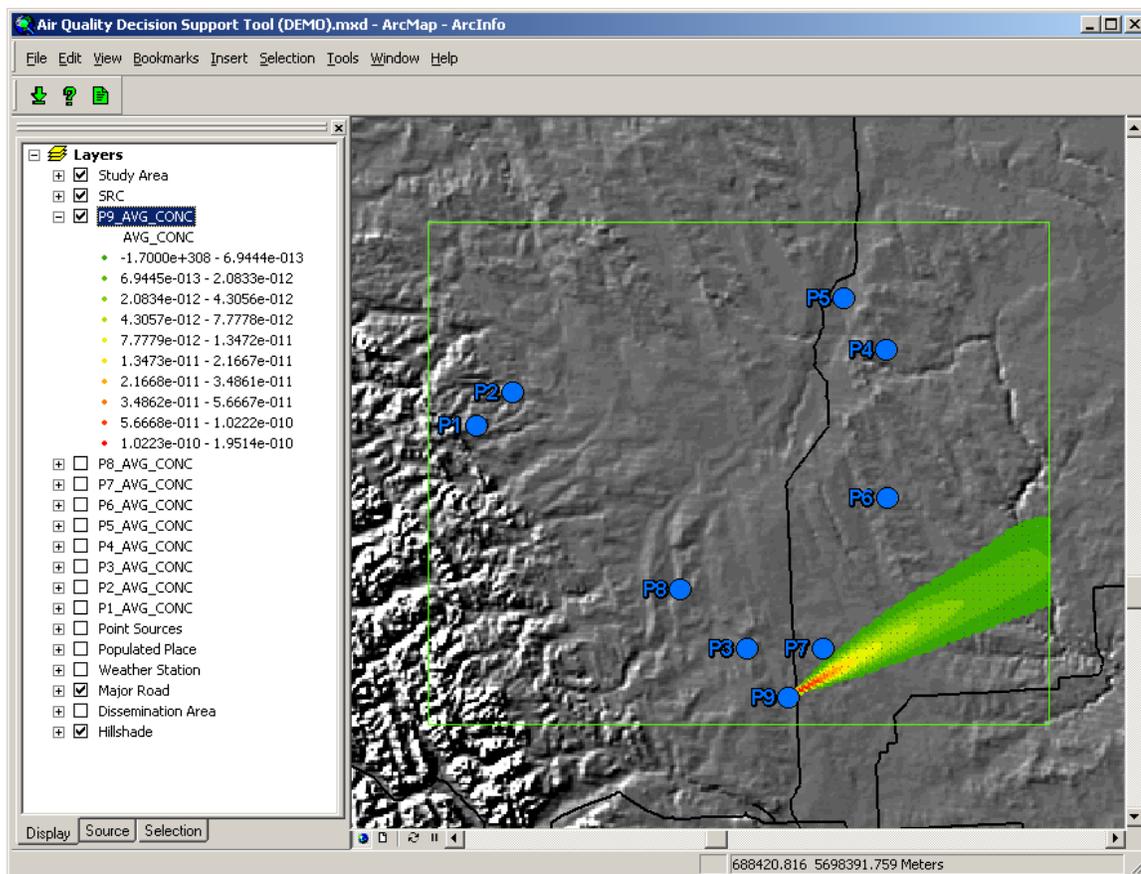


Figure 3.2.10 Import Tool – Average PM2.5 Concentration from Point Source P9

Figure 3.2.10 illustrates the Import Tool user interface displaying the average PM2.5 concentrations resulting from the emission of source P9. These values represent the average hourly PM2.5 concentrations read in from the CALPUFF output file. In this case red indicates average PM2.5 concentrations of 1.95×10^{-10} g or higher and green indicates average PM2.5 concentrations of 6.94×10^{-13} g or lower.

Comparing Figures 3.2.2 – 3.2.10, it is difficult to identify the emission sources that are more likely to have an impact on human health. In order to illustrate each plume in detail, each of the point shapefiles illustrated are rendered individually. This means that

the symbology class breaks will be different for the plume emitted from each pollution source. In other words, the colour red will indicate different PM_{2.5} concentration values in each of the nine figures. It is important to notice the values of the symbology classes in the table of contents on the left side of the figures. Table 3.2.1 presents the highest average ground level pollutant concentration that results from each pollutant source.

Table 3.2.1 Highest Average Ground Level Pollutant Concentration

Point Source	Concentration (ng/m ³)
P4	4.2097
P5	0.2830
P8	0.0945
P3	0.0845
P7	0.0499
P6	0.0325
P1	0.0313
P2	0.0233
P9	0.0195

These results indicate that the emissions from point sources P5 and P4 results in average concentrations roughly ten and one hundred times, respectively, higher than the other point sources. At this stage in the analysis, point sources P5 and P4 seem most likely to cause human health effects in the study area. However, this is not confirmed unless it can be demonstrated that a significant population is present in these relatively high average concentration areas and is absorbing relatively high proportions of pollutant released from these emission sources.

3.2.2 Contributing Source PM2.5 Intake Fraction for Total Population

Figure 3.2.11 illustrates the Analyze Tool user dialog configured to calculate the total population contributing source Intake Fraction for the average ground level pollutant concentrations. Running the Analyze Tool in this configuration results in nine shapefiles containing polygon features representing the Dissemination Areas each with an average Intake Fraction attribute. Each shapefile represents the average Intake Fractions that result from the emissions of a single pollutant source. Since there are nine sources in the study area, there are nine average Intake Fraction shapefiles (illustrated in Figures 3.2.12 – 3.2.20). These shapefiles are then symbolized using a natural break renderer with ten classes.

Analyze Dialog

Dissemination Area Layer:

Intake Fraction Type: Maximum Average

Analyze Source Contributions

Receptors:

Gender
 Everyone Males Females

Age

<input type="checkbox"/> 0 to 5	<input type="checkbox"/> 45 to 49
<input checked="" type="checkbox"/> All Ages	<input type="checkbox"/> 50 to 54
<input type="checkbox"/> 5 to 9	<input type="checkbox"/> 55 to 59
<input type="checkbox"/> 10 to 14	<input type="checkbox"/> 60 to 64
<input type="checkbox"/> 15 to 19	<input type="checkbox"/> 65 to 69
<input type="checkbox"/> 20 to 24	<input type="checkbox"/> 70 to 74
<input type="checkbox"/> 25 to 29	<input type="checkbox"/> 75 to 79
<input type="checkbox"/> 30 to 34	<input type="checkbox"/> 80 to 84
<input type="checkbox"/> 35 to 39	<input type="checkbox"/> 85 plus
<input type="checkbox"/> 40 to 44	

Output Folder:

Figure 3.2.11 Analyze Tool - User Dialog (Total Population Contributing Source Intake Fraction Configuration)

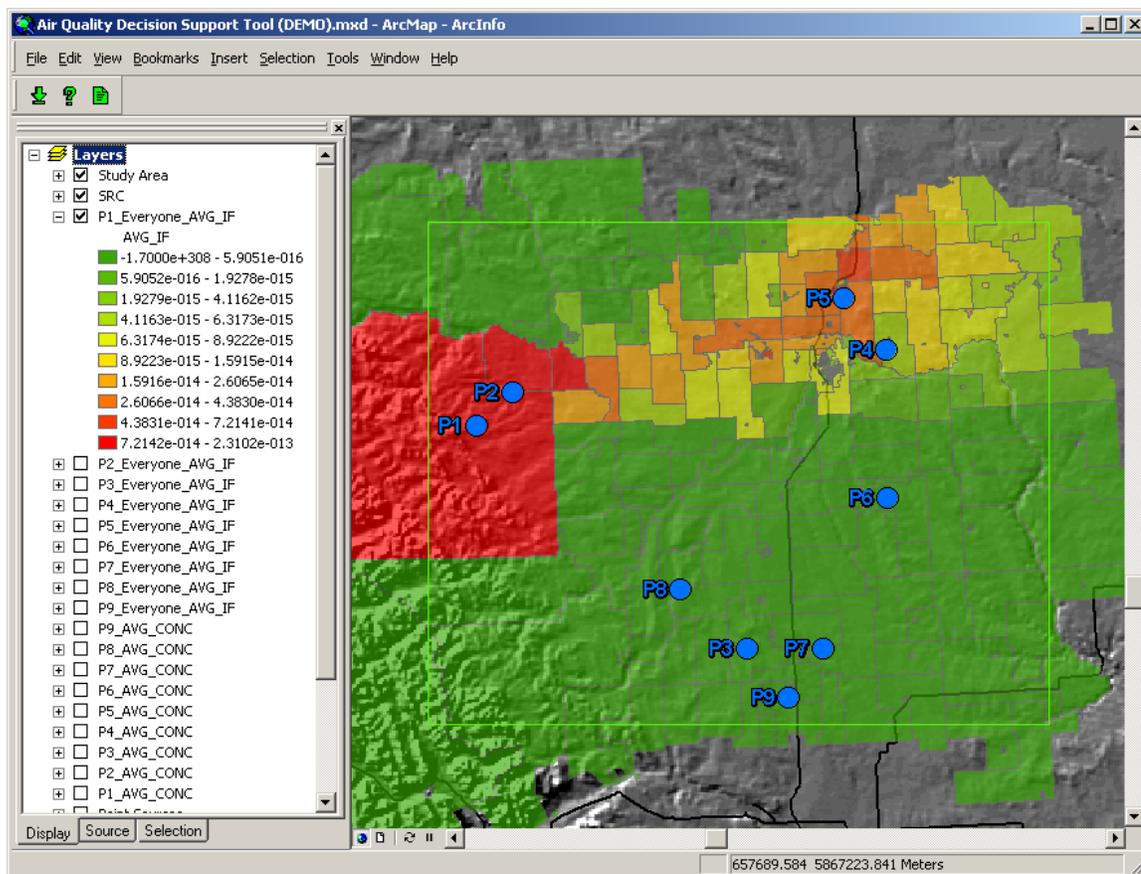


Figure 3.2.12 Analyze Tool – P1 Total Population Average Intake Fraction

Figure 3.2.12 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P1 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 3. In this case red indicates average PM_{2.5} Intake Fractions of 2.310×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 5.905×10^{-15} or lower.

$$iF_{DA} = \frac{\text{\# of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P1 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 3})$$

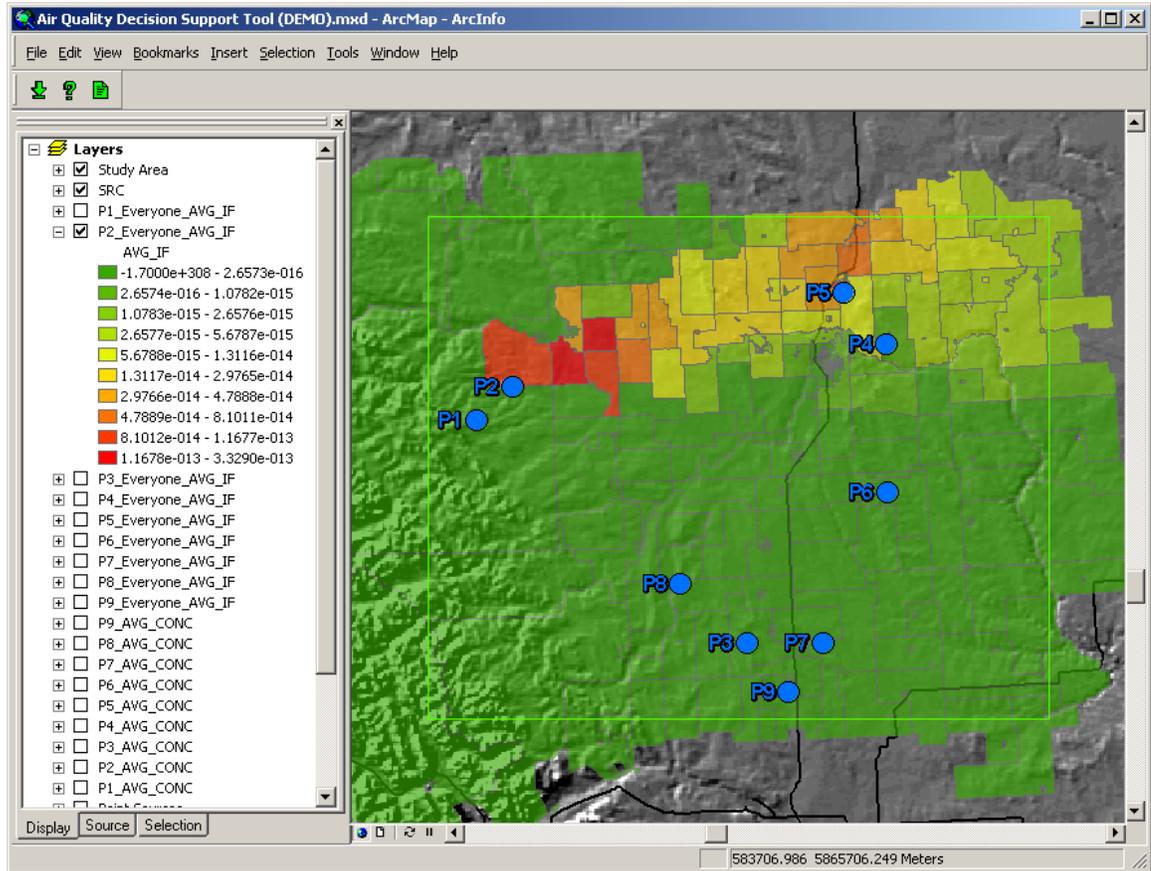


Figure 3.2.13 Analyze Tool – P2 Total Population Average Intake Fraction

Figure 3.2.13 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P2 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 4. In this case red indicates average PM_{2.5} Intake Fractions of 3.329×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 2.657×10^{-16} or lower.

$$iF_{DA} = \frac{\text{\# of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P2 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 4})$$

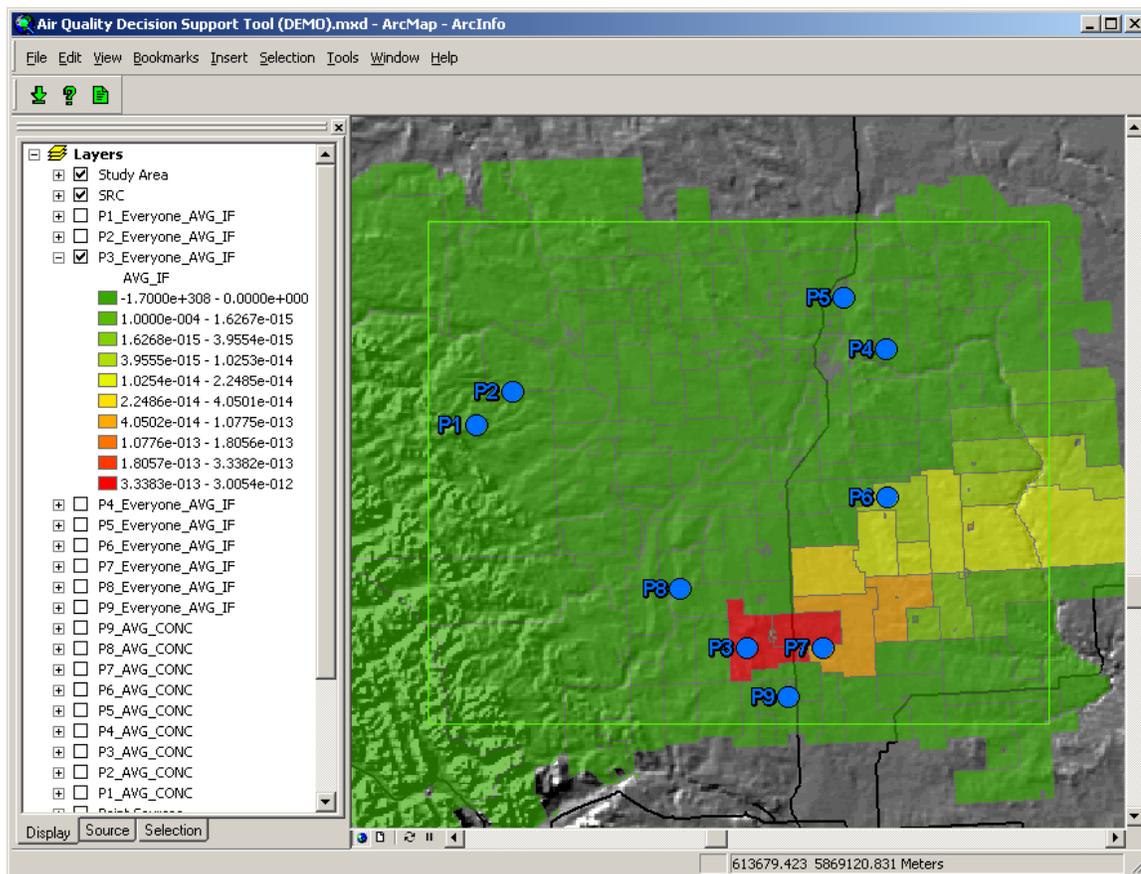


Figure 3.2.14 Analyze Tool – P3 Total Population Average Intake Fraction

Figure 3.2.14 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P3 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 5. In this case red indicates average PM_{2.5} Intake Fractions of 3.005×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 1.627×10^{-15} or lower.

$$iF_{DA} = \frac{\# \text{ of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P3 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 5})$$

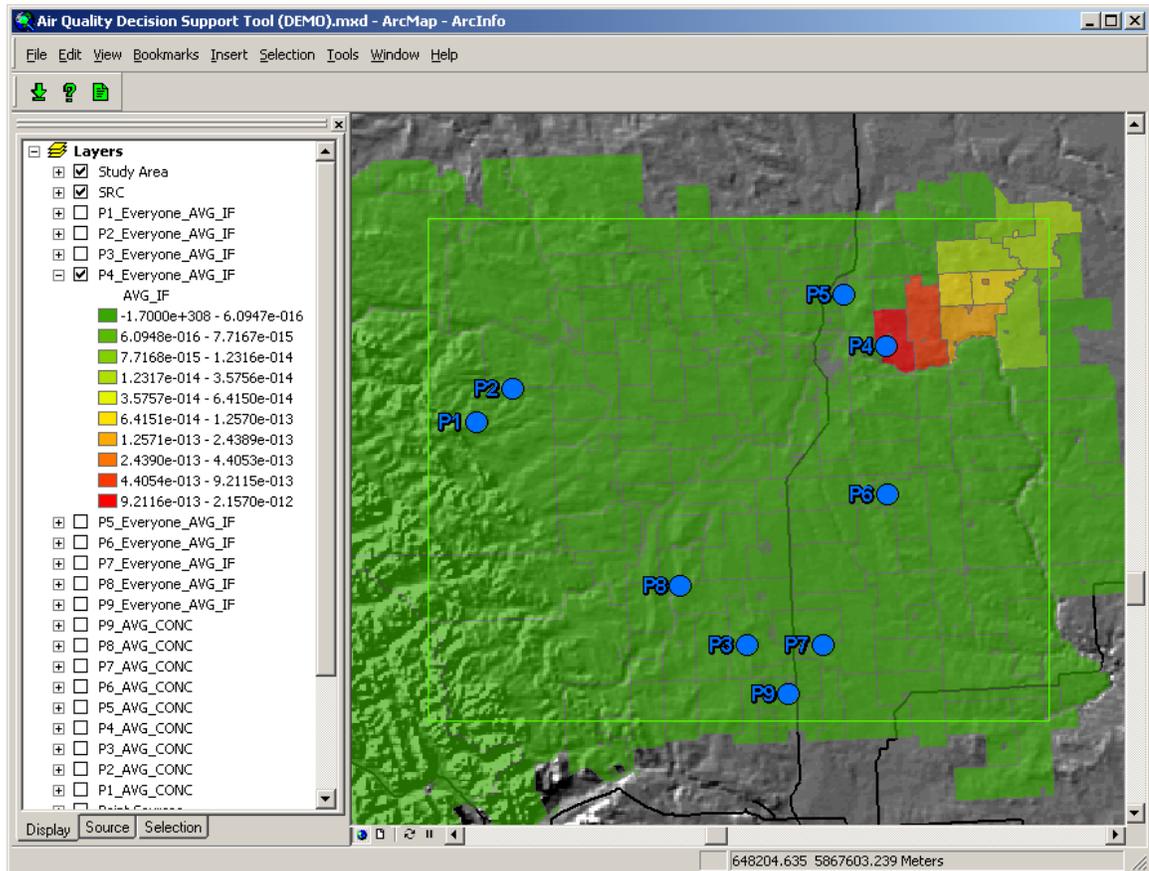


Figure 3.2.15 Analyze Tool – P4 Total Population Average Intake Fraction

Figure 3.2.15 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P4 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 6. In this case red indicates average PM_{2.5} Intake Fractions of 2.157×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 6.095×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of people in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P4 in each DA} \times \\ \text{average person's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 6})$$

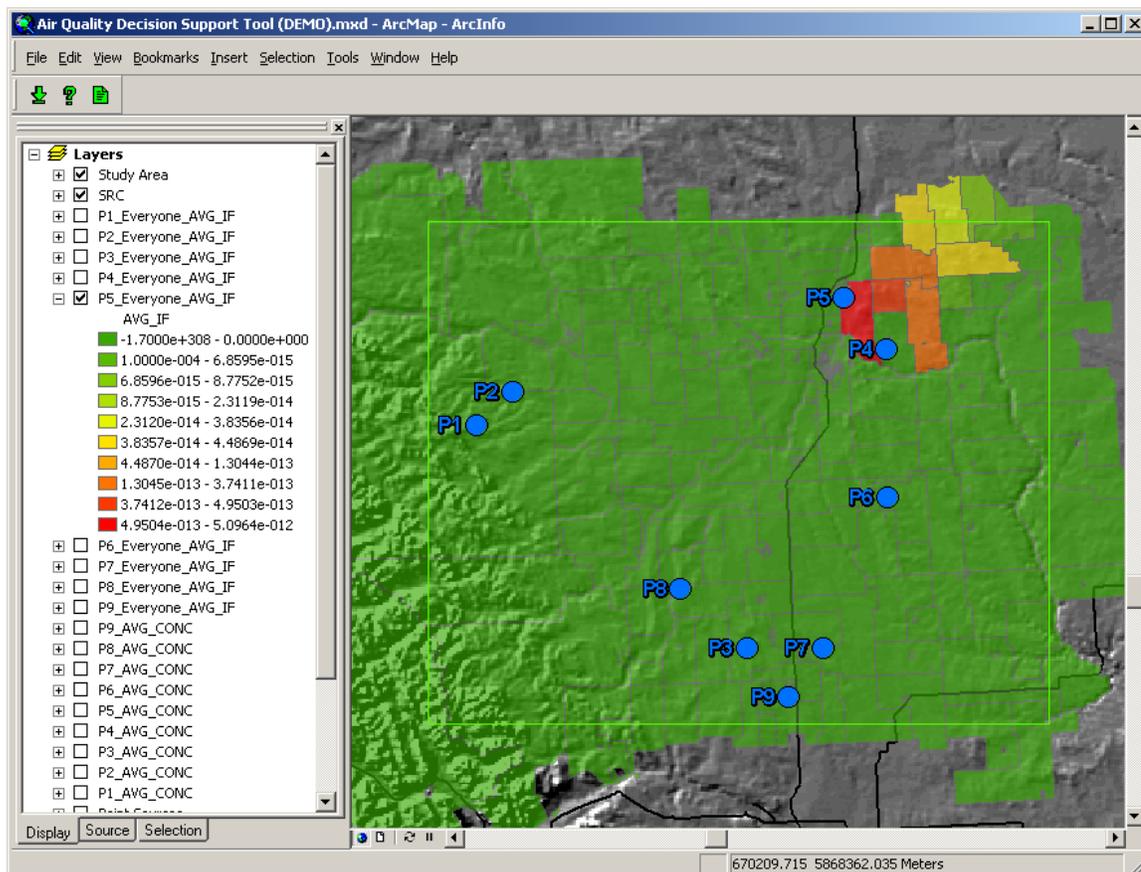


Figure 3.2.16 Analyze Tool – P5 Total Population Average Intake Fraction

Figure 3.2.16 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P5 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 7. In this case red indicates average PM_{2.5} Intake Fractions of 5.096×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 6.860×10^{-15} or lower.

$$iF_{DA} = \frac{\text{\# of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P5 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 7})$$

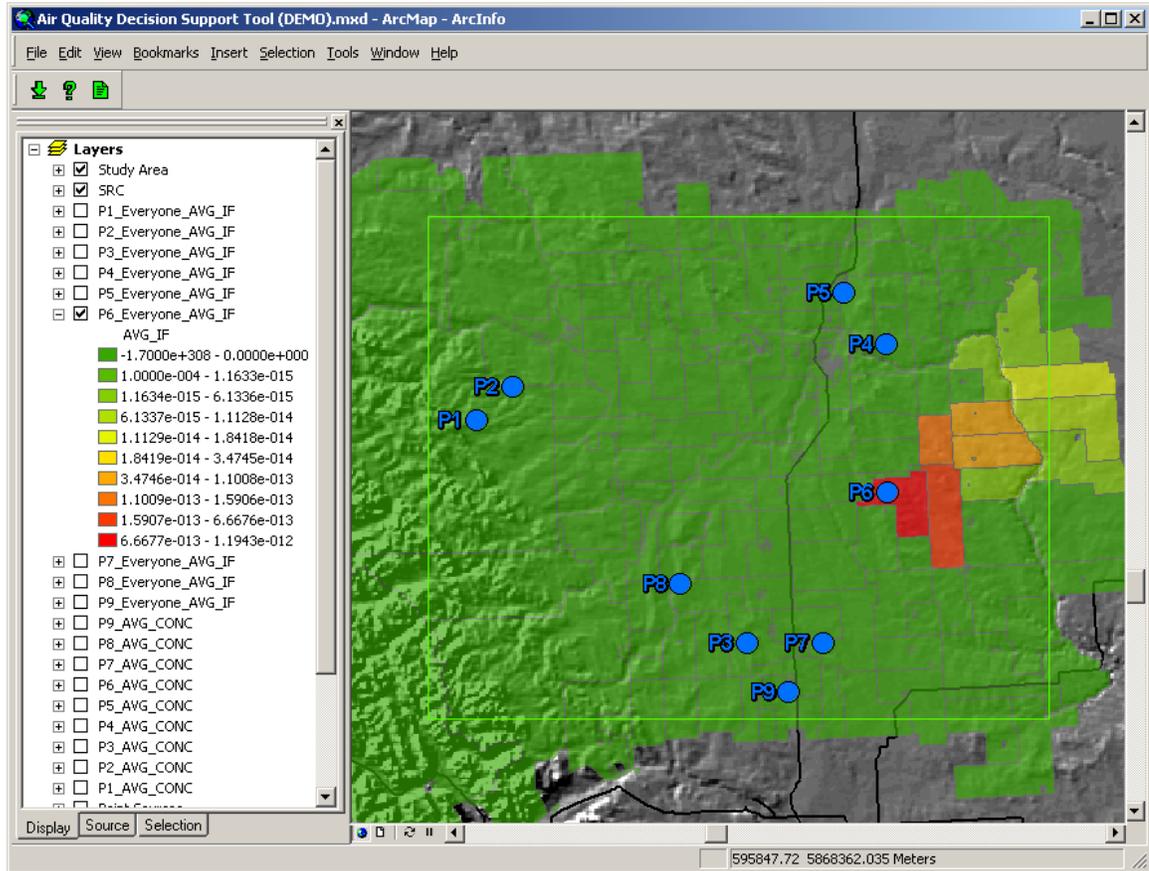


Figure 3.2.17 Analyze Tool – P6 Total Population Average Intake Fraction

Figure 3.2.17 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P6 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 8. In this case red indicates average PM_{2.5} Intake Fractions of 1.194×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 1.163×10^{-15} or lower.

$$iF_{DA} = \frac{\text{\# of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P6 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 8})$$

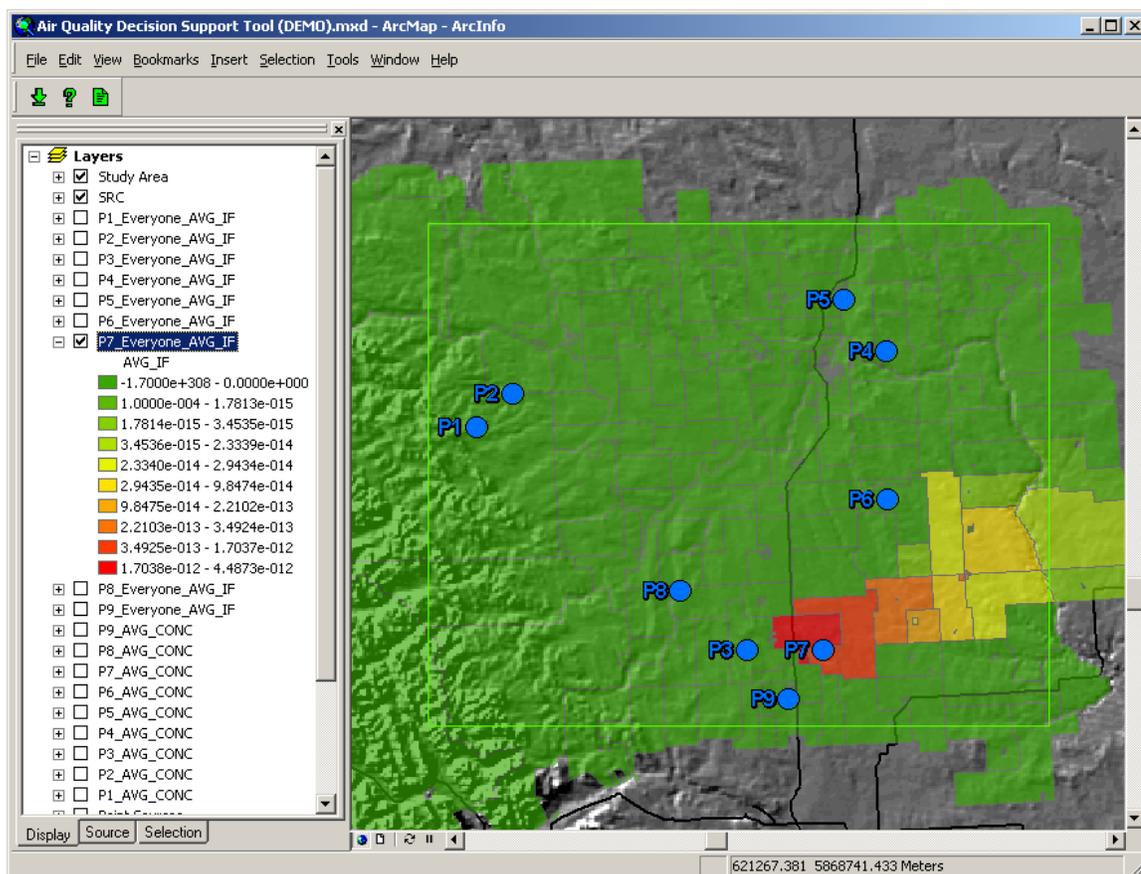


Figure 3.2.18 Analyze Tool – P7 Total Population Average Intake Fraction

Figure 3.2.18 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P7 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 9. In this case red indicates average PM_{2.5} Intake Fractions of 4.487×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 1.781×10^{-15} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of people in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P7 in each DA} \times \\ \text{average person's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 9})$$

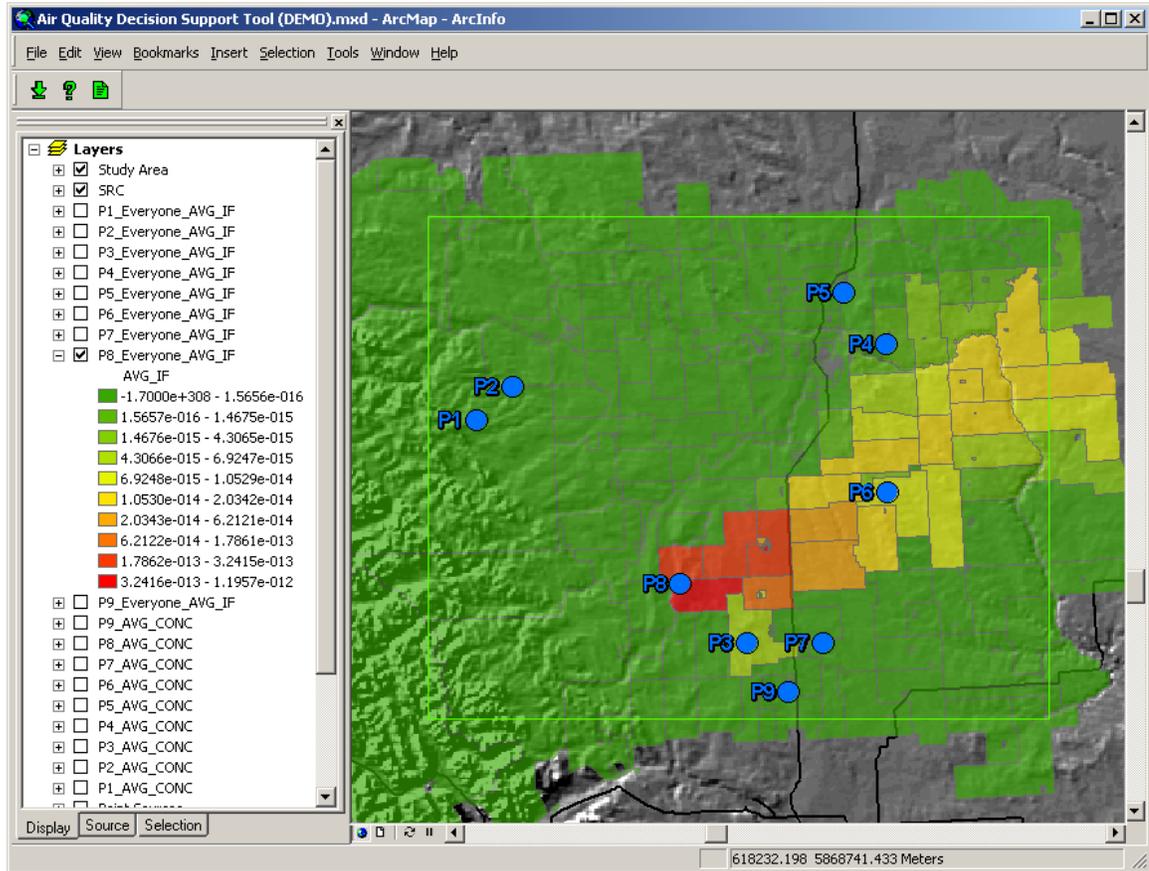


Figure 3.2.19 Analyze Tool – P8 Total Population Average Intake Fraction

Figure 3.2.19 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P8 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 10. In this case red indicates average PM_{2.5} Intake Fractions of 1.196×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 1.566×10^{-16} or lower.

$$iF_{DA} = \frac{\text{\# of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P8 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 10})$$

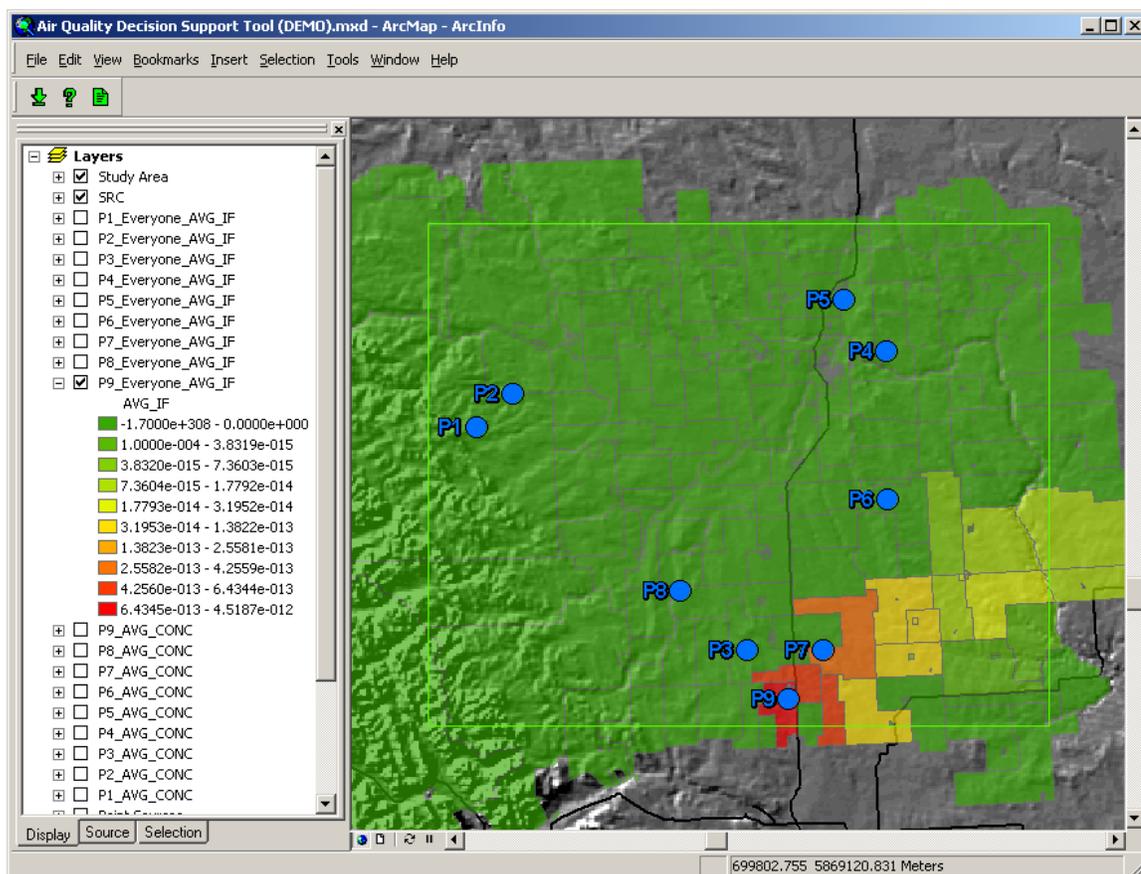


Figure 3.2.20 Analyze Tool – P9 Total Population Average Intake Fraction

Figure 3.2.20 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P9 for the total population. These values are obtained using the Intake Equation as illustrated in Equation 11. In this case red indicates average PM_{2.5} Intake Fractions of 4.519×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 3.832×10^{-15} or lower.

$$iF_{DA} = \frac{\text{\# of people in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P9 in each DA} \times \text{average person's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 11})$$

Visually comparing the individual source Intake Fraction distributions (Figures 3.2.12 - 3.2.20) with the concentration distributions of the corresponding source (Figures 3.2.2 – 3.2.10), it is obvious that the Intake Fraction is strongly influenced by the PM2.5 concentration distributions. For example, the only Dissemination Areas with Intake Fractions above 3.832×10^{-15} (symbolized as a dark green colour) in Figure 3.2.20 are located in the PM2.5 plume illustrated in Figure 3.2.10. The population of each Dissemination Area has an effect on the Intake Fraction, as well. A closer inspection of Figures 3.2.12 – 3.2.20 (especially Figures 3.2.12 and 3.2.13) and comparison with their corresponding concentration distributions found in Figures 3.2.2 – 3.2.10 reveals that there are several Dissemination Area polygons that experience relatively low concentrations, but relatively high Intake Fractions. The opposite can also be observed. Some Dissemination Areas that experience relatively high concentrations have relatively low Intake Fractions. Considering that the number of people and the average PM2.5 concentration are both variables in Equations 3 - 11, it is expected that the resulting Intake Fraction will depend on the combination of population and concentration. In other words, Intake Fraction is an estimate of exposure.

3.2.3 Contributing Source PM2.5 Intake Fraction Contributions for Total Population

Figure 3.2.21 illustrates the Report Tool user dialog configured to calculate the Intake Fraction contributions to the total population from each of the nine point sources. Clicking the Report button with the Report Tool user dialog in this configuration results in the addition of an Intake Fraction contribution attribute to the point source shapefile created by the Import Tool (illustrated in Figure 3.1.6). This shapefile is then symbolized using a natural break renderer with ten classes. Figure 3.2.22 illustrates the results of the Report Tool.



Figure 3.2.21 Report Tool – User Dialog (Total Population Contributing Source Intake Fraction Configuration)

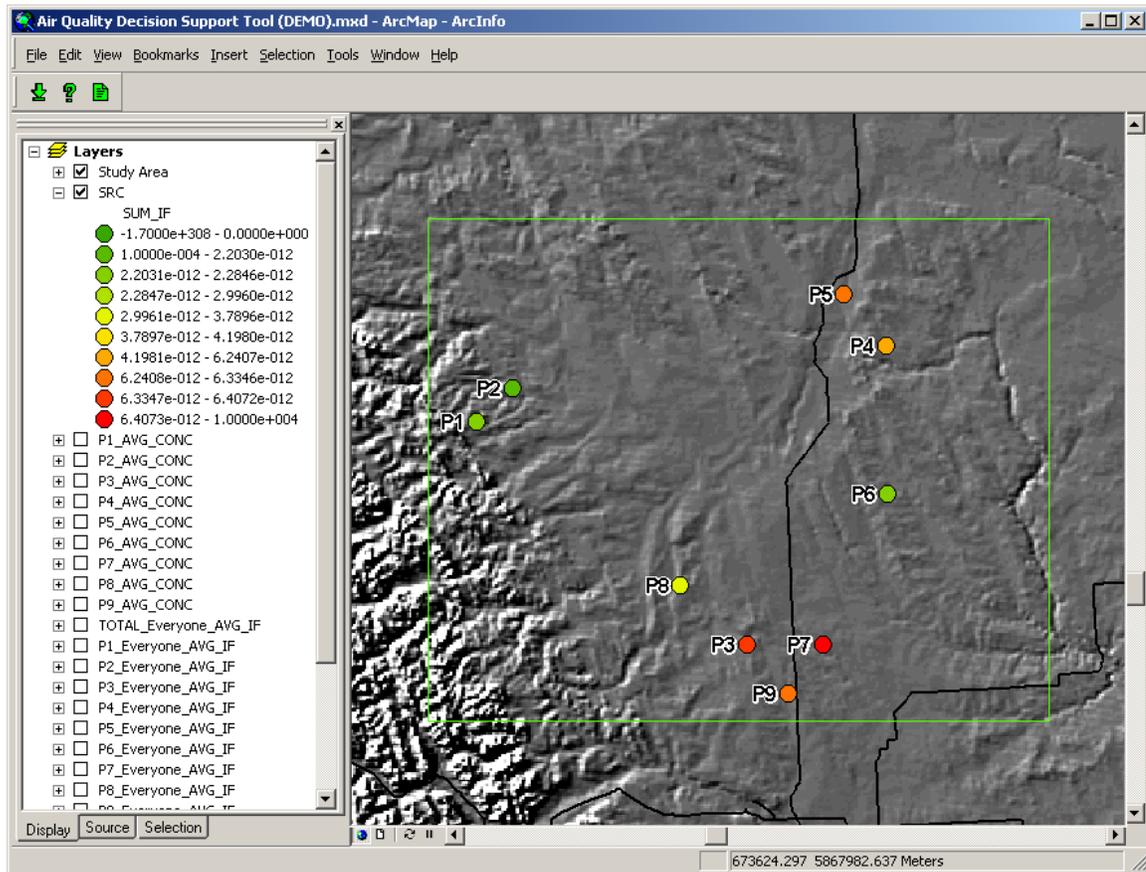


Figure 3.2.22 Report Tool – Point Sources Ranked based on Intake Fraction Contribution for Total Population

Figure 3.2.22 illustrates the Report Tool user interface displaying locations of the PM_{2.5} emission sources, symbolized based on their relative Intake Fraction contributions to

everyone in the study area. These Intake Fraction contributions were calculated by summing the Intake Fraction contributions from each Dissemination Area for each emission source. Red indicates emission sources with the relatively high Intake Fraction contributions and green indicates emission sources with relatively low Intake Fraction contributions. In this case, emission source P7 has the highest Intake Fraction contribution and emission source P2 has the lowest Intake Fraction contribution.

Table 3.2.2 presents the Intake Fraction contributions from each of the nine point sources. Despite the analysis of the results of the Import Tool (Figures 3.2.2 – 3.2.10 and Table 3.2.1) indicating that point sources P4 and P5 created significantly higher average PM2.5 concentrations than the other sources, point source P7 has the highest estimated Intake Fraction. In other words, a higher fraction of pollution that is emitted from point sources P7 can be absorbed by the population compared to pollution emitted from the other point sources.

Table 3.2.2 Point Source Intake Fraction Contributions to Total Population

Point Source	Intake Fraction Contribution (10^{-12})
P7	7.4590
P3	6.4070
P9	6.3346
P5	6.2407
P4	4.1980
P8	2.9960
P1	2.2846
P6	2.2030
P2	1.9592

This result demonstrates the usefulness of this decision support system and Intake Fraction as an estimation of exposure. Even though the average ground level pollutant concentration resulting from the emissions of point source P7 was almost one hundred times lower than the highest values it is the most significant source. This ranking does not imply that emission source P7 is the most dangerous source. However, it does imply that exposure is most sensitive to changes in emission characteristics of P7. By the same logic, exposure is least sensitive to changes in the emission characteristics of emission source P2. From a decision support perspective, these results indicate that decreasing emissions from P7 would result in a higher proportional drop in pollution absorption by the population than decreasing the emissions of any other source. Conversely, increasing the emissions from P2 would result in a lower increase in pollution absorption by the population than increasing the emissions of any other source.

3.3 Contributing Source Intake Fraction for Sub-Populations

Contributing Intake Fraction for a sub-population is an estimate of the fraction of the pollutant emitted by each individual modeled source that is breathed in by a sub-population (ex. Persons 65 years of age and older) in the study area. A separate Intake Fraction calculation is completed for each PM_{2.5} emitting source and each sub-population considered. The results from two sub-populations are presented in this section: (i) persons 14 years of age or younger (children) and (ii) persons 65 years of age or older (seniors).

This configuration requires the Import Tool to be run in the same configuration as the Total Population Contributing Source Intake Fraction. Please refer to Figures 3.2.1 – 3.2.10 and Table 3.2.1.

3.3.1 Contributing Source PM2.5 Intake Fraction for Children and Seniors

Figure 3.3.1 illustrates the Analyze Tool user dialog configured to calculate the contributing source Intake Fraction for the average ground level pollutant concentrations for children. Figure 3.3.2 illustrates the Analyze Tool user dialog configured to calculate the contributing source Intake Fraction for the average ground level pollutant concentrations for seniors. Running the Analyze Tool in these configuration results in eighteen shapefiles containing polygon features representing Dissemination Areas, each with an average Intake Fraction attribute. Each shapefile represents the average Intake Fractions of a single sub-population that result from the emissions of a single pollutant source. Since there are nine sources in the study area and two sub-populations, there are eighteen average Intake Fraction shapefiles (illustrated in Figures 3.3.3 – 3.3.20). These shapefiles are then symbolized using a natural break renderer with ten classes.

The image shows a software dialog box titled "Analyze Dialog". It contains the following elements:

- Dissemination Area Layer:** A dropdown menu set to "Dissemination Area".
- Intake Fraction Type:** Two radio buttons: "Maximum" (unselected) and "Average" (selected).
- Analyze Source Contributions:** A checked checkbox.
- Receptors:** A section containing:
 - Gender:** Three radio buttons: "Everyone" (selected), "Males" (unselected), and "Females" (unselected).
 - Age:** A list of age ranges with checkboxes:
 - 0 to 5
 - 5 to 9
 - 10 to 14
 - 15 to 19
 - 20 to 24
 - 25 to 29
 - 30 to 34
 - 35 to 39
 - 40 to 44
 - 45 to 49
 - 50 to 54
 - 55 to 59
 - 60 to 64
 - 65 to 69
 - 70 to 74
 - 75 to 79
 - 80 to 84
 - 85 plus
 - All Ages

- Output Folder:** A text field containing "D:\Air Quality Decision Support To" and a "Browse" button.
- Buttons:** "Analyze" and "Cancel" buttons at the bottom.

Figure 3.3.1 Analyze Tool - User Dialog (Children Contributing Source Intake Fraction Configuration)

The image shows a software dialog box titled "Analyze Dialog". It contains the following elements:

- Dissemination Area Layer:** A dropdown menu set to "Dissemination Area".
- Intake Fraction Type:** Two radio buttons: "Maximum" (unselected) and "Average" (selected).
- Analyze Source Contributions:** A checked checkbox.
- Receptors:**
 - Gender:** Three radio buttons: "Everyone" (selected), "Males" (unselected), and "Females" (unselected).
 - Age:** A grid of checkboxes for age groups:

<input type="checkbox"/>	0 to 5	<input type="checkbox"/>	45 to 49
<input checked="" type="checkbox"/>	All Ages	<input type="checkbox"/>	50 to 54
<input type="checkbox"/>	10 to 14	<input type="checkbox"/>	55 to 59
<input type="checkbox"/>	15 to 19	<input type="checkbox"/>	60 to 64
<input type="checkbox"/>	20 to 24	<input checked="" type="checkbox"/>	65 to 69
<input type="checkbox"/>	25 to 29	<input checked="" type="checkbox"/>	70 to 74
<input type="checkbox"/>	30 to 34	<input checked="" type="checkbox"/>	75 to 79
<input type="checkbox"/>	35 to 39	<input checked="" type="checkbox"/>	80 to 84
<input type="checkbox"/>	40 to 44	<input checked="" type="checkbox"/>	85 plus
- Output Folder:** A text field containing "D:\Air Quality Decision Support To" and a "Browse" button.
- Buttons:** "Analyze" and "Cancel" buttons at the bottom.

Figure 3.3.2 Analyze Tool - User Dialog (Seniors Contributing Source Intake Fraction Configuration)

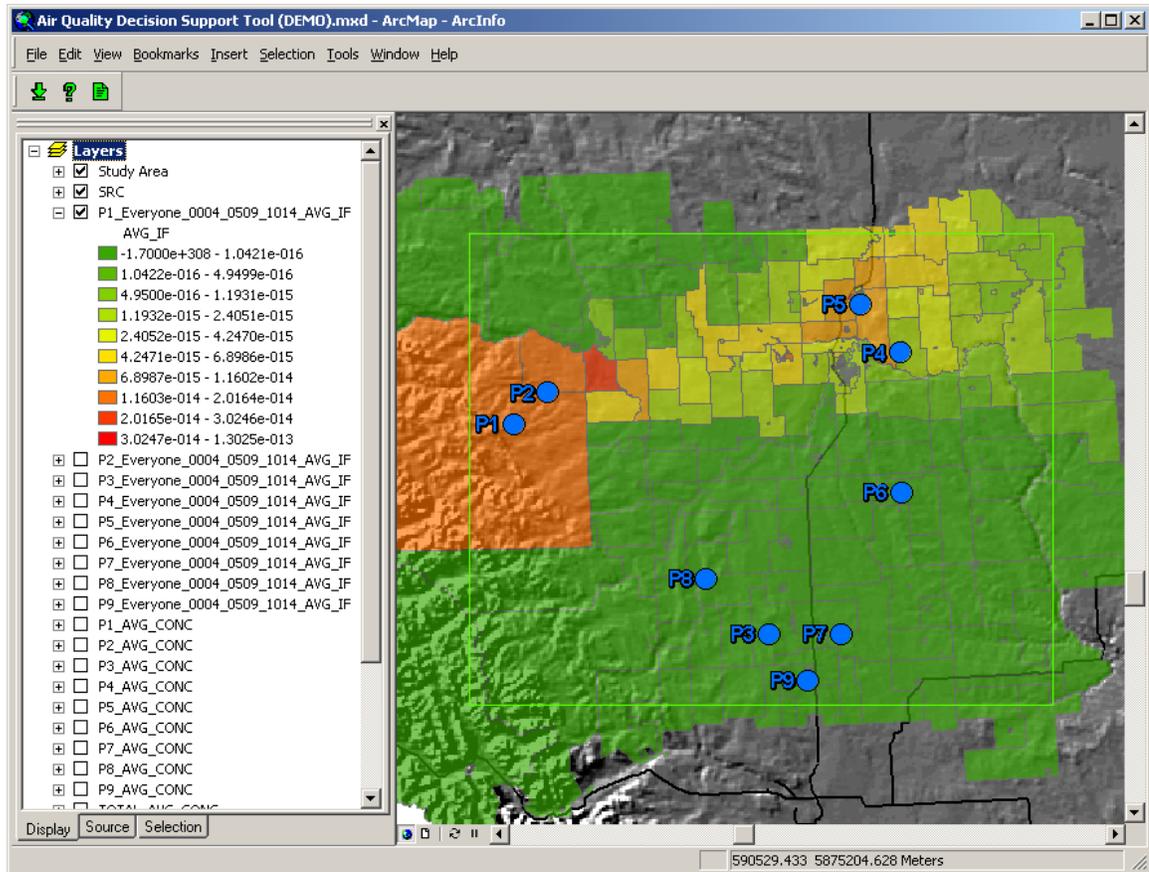


Figure 3.3.3 Analyze Tool – P1 Children Population Average Intake Fraction

Figure 3.3.3 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P1 for children. These values are obtained using the Intake Equation as illustrated in Equation 12. In this case red indicates average PM_{2.5} Intake Fractions of 1.303×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 1.042×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P1 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 12})$$

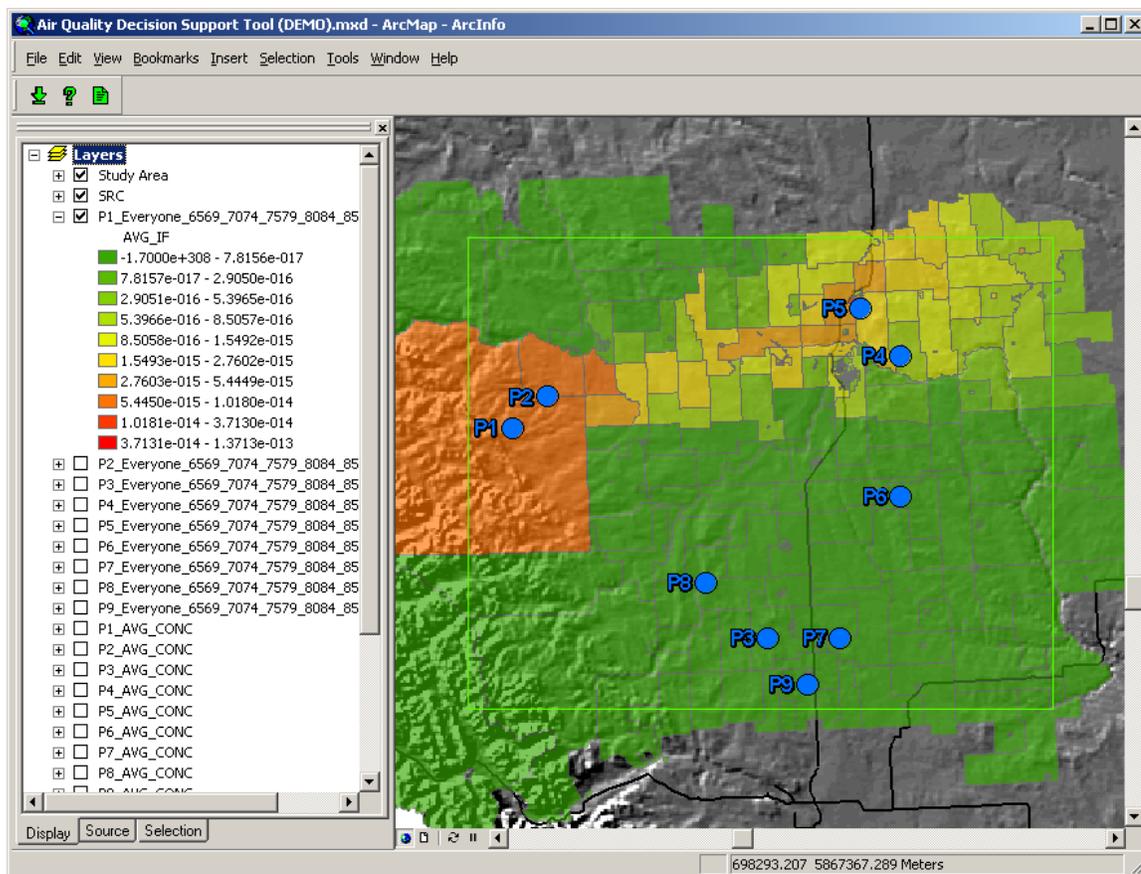


Figure 3.3.4 Analyze Tool – P1 Seniors Population Average Intake Fraction

Figure 3.3.4 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P1 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 13. In this case red indicates average PM_{2.5} Intake Fractions of 1.371×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 7.816×10^{-17} or lower.

$$iF_{DA} = \frac{\text{\# of seniors in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P1 in each DA} \times \text{average seniors' breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 13})$$

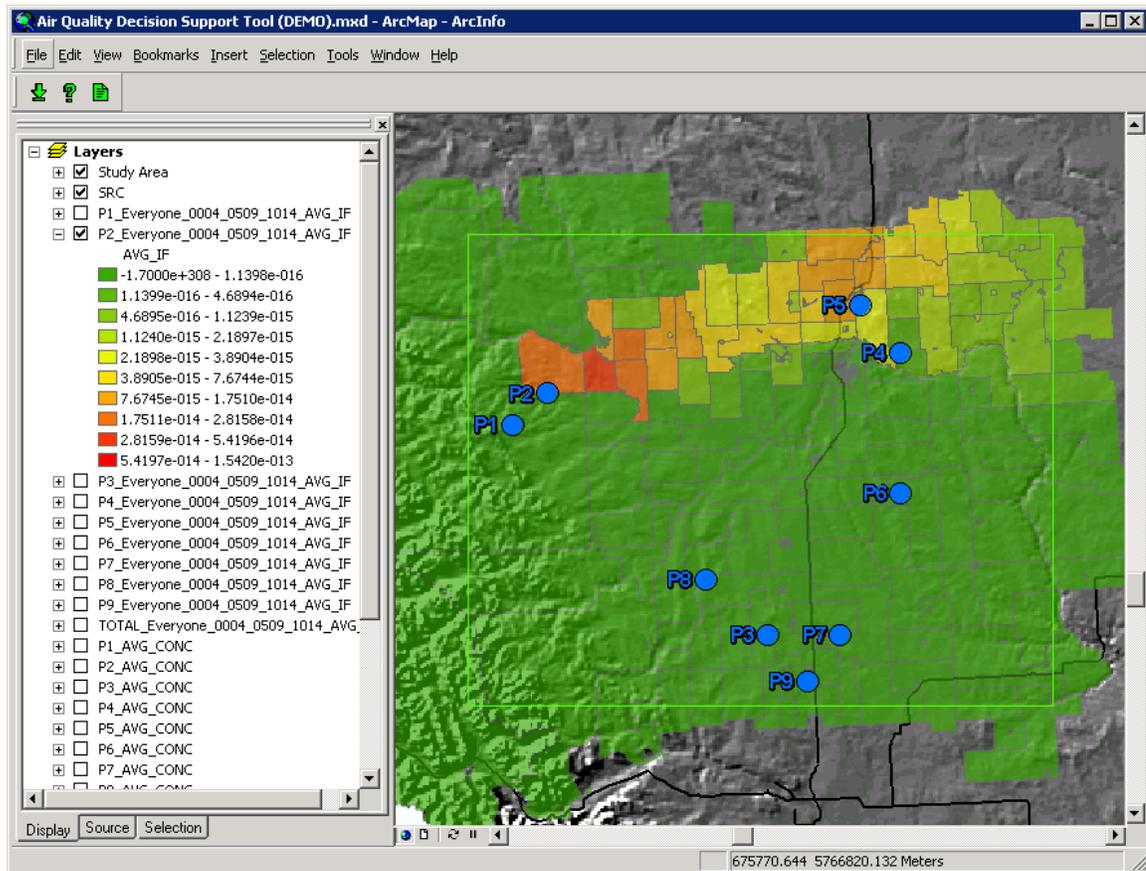


Figure 3.3.5 Analyze Tool – P2 Children Population Average Intake Fraction

Figure 3.3.5 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P2 for children. These values are obtained using the Intake Equation as illustrated in Equation 14. In this case red indicates average PM_{2.5} Intake Fractions of 1.542×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 1.140×10^{-16} or lower.

$$iF_{DA} = \frac{\text{\# of children in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P2 in each DA} \times \text{average children's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 14})$$

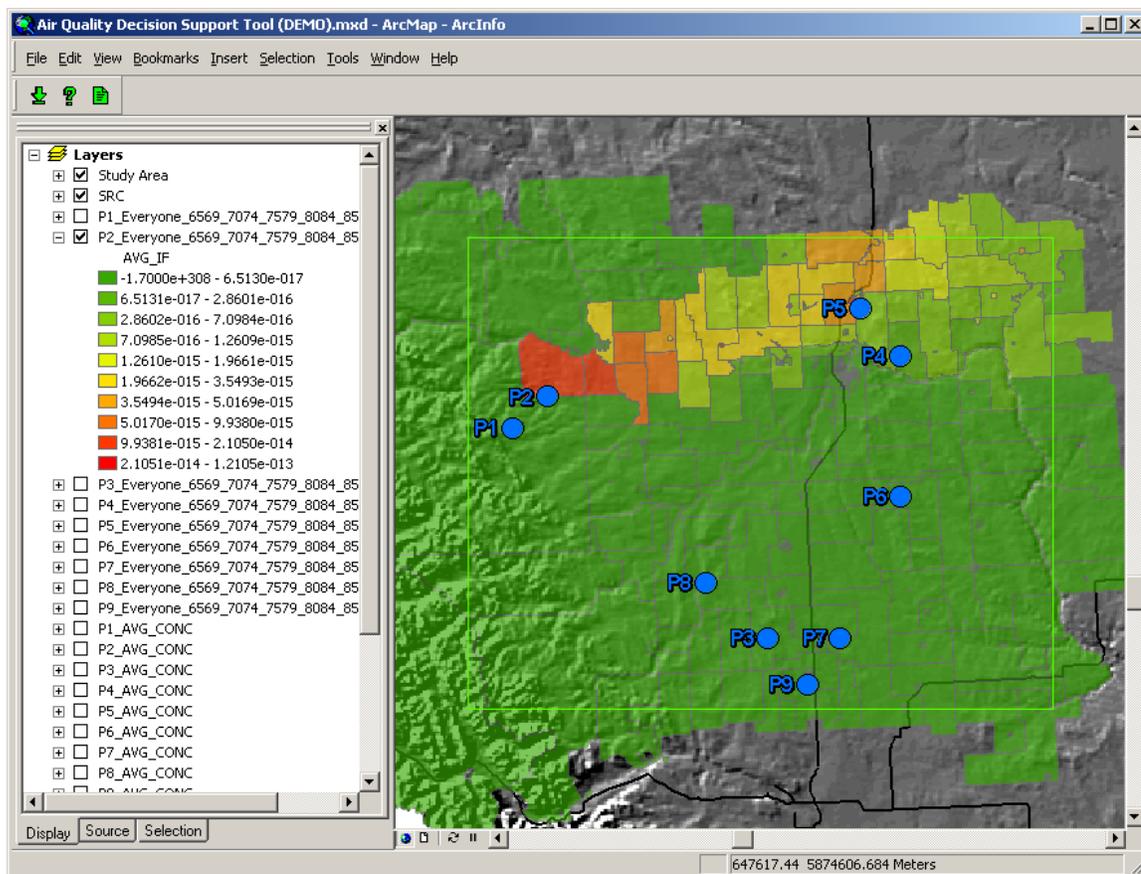


Figure 3.3.6 Analyze Tool – P2 Seniors Population Average Intake Fraction

Figure 3.3.6 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P2 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 15. In this case red indicates average PM_{2.5} Intake Fractions of 1.211×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 6.513×10^{-17} or lower.

$$iF_{DA} = \frac{\text{\# of seniors in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P2 in each DA} \times \text{average seniors' breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 15})$$

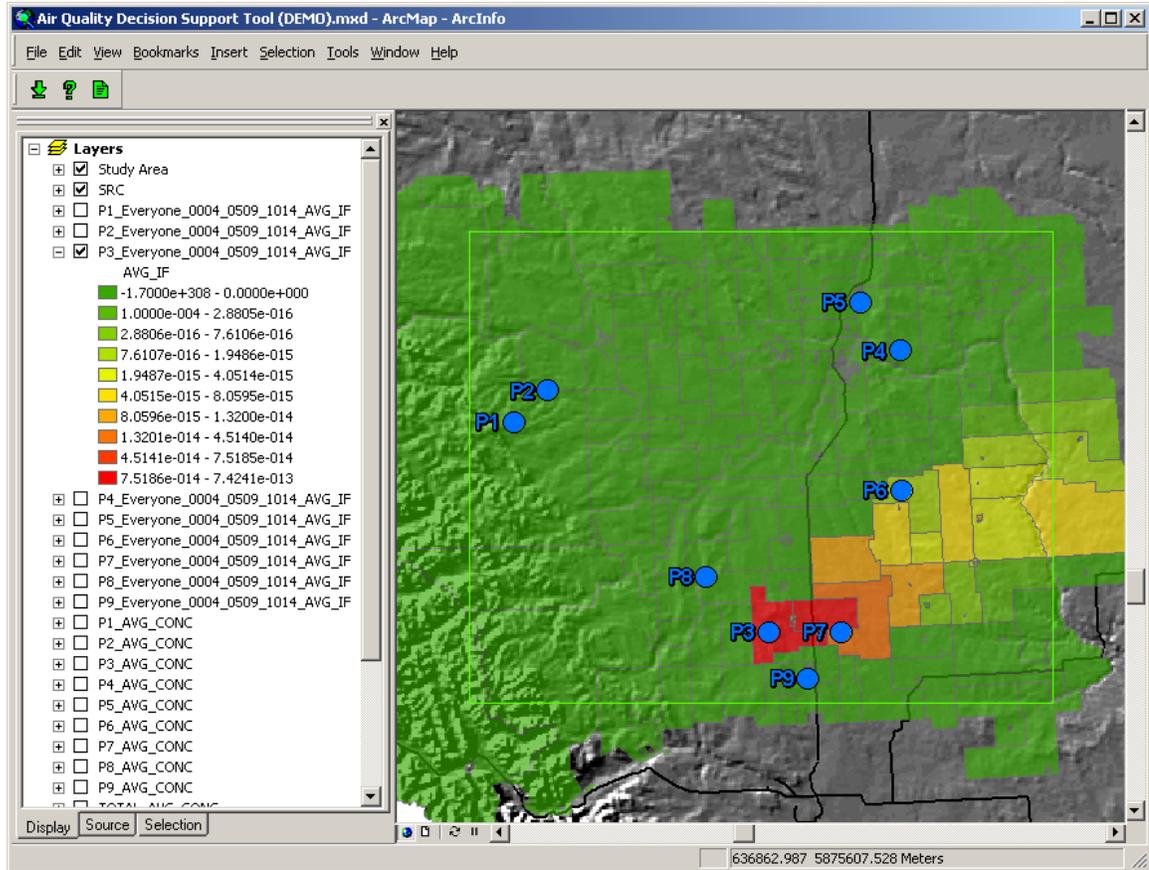


Figure 3.3.7 Analyze Tool – P3 Children Population Average Intake Fraction

Figure 3.3.7 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P3 for children. These values are obtained using the Intake Equation as illustrated in Equation 16. In this case red indicates average PM_{2.5} Intake Fractions of 7.424×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 2.881×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P3 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 16})$$

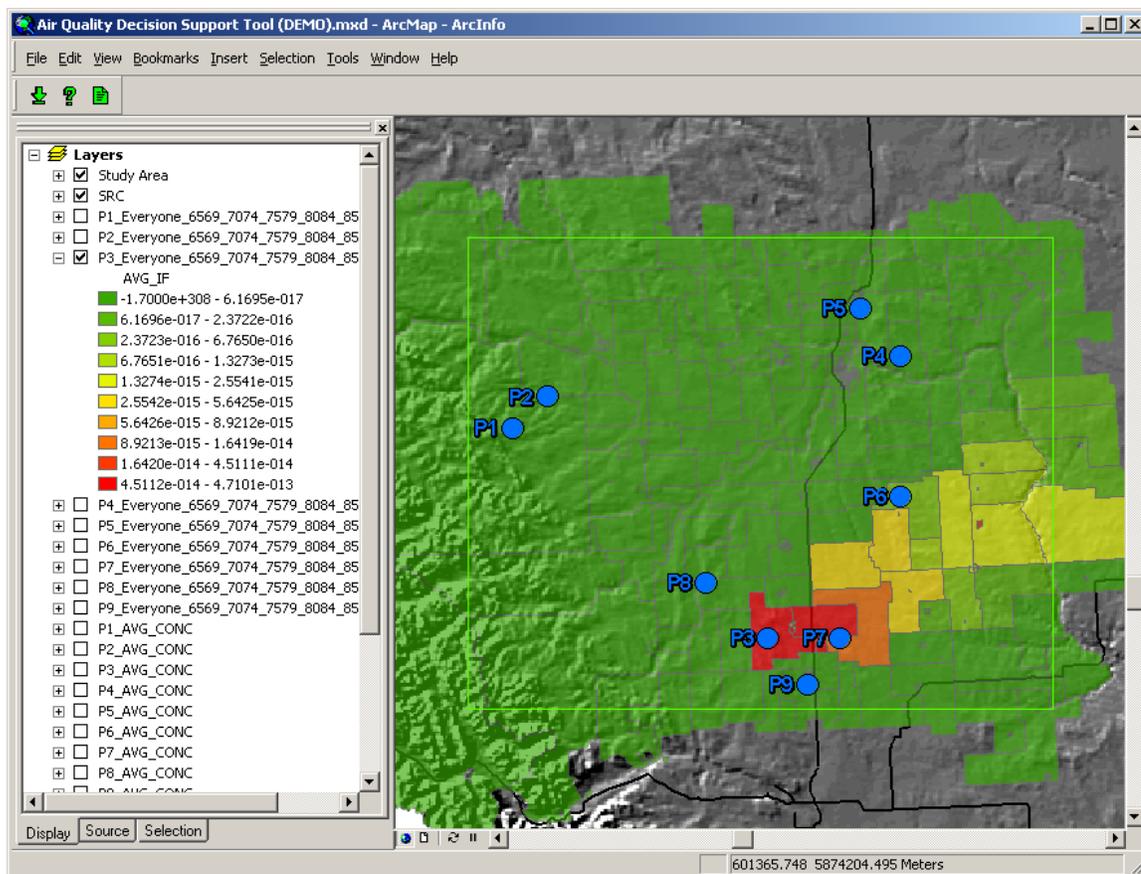


Figure 3.3.8 Analyze Tool – P3 Seniors Population Average Intake Fraction

Figure 3.3.8 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P3 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 17. In this case red indicates average PM_{2.5} Intake Fractions of 4.710×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 6.170×10^{-17} or lower.

$$iF_{DA} = \frac{\text{\# of seniors in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P3 in each DA} \times \text{average seniors' breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 17})$$

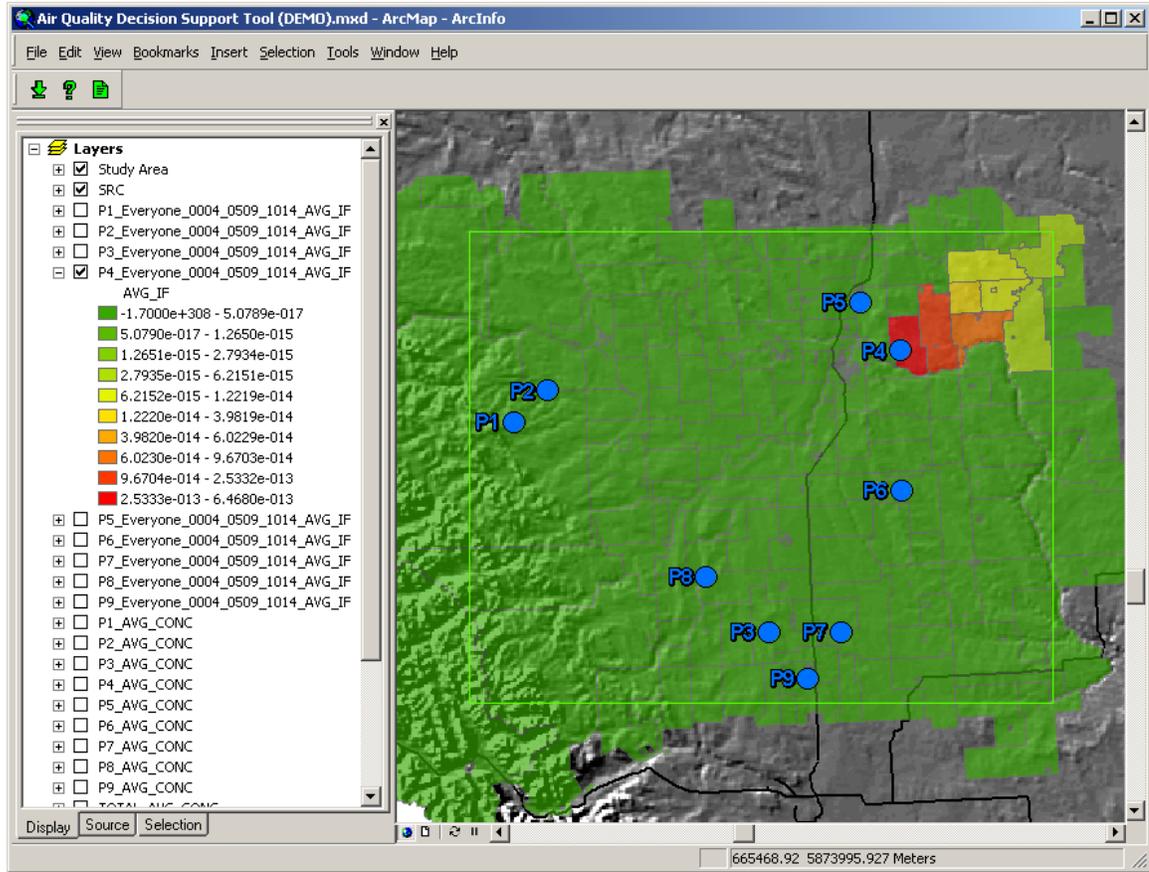


Figure 3.3.9 Analyze Tool – P4 Children Population Average Intake Fraction

Figure 3.3.9 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P4 for children. These values are obtained using the Intake Equation as illustrated in Equation 18. In this case red indicates average PM_{2.5} Intake Fractions of 6.468×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 5.079×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P4 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 18})$$

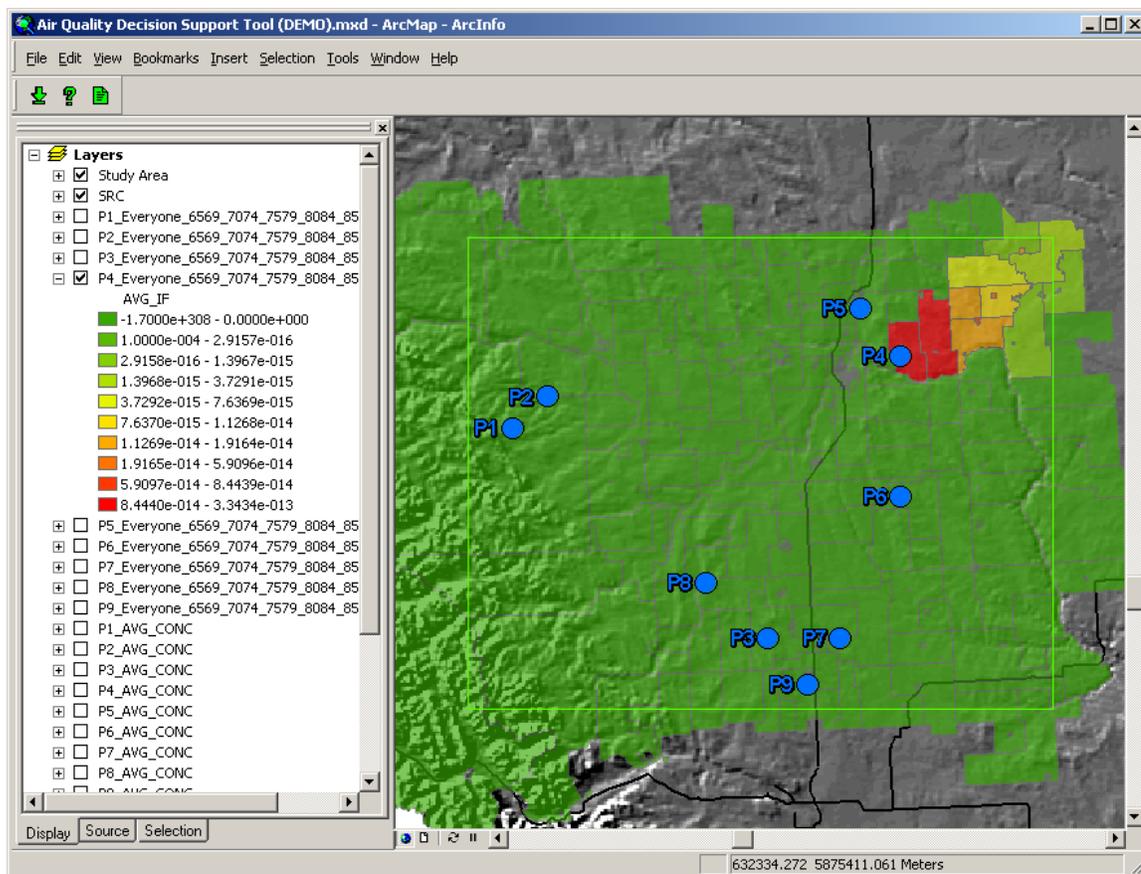


Figure 3.3.10 Analyze Tool – P4 Seniors Population Average Intake Fraction

Figure 3.3.10 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P4 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 19. In this case red indicates average PM_{2.5} Intake Fractions of 3.343×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 2.916×10^{-15} or lower.

$$iF_{DA} = \frac{\text{\# of seniors in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P4 in each DA} \times \text{average seniors' breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 19})$$

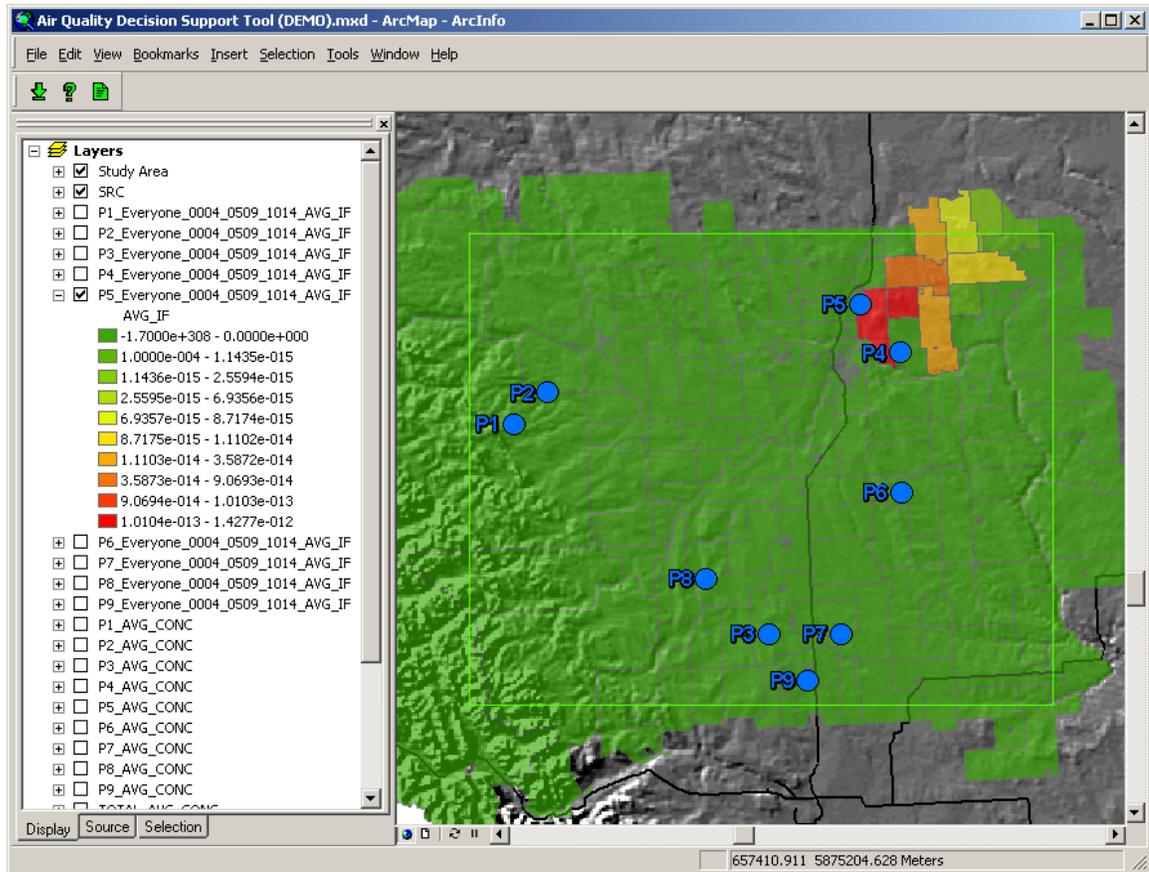


Figure 3.3.11 Analyze Tool – P5 Children Population Average Intake Fraction

Figure 3.3.11 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P5 for children. These values are obtained using the Intake Equation as illustrated in Equation 20. In this case red indicates average PM_{2.5} Intake Fractions of 1.428×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 1.1435×10^{-15} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P5 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 20})$$

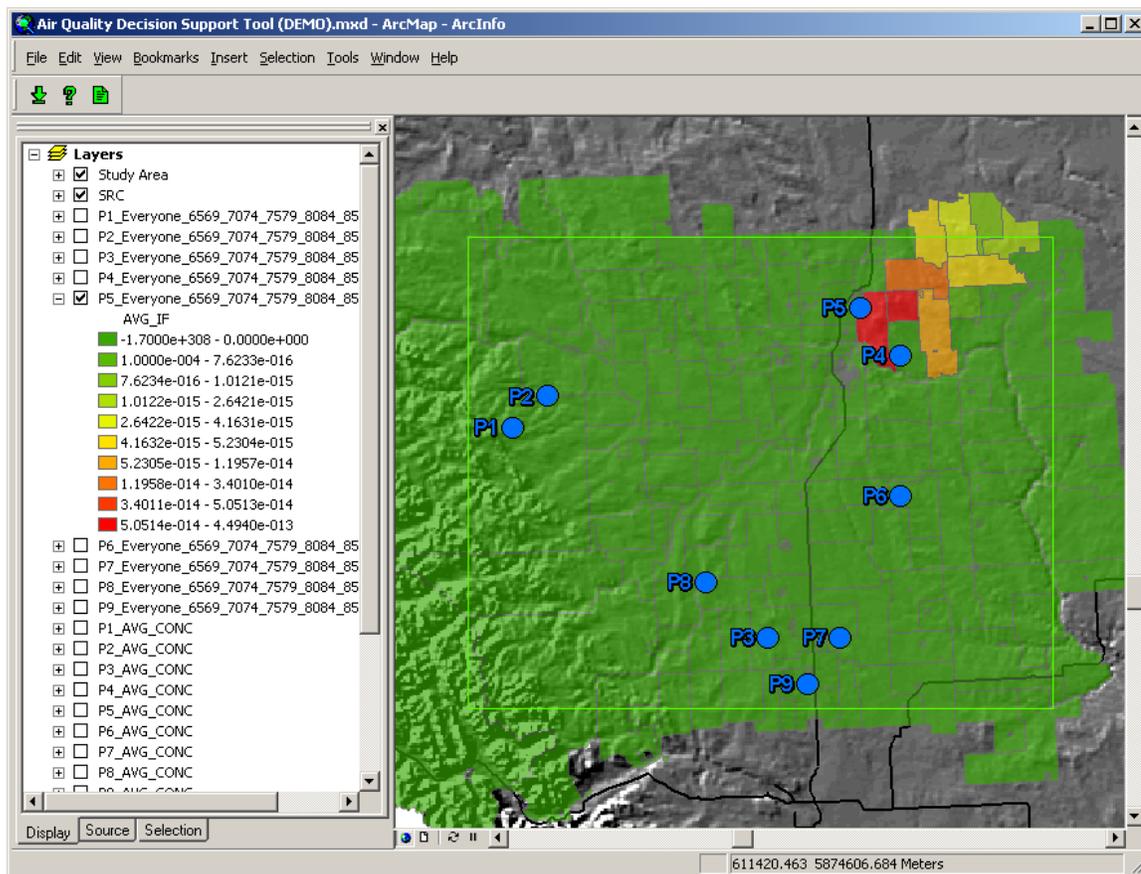


Figure 3.3.12 Analyze Tool – P5 Seniors Population Average Intake Fraction

Figure 3.3.12 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P5 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 21. In this case red indicates average PM_{2.5} Intake Fractions of 4.494×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 7.623×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of seniors in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P5 in each DA} \times \\ \text{average seniors' breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 21})$$

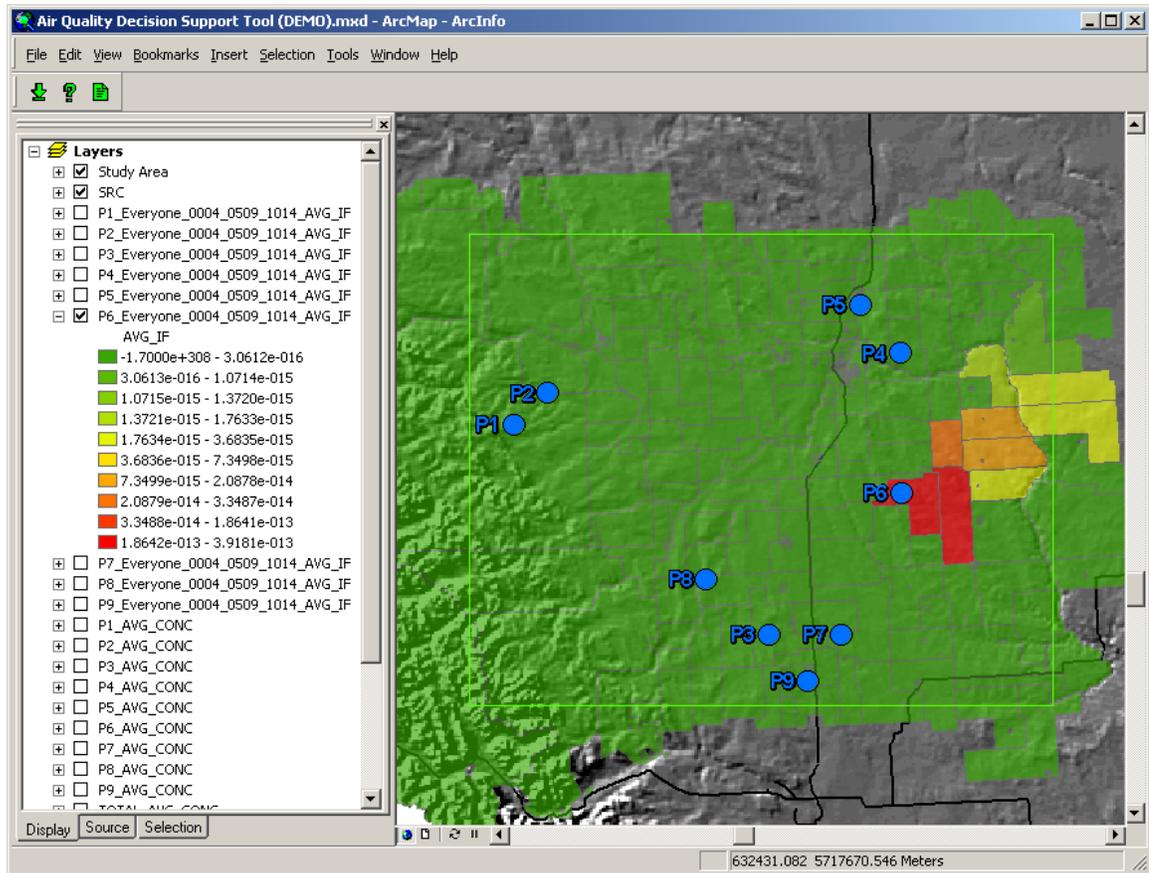


Figure 3.3.13 Analyze Tool – P6 Children Population Average Intake Fraction

Figure 3.3.13 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P6 for children. These values are obtained using the Intake Equation as illustrated in Equation 22. In this case red indicates average PM_{2.5} Intake Fractions of 3.918×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 3.061×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P6 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 22})$$

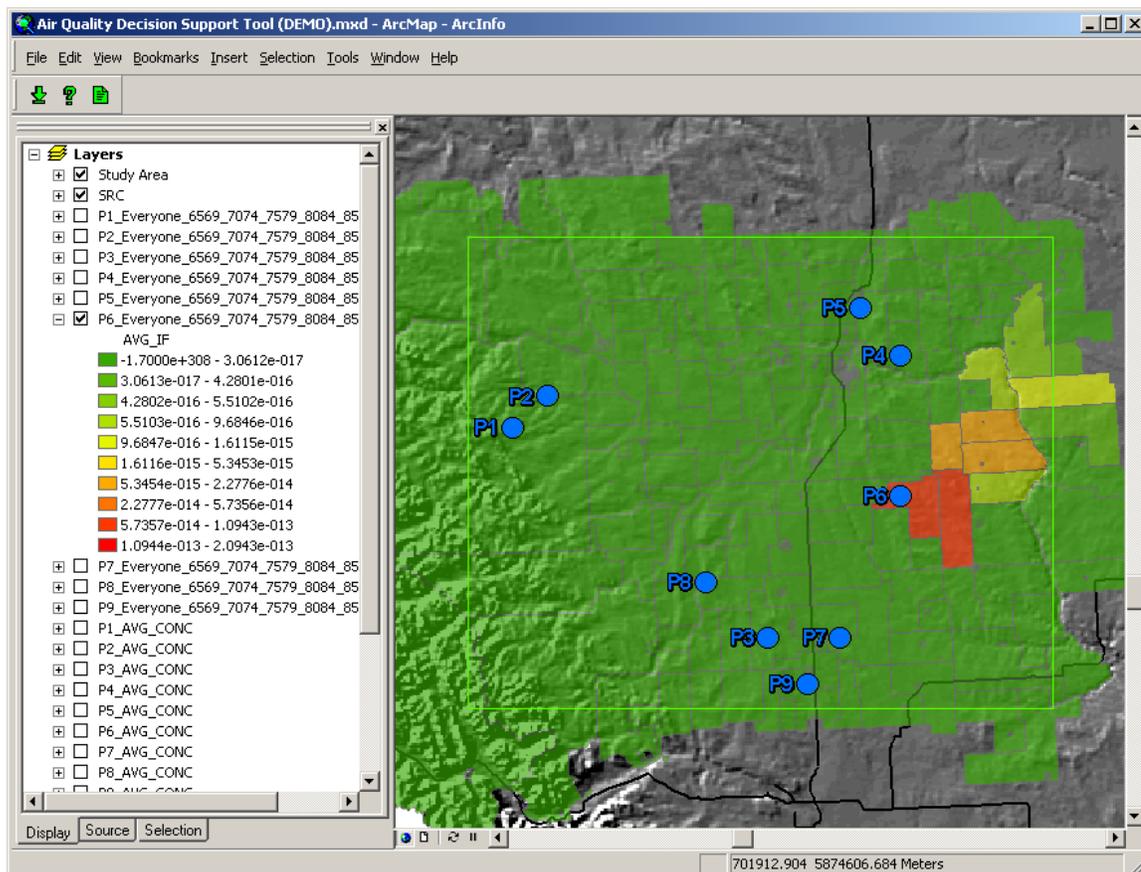


Figure 3.3.14 Analyze Tool – P6 Seniors Population Average Intake Fraction

Figure 3.3.14 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P6 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 23. In this case red indicates average PM_{2.5} Intake Fractions of 2.094×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 3.061×10^{-17} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of seniors in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P6 in each DA} \times \\ \text{average seniors' breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 23})$$

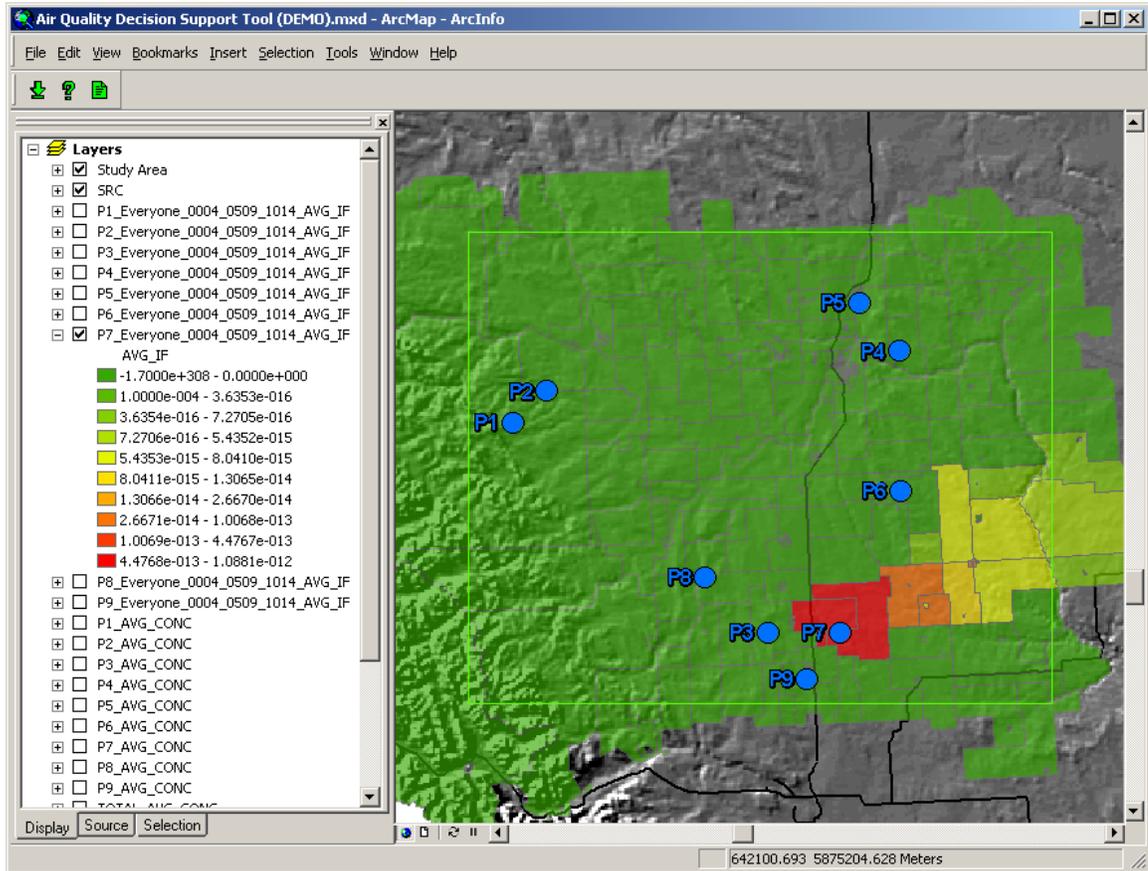


Figure 3.3.15 Analyze Tool – P7 Children Population Average Intake Fraction

Figure 3.3.15 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P7 for children. These values are obtained using the Intake Equation as illustrated in Equation 24. In this case red indicates average PM_{2.5} Intake Fractions of 1.088×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 3.635×10^{-16} or lower.

$$iF_{DA} = \frac{\text{\# of children in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P7 in each DA} \times \text{average children's breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 24})$$

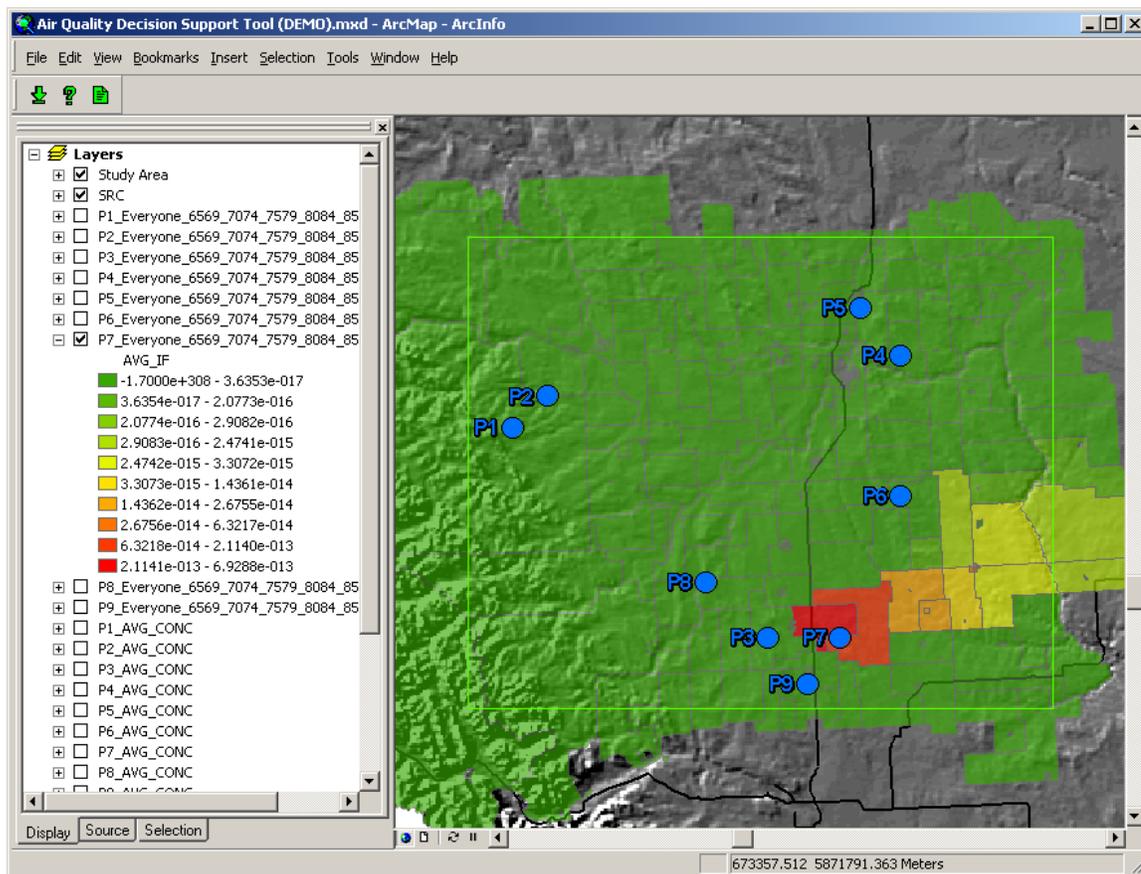


Figure 3.3.16 Analyze Tool – P7 Seniors Population Average Intake Fraction

Figure 3.3.16 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P7 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 25. In this case red indicates average PM_{2.5} Intake Fractions of 6.929×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 3.635×10^{-17} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of seniors in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P7 in each DA} \times \\ \text{average seniors' breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 25})$$

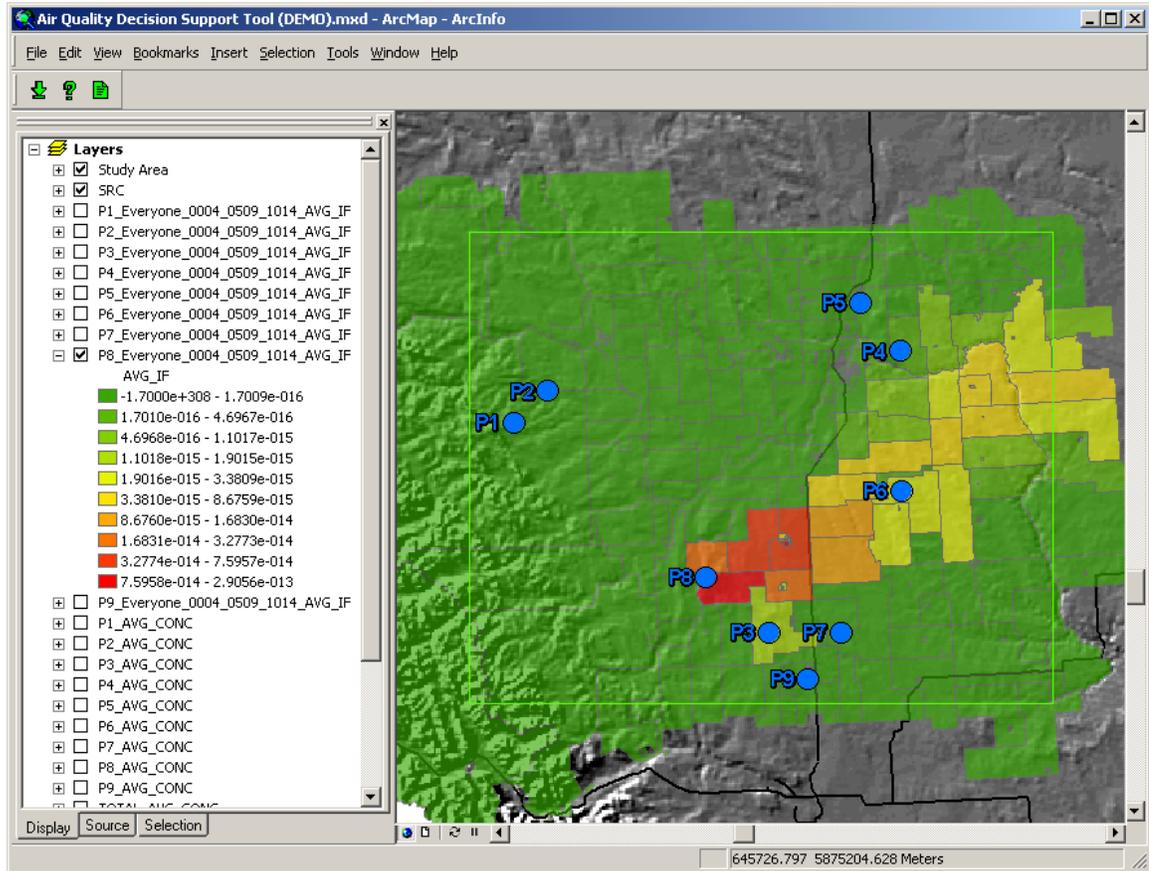


Figure 3.3.17 Analyze Tool – P8 Children Population Average Intake Fraction

Figure 3.3.17 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P8 for children. These values are obtained using the Intake Equation as illustrated in Equation 26. In this case red indicates average PM_{2.5} Intake Fractions of 2.906×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 1.701×10^{-16} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P8 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 26})$$

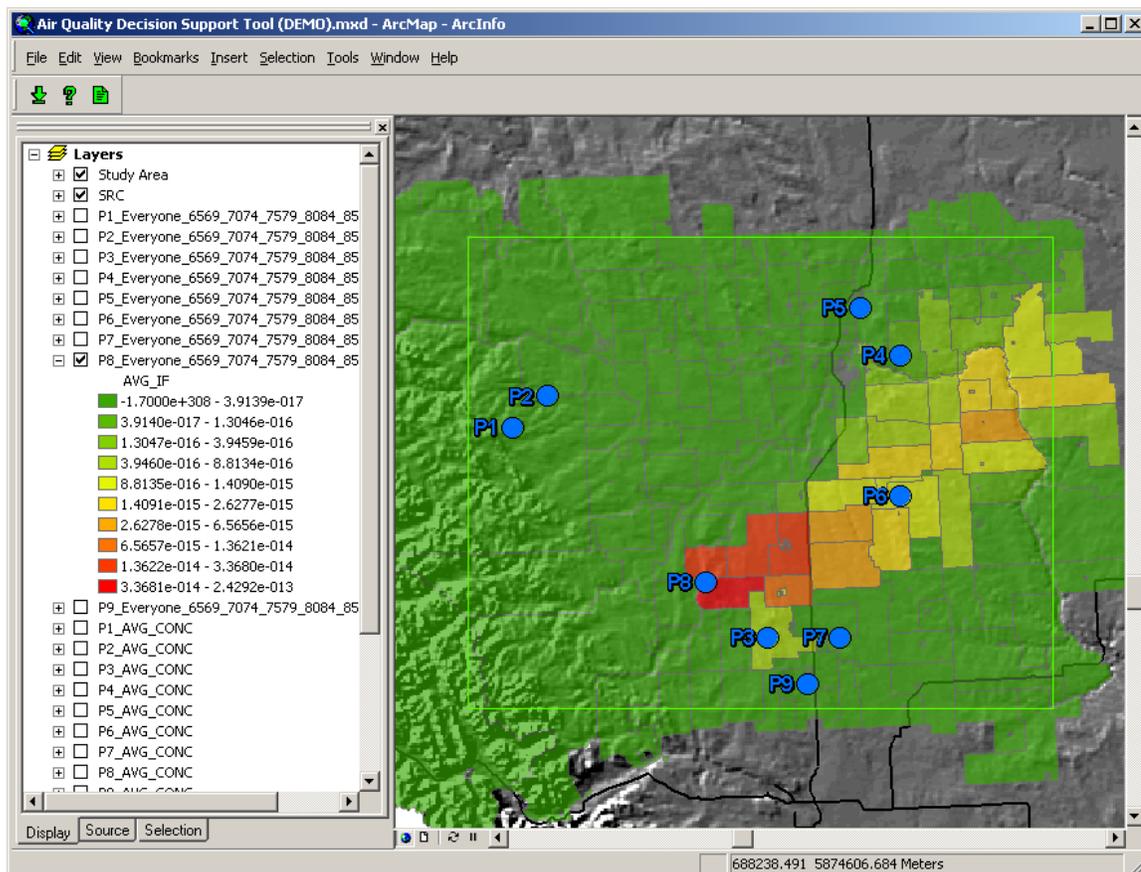


Figure 3.3.18 Analyze Tool – P8 Seniors Population Average Intake Fraction

Figure 3.3.18 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P8 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 27. In this case red indicates average PM_{2.5} Intake Fractions of 2.429×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 3.914×10^{-17} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of seniors in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P8 in each DA} \times \\ \text{average seniors' breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 27})$$

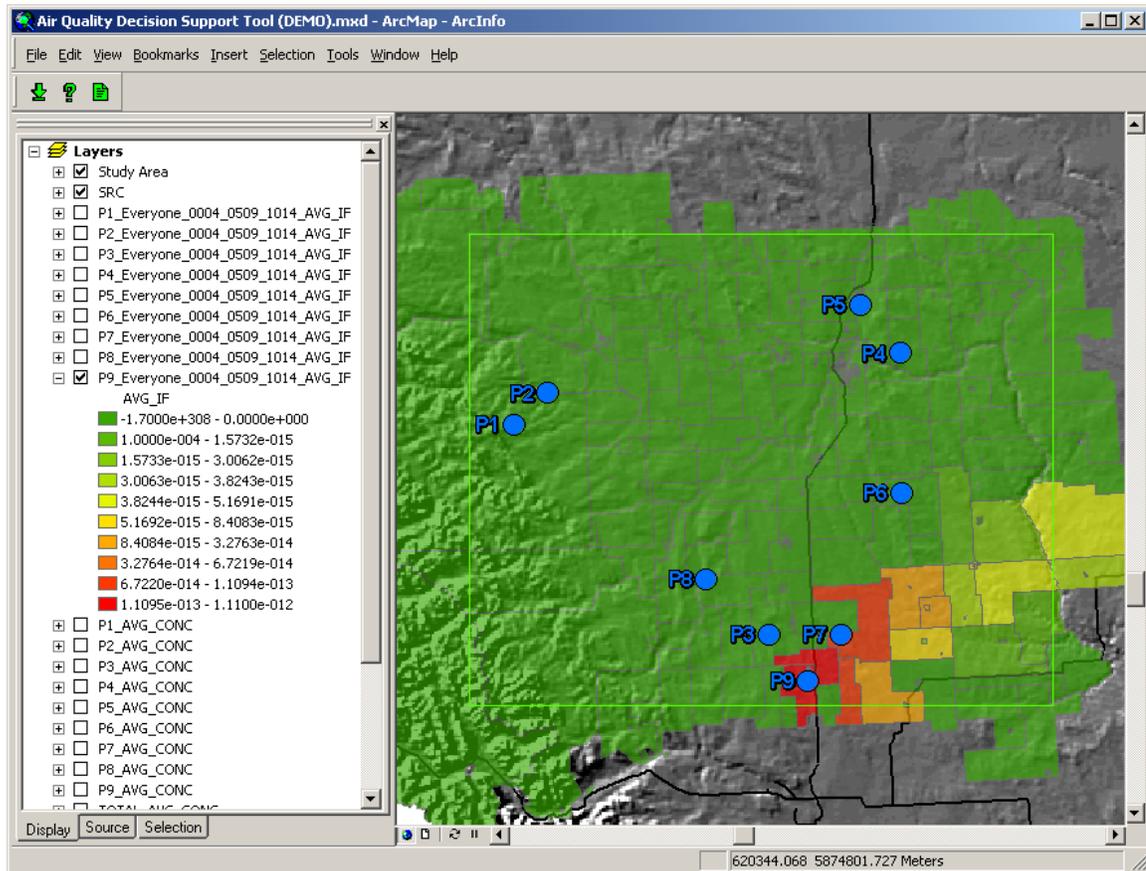


Figure 3.3.19 Analyze Tool – P9 Children Population Average Intake Fraction

Figure 3.3.19 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P9 for children. These values are obtained using the Intake Equation as illustrated in Equation 28. In this case red indicates average PM_{2.5} Intake Fractions of 1.110×10^{-12} or higher and green indicates average PM_{2.5} Intake Fractions 1.573×10^{-15} or lower.

$$iF_{DA} = \frac{\begin{array}{l} \# \text{ of children in each DA} \times \\ \text{average PM}_{2.5} \text{ concentration contribution from source P9 in each DA} \times \\ \text{average children's breathing rate} \end{array}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 28})$$

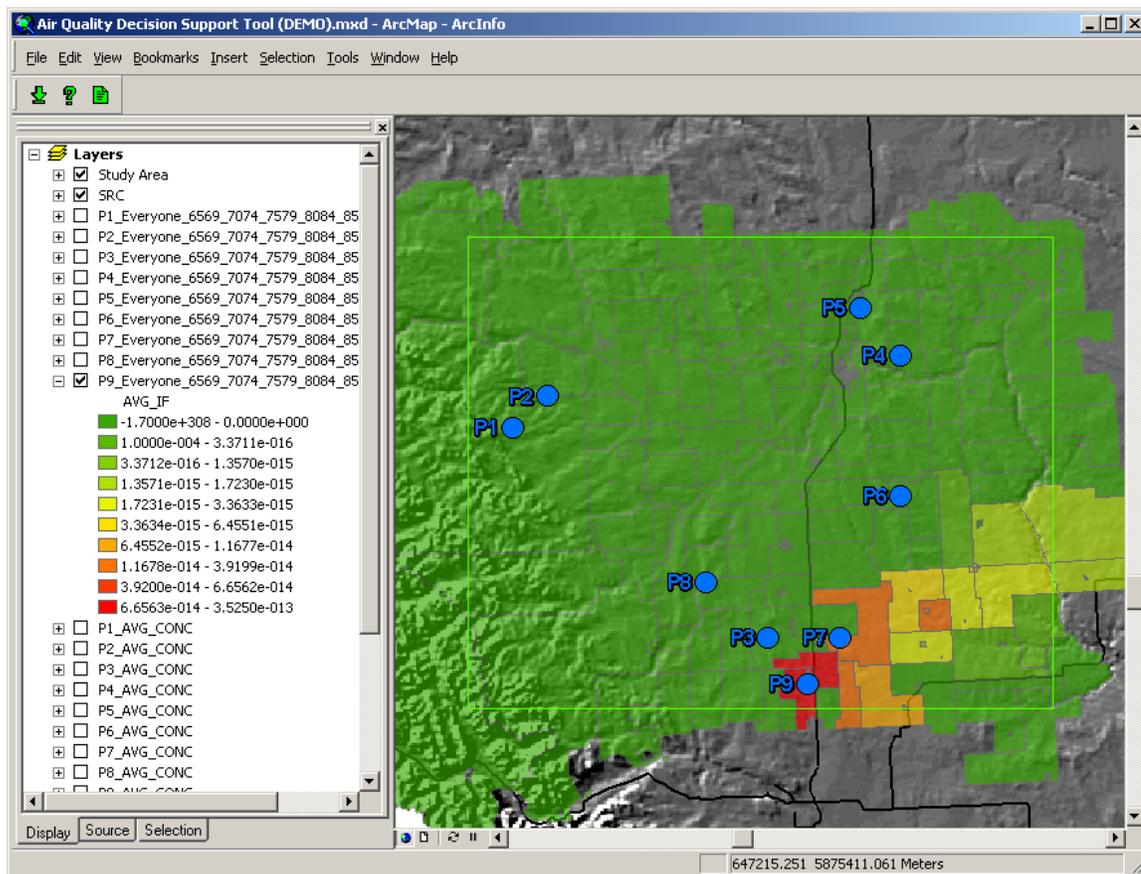


Figure 3.3.20 Analyze Tool – P9 Seniors Population Average Intake Fraction

Figure 3.3.20 illustrates the Analyze Tool user interface displaying the average PM_{2.5} Intake Fraction from pollution source P9 for seniors. These values are obtained using the Intake Equation as illustrated in Equation 29. In this case red indicates average PM_{2.5} Intake Fractions of 3.525×10^{-13} or higher and green indicates average PM_{2.5} Intake Fractions 3.371×10^{-16} or lower.

$$iF_{DA} = \frac{\# \text{ of seniors in each DA} \times \text{average PM}_{2.5} \text{ concentration contribution from source P9 in each DA} \times \text{average seniors' breathing rate}}{\text{total amount of PM}_{2.5} \text{ emitted}} \quad (\text{Equation 29})$$

The most important observations from the results of the Analyze Tool in this configuration are the differences between the Intake Fractions experienced by children compared to the Intake Fractions experienced by seniors from the same emission source. Table 3.3.1 shows a comparison between the highest Intake Fractions for children and seniors from the same emission sources. For example, the average Intake Fraction contribution from emission source P5 for children is three times higher than for seniors. This demonstrates that Intake Fraction varies depending on the sub-population considered. The concentrations used to calculate the Intake Fractions for both children and seniors are the same. The differences in the Intake Fractions between children and seniors is due to the difference between the number of children and the number of seniors in each Dissemination Area as well as their difference in breathing rate. Since this is altering a variable in the Intake Fraction equation (Equation 1), these results are expected.

Table 3.3.1 Average PM2.5 Intake Fraction Contributions for Children and Seniors

Emission Source	iF for Children ($\times 10^{-13}$)	iF for Seniors ($\times 10^{-13}$)
P1	1.3025	1.3713
P2	1.5420	1.2105
P3	7.4241	4.7101
P4	6.4680	3.3434
P5	14.277	4.4940
P6	3.9181	2.0943
P7	10.881	6.9288
P8	2.9056	2.4292
P9	11.100	3.5250

3.3.2 Contributing Source PM2.5 Intake Fraction Contributions for Children and Seniors

Figure 3.3.21 illustrates the Report Tool user dialog configured to calculate the children Intake Fraction contributions from each of the nine point sources. Figure 3.3.22 illustrates the Report Tool user dialog configured to calculate the senior Intake Fraction contributions from each of the nine point sources. Running the Report Tool in this configuration results in the addition of an Intake Fraction contribution attribute to the point source shapefile created by the Import Tool (illustrated in Figure 3.1.6). This shapefile is then symbolized using a natural break renderer with nine classes. Figure 3.3.23 and Table 3.3.2 illustrate the results of the Report Tool for children and Figure 3.3.24 and Table 3.3.3 illustrates the results of the Report Tool for seniors.

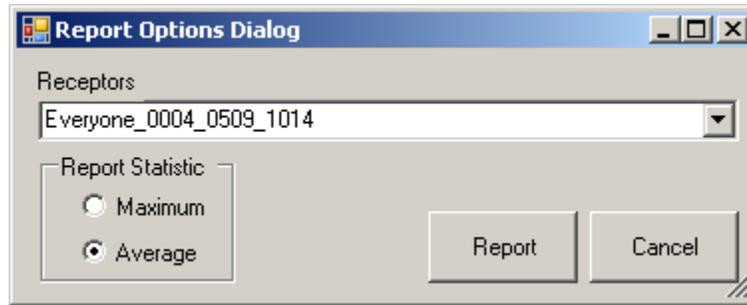


Figure 3.3.21 Report Tool – User Dialog (Children Contributing Source Intake Fraction Configuration)

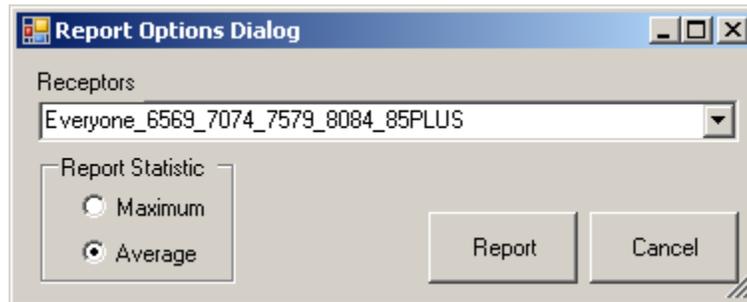


Figure 3.3.22 Report Tool – User Dialog (Senior Contributing Source Intake Fraction Configuration)

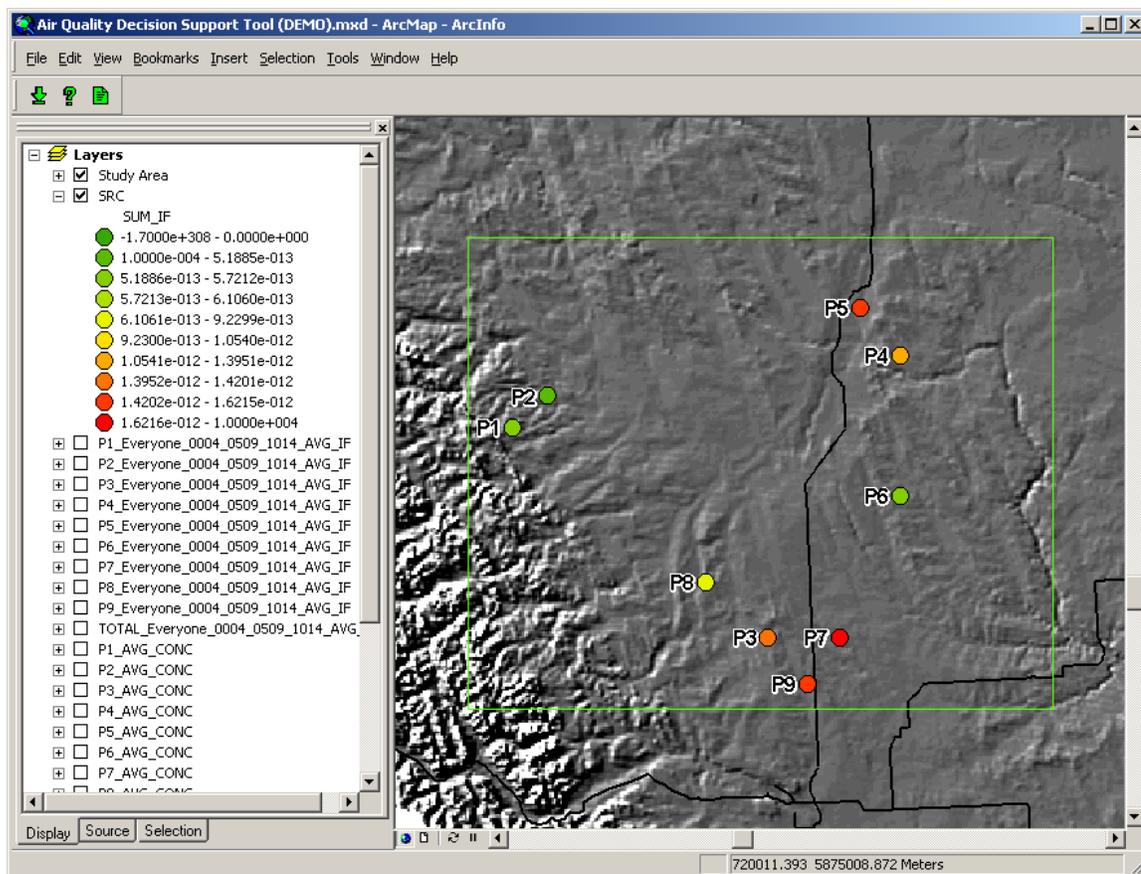


Figure 3.3.23 Report Tool – Point Sources Ranked on Intake Fraction Contribution to Children

Table 3.3.2 Point Source Intake Fraction Contributions to Children

Point Source	Intake Fraction Contribution (10^{-13})
P7	17.612
P5	16.215
P9	14.201
P3	13.951
P4	10.540
P8	6.1060
P6	5.7212
P1	5.1885
P2	4.4928

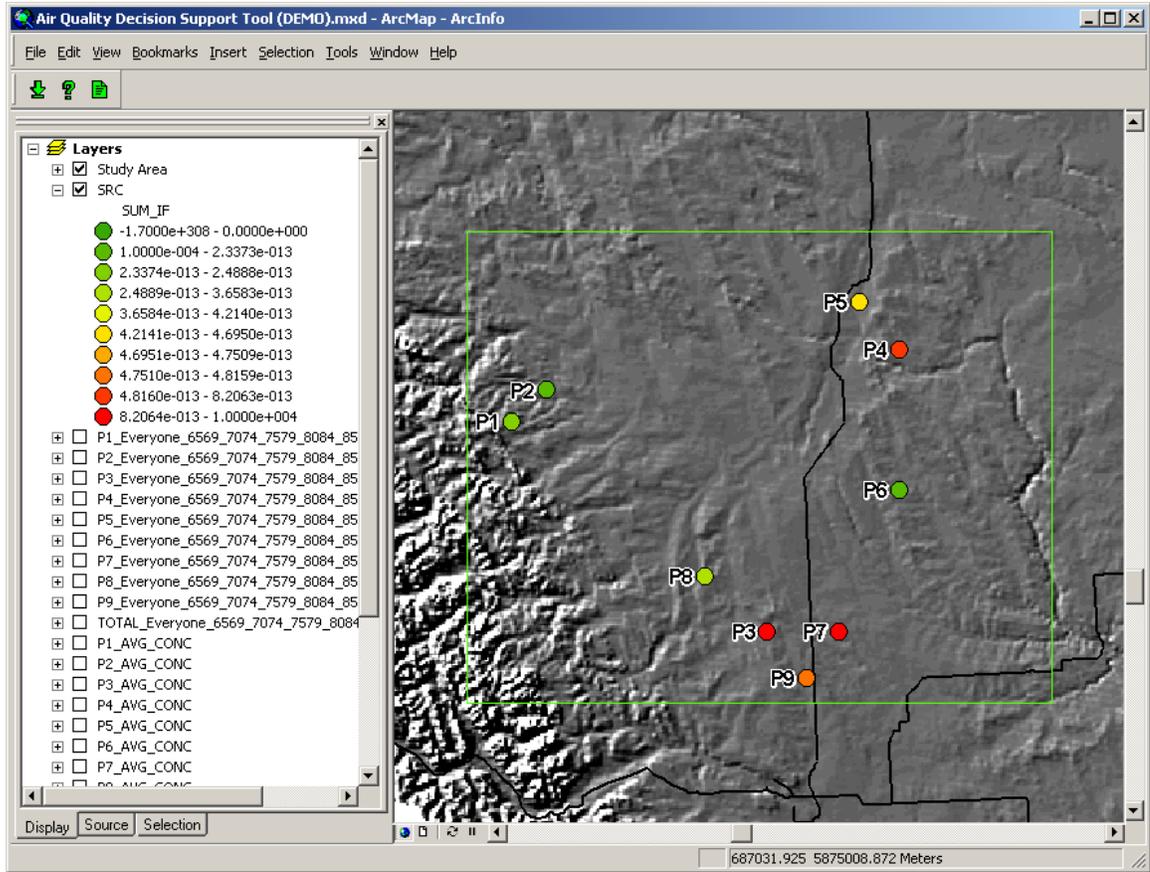


Figure 3.3.24 Report Tool – Point Sources Ranked on Intake Fraction Contribution to Seniors

Table 3.3.3 Point Source Intake Fraction Contributions to Seniors

Point Source	Intake Fraction Contribution (10^{-13})
P7	10.253
P3	8.2063
P4	4.8159
P9	4.7509
P5	4.6950
P8	3.6583
P1	2.4888
P6	2.3373
P2	2.1992

Comparing Figure 3.3.23 with Figure 3.3.24 and Table 3.3.2 with Table 3.3.3, it is apparent that the intake fraction varies with the sub-population. For example, point source P5 has the second highest Intake Fraction contribution to children, but is only the fifth highest Intake Fraction contributor for seniors. From a decision support perspective, the selection of a sub-population introduces susceptibility into the air quality analysis. For example, if a decision maker has information indicating that children are more sensitive to higher concentrations of a specific pollutant than the rest of the population, the point sources can be ranked according to their Intake Fraction contribution to children alone (as in Figure 3.3.22). The results from the Report Tool in this configuration demonstrate the flexibility of this decision support tool.

Chapter 4: Conclusion

The objective of this research was to create a new air quality decision support system. To avoid overlap with existing work in this area, the created system had to focus on individual air pollution source contributions and support option screening while streamlining the loose-coupling integration of an air dispersion model with a GIS. The capabilities of the developed air quality decision support system were then demonstrated using PM_{2.5} emission data and meteorological data for June 2002 in central Alberta.

The results demonstrated that the objectives of this research were met. The developed air quality decision support system uses contributing source Intake Fraction estimates to prioritize pollution point sources in terms of human population exposure potential. This allows a decision maker to identify the sources that the population is most sensitive to. In other words, a reduction in emission from the sources identified as higher priority will have a proportionally greater effect on reducing the pollution absorption by the population than a reduction in emission from sources identified as lower priority. The opposite is also true. If an increase in emissions is necessary, the sources identified as lower priority will have a proportionally smaller effect on the pollution absorption by the population than sources identified as higher priority. This offers decision makers a starting point for investigating more detailed emission regulation or mitigation options. The system allows decision makers to screen their options, streamlining the decision

making process. Rather than developing an emission regulation scenario from a template or even intuition, then testing it, decision makers can develop these scenarios by focusing on sources that are prioritized based on their Intake Fractions.

The loose-coupling technique used in the developed decision support system has been effectively streamlined to the point that it has become seamless. Through the development of a custom toolbar in ArcMap, the outputs from CALPUFF can be read into an ArcMap document simply by clicking a button. The analysis on the imported CALPUFF ground level concentrations can be completed just as easily. This demonstrates a loose-coupling approach that is as streamlined as possible.

There are several enhancements that would improve the usefulness of the developed air quality decision support tool. Currently the system focuses on Intake Fractions, which is an estimate of relative population absorption. It would be interesting to also estimate absolute population absorption. This first enhancement would simply require the removal of the emission variable from the Intake Fraction equation (Equation 1) and some changes to the user interface. This would provide the user with an estimate of the absolute exposure to compliment the estimate of the relative exposure that is provided by the Intake Fraction.

When importing CALPUFF concentrations from a one month modeling period the runtime of the Import Tool can be as high as twenty minutes. A second enhancement would

involve some algorithm changes, specifically concerning variable handling and memory management that would drastically improve the processing speed of the Import Tool.

A third, and very ambitious, enhancement involves exchanging the desktop GIS for a web-based GIS. This decision support system is built as an add-in to ArcMap software, which requires a very expensive annual license. Offering this system on a web-based GIS platform (such as ArcGIS Server) would increase availability to decision makers and even the general population at no cost to the user.

To summarize, this air quality decision support system is a useful tool for prioritizing point sources of air pollution based on their Intake Fraction contributions to a selected population or sub-population. It accomplishes this efficiently through the optimization of a loose-coupling technique between the CALPUFF air dispersion model and ArcMap GIS software. The system provides support for often ignored air quality option screening, allowing it to complement existing air quality decision support systems (such as BenMAP). This software can be installed and run on any desktop computer with a operational ArcGIS Desktop license.

References

- Atmospheric Study Group at TRC. CALPUFF. Computer software. The Calpuff Modeling System. Vers. 6. TRC, 27 June 2008. Web. 9 Feb. 2009.
- Beach, L. R. "BROADENING THE DEFINITION OF DECISION MAKING: The Role of Prechoice Screening of Options." *Psychological Science* 4.4 (1993): 215-20. *SAGE Journals Online*. SAGE, July 1993. Web. 3 July 2011.
- Bennett, D. H., T. E. McKone, J. S. Evans, W. W. Nazaroff, M. D. Margni, O. Jolliet, and K. R. Smith. "Defining Intake Fraction." *Environmental Science & Technology* 36.9 (2002): 206A-11A. Print.
- Canada. Government of Alberta. Alberta Environment. *Clean Air Strategy*. Alberta Environment. Web. 3 July 2011.
- Canada. Government of Alberta. Alberta Environment. *Particulate Matter and Ozone Management Plan Guidance Document*. Alberta Environment. Web. 3 July 2011.
- Canada. Government of Alberta. Ministry of Transportation. *Functional Planning Study for QE2 Highway - Ellerslie Road to South Leduc*. Web. 15 Dec. 2009.
- Cao, J., W. Li, J. Tan, W. Song, X. Xu, C. Jiang, G. Chen, R. Chen, W. Ma, B. Chen, and H. Kan. "Association of Ambient Air Pollution with Hospital Outpatient and Emergency Room Visits in Shanghai, China." *Science of The Total Environment* 407.21 (2009): 5531-536. *SciVerse*. Science Direct, 15 Oct. 2009. Web. 28 Nov. 2009.
- Carella, B., and P. Mudu. "Exposure to Air Pollution: An Intake Fraction Application in Turin Province." *Archives of Environmental & Occupational Health* 64.3 (2009): 156-63. *Taylor Francis Online*. Taylor Francis Group, 8 July 2010. Web. 15 Aug. 2010.
- ECOTECH "EnviMan Software." *ECOTECH*. Web. 9 Dec. 2009. <<http://www.ecotech.com.au/data-acquisition/air-quality-modelling-software>>.
- Elbir, T. "A GIS Based Decision Support System for Estimation, Visualization and Analysis of Air Pollution for Large Turkish Cities." *Atmospheric Environment* 38.27 (2004): 4509-517. *SciVerse*. Science Direct, 9 July 2004. Web. 6 Oct. 2009.
- ESS "AirWare: Urban Air Quality Assessment and Management." *AirWare*. Environmental Software and Services. Web. 9 Dec. 2009. <<http://www.ess.co.at/AIRWARE/>>.

Fann, N. "EPA Science Advisory Board BenMAP Briefing." *BenMAP Presentation to EPA Science Advisory Board*. United States Environmental Protection Agency, Mar. 2007. Web. 19 Nov. 2009. <www.epa.gov/air/benmap/docs/SAB_BenMAP_Briefing_3-15.pdf>

Fann, N. "International BenMAP Briefing." *BenMAP Presentation to United Nations*. United States Environmental Protection Agency, May 2007. Web. 19 Nov. 2009. <http://www.epa.gov/air/benmap/docs/BenMAP_Briefing_International.pdf>.

Hoff, R., H. Zhang, N. Jordan, A. Prados, J. Engel-Cox, A. Huff, S. Weber, E. Zell, S.

Isakov, V., J. Touma, J. Burke, D. Lobdell, T. Palma, A. Rosenbaum, and H. Zkaynak. "Combining Regional- and Local-Scale Air Quality Models with Exposure Models for Use in Environmental Health Studies." *Journal of the Air & Waste Management Association* 59.4 (2009): 461-72.

Kondragunta, J. Szykman, B. Johns, F. Dimmick, A. Wimmers, J. Al-Saadi, and C. Kittaka. "Applications of the Three-Dimensional Air Quality System to Western U.S. Air Quality: IDEA, Smog Blog, Smog Stories, AirQuest, and the Remote Sensing Information Gateway." *Journal of the Air & Waste Management Association* 59.8 (2009): 980-89. *Refdoc.fr*. Centre National De La Recherche Scientifique. Web. 28 Oct. 2009.

Levy, J. I., S. L. Greco, and J. D. Spengler. "The Importance of Population Susceptibility for Air Pollution Risk Assessment: A Case Study of Power Plants Near Washington, DC." *Environmental Health Perspectives* 110.12 (2002): 1253-260. *PubMed Central*. National Institute of Environmental Health Science, Dec. 2002. Web. 14 Apr. 2009.

Li, Ji, and J. Hao. "Application of Intake Fraction to Population Exposure Estimates in Hunan Province of China." *Journal of Environmental Science and Health*, 38.6 (2003): 1041-054. *PubMed*. National Center for Biotechnology Information, June 2003. Web. 6 Oct. 2009.

Lopez, M., M. Zuk, V. Garibay, G. Tzintzun, R. Iniestra, and A. Fernandez. "Health Impacts from Power Plant Emissions in Mexico." *Atmospheric Environment* 39.7 (2005): 1199-209. *SciVerse*. Science Direct, 23 Dec. 2004. Web. 14 Apr. 2009.

Maantay, J., J. Tu, and A. Maroko. "Loose-coupling an Air Dispersion Model and a Geographic Information System (GIS) for Studying Air Pollution and Asthma in the Bronx, New York City." *International Journal of Environmental Health Research* 19.1 (2009): 59-79. *Taylor Francis Online*. Taylor Francis Group, 24 Feb. 2009. Web. 6 Oct. 2009.

Maguire, D. J. "Chapter 1: An Overview and Definition of GIS." *Geographical Information Systems Principles and Applications*. Essex, UK: Longman Scientific & Technical, 1991. v. 1: Principles., 1991. 9-20. *Cgiar.org*. Consultative Group on International Agricultural Research. Web. 3 July 2011.

Moschandreas, D. J., J. Watson, P. D'Abreton, J. Scire, T. Zhu, W. Klein, and S. Saxena. "Chapter Three: Methodology of Exposure Modeling." *Chemosphere* 49.9 (2002): 923-46. *SciVerse*. Science Direct, 24 Oct. 2002. Web. 14 Apr. 2009.

NILU "What Is AirQUIS?" *NILU - Norsk Institutt for Luftforskning*. Web. 9 Dec. 2009. <<http://www.nilu.no/aqm/airquis/>>.

Rose, N., C. Cowie, R. Gillett, and G. B. Marks. "Weighted Road Density: A Simple Way of Assigning Traffic-related Air Pollution Exposure." *Atmospheric Environment* 43.32 (2009): 5009-014. *SciVerse*. Science Direct, 7 July 2009. Web. 10 Oct. 2009.

Scire, J. "CALPUFF Modeling." CALPUFF Training Course. Southern Alberta Institute of Technology, Calgary, Alberta, Canada. 9 Feb. 2009. Lecture.

Stevens, G., B. De Foy, J. J. West, and J. I. Levy. "Developing Intake Fraction Estimates with Limited Data: Comparison of Methods in Mexico City." *Atmospheric Environment* 41.17 (2007): 3672-683. *SciVerse*. Science Direct, 23 Jan. 2007. Web. 14 Nov. 2009.

US EPA "Basic Information | BenMAP | US EPA." *US Environmental Protection Agency*. Web. 19 Nov. 2009. <<http://www.epa.gov/air/benmap/basic.html>>.

US EPA "Decision Support Tools: Air | GEOSS | US EPA." *US Environmental Protection Agency*. Web. 19 Nov. 2011. <http://www.epa.gov/GEOSS/eos/txt_tools_air.html>.

Zhou, Y., J. I. Levy, J. K. Hammitt, and J. S. Evans. "Estimating Population Exposure to Power Plant Emissions Using CALPUFF: a Case Study in Beijing, China." *Atmospheric Environment* 37.6 (2003): 815-26. *SciVerse*. Science Direct, 28 Jan. 2003. Web. 14 Apr. 2009.

Zou, B., J. G. Wilson, F. B. Zhan, and Y. Zeng. "Air Pollution Exposure Assessment Methods Utilized in Epidemiological Studies." *Journal of Environmental Monitoring* 11.3 (2009): 475-90. *RSC Publishing*. RSC Publishing, 13 Feb. 2009. Web. 10 Oct. 2009.

Zou, B., J. G. Wilson, F. B. Zhan, and Y. Zeng. "Spatially Differentiated and Source-specific Population Exposure to Ambient Urban Air Pollution." *Atmospheric Environment* 43.26 (2009): 3981-988. *SciVerse*. Science Direct, 27 May 2009. Web. 6 Oct. 2009.

WHO. *Methods of Assessing Risk to Health from Exposure to Hazards Released from Landfills*. Copenhagen: World Health Organization, 2000.