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PM2.5 dispersion modelling from La Ronde fireworks events in Montreal using AERMOD and ArcMap

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PM2.5 DISPERSION MODELLING FROM LA RONDE FIREWORKS EVENTS IN MONTREAL USING AERMOD AND ARCMAP

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ABSTRACT

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Particulate matter from fireworks events are poorly understood sources of PM2.5 despite their potential to add significant quantities of PM2.5 to the atmosphere. PM2.5 has been found to aggravate various cardiovascular and respiratory illnesses and has been linked to premature death.

Each year La Ronde amusement park on Sainte-Helene Island exhibits numerous firework events in what is considered one of the world's premiere pyrotechnic competitions. These individual events are the centre of study for this project. Each event was modelled using Lakes Environmental's version of AERMOD, which estimated PM2.5 concentration plumes which then underwent geospatial analysis using ArcMap.

This project details the PM2.5 plume dynamics from La Ronde fireworks events from 1990-2004, and how these events impact a ten kilometer radius around the island of Sainte-Helene in Montreal, Canada.

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Table of Contents

List of Tables

List of Figures

Page

List of Appendices

Chapter 1- Introduction

1.1-Overview

Particulate matter (PM) is an atmospheric pollutant which is produced from a variety of anthropogenic sources, most notably from combustion reactions. A growing body of evidence suggests that there is no known threshold whereby negative health effects from exposure to particulate matter are not observed. Exposure to particulate matter has been identified as causing a variety of respiratory, cardiovascular and topical illnesses. The size of a PM2.5 particle can be any size less than or equal to 2.5μm. In terms of chemical composition, PM2.5 can literally have infinite combinations of metals, carbonaceous products, as well as liquid and semi-volatile components. The more reactive portions of particulate matter are theorized to be responsible for the majority of morbidity and mortality effects associated with PM2.5 exposure (Squadrito, 2001).

A growing body of evidence suggests that pyrotechnic displays are a short but significant source of PM2.5 emissions. Throughout the world, fireworks are used during holidays and celebrations and research suggests that PM2.5 levels on these days are many-fold higher than the normal ambient levels (Kulshrestha, 2004; Barman, 2008; Drewnick, 2006; Vecchi, 2008)

Every year, La Ronde amusement park on the island of Sainte-Helene in Montreal hosts an international pyrotechnics competition at which approximately ten half-hour fireworks displays are showcased over the spring-summer season. The PM2.5 plumes produced by these events are the focus of this project.

PM2.5 plumes were modelled using Lakes Environmental's AERMOD retail software package. This software package is based on the US Environmental Protection

Agency's AERMOD software. Meteorology data from Environment Canada collected proximally to La Ronde fireworks locations was used as a primary input into AERMOD to allow modelling. AERMOD's estimated plumes were further analyzed geospatially using a variety of tools from ArcMap.

1.2- Purpose and Objectives

The objectives of this research are firstly to quantify and describe the nature and extent of PM2.5 plumes from La Ronde fireworks events. To accomplish this task, AERMOD, ArcMap and meteorology data from Environment Canada are used. Secondly, to analyze the plume results in the context of the geography of Montreal with special focus on possible adverse effects to the population and environment of Montreal. Finally, to make recommendations on how the results of the research should be used to minimize or reduce the adverse effects of fireworks events.

Chapter 2- Characteristics of Particulate Matter

2.1- Particulate Matter

2.1.1- Definition and Types of Particulate Matter

Particulate matter, for the purposes of this study, is generally divided into three sizes; PM10, PM2.5 and PM0.1. PM10 refers to airborne particles whose aerodynamic diameter is less than 10μm. PM10 is often referred to as inhalable coarse particulate matter because most of its mass is taken up by particles with an aerodynamic diameter at the upper limit of what is inhalable. Most particles larger than PM10 do not reach the lungs but are deposited into the nasal cavities, throat and mouth (US EPA, 2008). The PM2.5 fraction includes all particles with an aerodynamic diameter less than 2.5μm. The PM2.5 fraction is often called fine or respirable particles because their size permits them to enter deep into the lung to the gas-exchange region (Brunekreef, 2002). Finally the smallest fraction, PM0.1 also known as ultrafine particulate matter, is that which includes all particles less than 0.1μm (Barone, 2008).

2.1.2- Primary versus Secondary Particulate Matter

Particulate matter can be classified into two groups of pollutants: primary pollutants, which are directly emitted into the environment, and secondary, which form in the atmosphere through the assemblage of precursor pollutants already in the environment. For example, particulate matter can be found in the primary phase in the form of soot directly emitted from a combustion engine into the atmosphere, or it can be a secondary pollutant formed from the interactions between unspent hydrocarbons, nitrates, sulphates, and other pollutants. Sunlight can also be a necessary catalyst for the formation of some secondary particulate species (Schauer, 1996).

2.1.3- Size and Shape

The most accepted way of describing a particulate is by measuring its aerodynamic diameter, which is the diameter of a particle if it were an idealized sphere of unit density (1 g/ml). In reality, particulates come in a multitude of shapes and dimensions meaning that particles that are of the same aerodynamic diameter, such as PM2.5, may be vastly different in terms of their actual dimensions. The reason that there is so much variation in particle dimensions, even among particles of the same aerodynamic diameter, is due to the different sources of particles, compositions and arrangements of the constituents of particles, and the processes that have led to the formation of the particles (Harrison, 2000).

2.2- Sources of PM2.5

PM2.5 comes from many sources, most of which are anthropogenic (Wall, 1988). Although there are some natural sources of particulate matter as well as particulate matter composed of natural materials, research suggests that manmade particulate matter is the source of morbidity and mortality, not natural particles (Ghio, 2001). The main anthropogenic sources of PM2.5 are combustion sources such as fires, internal combustion engines, flares, kilns and energy generation plants such as coal and oil. Natural sources of PM2.5 include volcanic activity, natural erosion processes and forest fires (Watson, 2001).

2.2.1- PM2.5 Sources in a Urban Canadian City

Throughout the world different cities have different sources of PM2.5 depending on the type of fuel used for energy generation, age and size of automotive fleet, type of fuel used in the automotive fleet, and types of industry present in the urban area. Canadian cities are fairly homogeneous and as such the sources of PM2.5 in one city would be relatively representative of the sources of other urban areas. Urban areas in Canada are exposed to particulate matter from multiple sources; coal energy generation and transportation sources produce airborne sulfate, and transportation also contributes to NOx which has also been found to come from upwind rural and suburban areas. The rural and suburban sources of NOx are transportation sources as well as agricultural land uses that require fertilizers or produce ammonia (Lee, 2003).

The quantity of PM2.5 in Canadian urban areas has been found to increase in the summer as compared to other seasons because of the prevailing wind direction that blows more regularly from the mid-west U.S. where a large portion of energy is derived from coal sources. In addition to wind direction, the summer also precipitates increased particulate matter formation due to more hours of sunlight and greater intensity in sunlight permitting enhanced formation of photochemical smog. Finally the summer season also results in greater transport use and energy use resulting in higher emissions from combustion sources (Lee, 2003).

Particulate matter in Canadian urban areas has been found to contain several metals; aluminum, calcium, iron, magnesium, manganese, barium and chromium. Manganese comes from MMT (Methylcyclopentadienyl Manganese Tricarbonyl), a fuel additive used in automotive vehicles in Canada. Several of the metals, Al, Ca and Mg, have been linked to road dust. The remaining metals, Fe, Cu, and Zn, are all theorized to have come from automotive use, be that from lubricating oils, tire and brake wear, or engine breakdown (Lee, 2003).

During the winter season sodium and chlorine from road salt are additional sources of particulates. The use of sodium chloride on roads in the winter is meant for de-icing; however, these materials clearly become airborne as part of particulate matter (Lee, 2003).

2.3- Constituents of Particles

2.3.1- Metal Content

Many particulates are composed of metals which have been suggested to be the source of many of the health issues associated with inhalable particulates. Research also suggests that the quantity of particulate matter may not be as important as the dose of bioavailable transition metals present for determining the severity of inflammatory responses in respiratory systems (Costa, 1997). These effects are especially acute in receptors with compromised cardio/respiratory systems. Some of the metals that are present in PM2.5 include iron, nickel, vanadium, and zinc, and most are water soluble making them highly bioavailable. Some particulate matter may have metals that are not water soluble but could become so in the presence of acid reactions thereby making them bioavailable. Metal-rich particulate matter has been found to reduce permeability and cause cellular injury to respiratory pathways. The severity of damage is related to the dose size of metal as well as its bioavailability. Exposure to metal-rich particulate matter in humans can require a recovery period of, on average, 96 hours depending on the type of metal present in the particulates. PM2.5 containing elevated levels of Ni have been found to cause more damage to respiratory pathways requiring a longer period of time for recovery. In contrast, particulate matter with metal present that was not bioavailable did not result in cellular damage like samples with bioavailable metal. Research has also indicated that interactions among metals and between metals and other pollutants may lead to increased toxicity (Costa, 1997).

2.3.2- Liquid Aerosol Content of PM2.5

In addition to being composed of metals and natural solid materials, PM2.5 can also have fine liquid constituents (Harrison, 1997). These liquid materials will often bond to pre-existing solid particles in the atmosphere creating secondary pollutants. There are several reasons that explain why liquid aerosols bond readily to existing airborne particles: First, particulate matter has a very large surface area on which molecules may become attached and second, the molecular constituents of particulate matter range from polar to non-polar, cations to anions, basic to acidic(Jang, 1997; Lee, 2001). PM2.5 has been found to contain polyaromatic hydrocarbons, which are a large group of chemicals composed of varying lengths of carbon chains with attached elements (Tsapakis, 2002). These molecules come from a variety of sources including solvents, fuels, cleaners and paints. Liquid aerosol sources are major contributors to atmospheric PM2.5 but are unfortunately poorly understood and researched partly due to the fact that the mechanisms that lead to secondary particulate matter formation are numerous and extremely complex (Harrison, 2008).

2.4- Dispersion Behaviour

Particulate matter dispersion is, like most pollutants, affected by several key factors; mass of pollutant, wind speed, temperature of emission, topography and elevation of emission. Particulates of all sizes are acted on equally by the forces of gravity; however, greater mass particulates, like PM10, require stronger forces than lower mass particulates to stay aloft. As such, a light breeze may be able to keep PM2.5 in suspension whereas it may not be sufficient to keep PM10 aloft. In addition to this is the fact that smaller particles experience greater friction per unit mass because they have a higher surface area to mass ratio. This concept is referred to as settling speed and essentially implies that the greater the mass of a particulate, the faster its settling speed (Wang, 2007). Wind speed may act upon a particle by transferring directional energy to the particle thereby redirecting it or carrying it further in the direction of the acting force (Wang, 2007).

Particulate matter is often emitted from combustion sources whereby the gases formed during combustion are hotter than the ambient air. In this case the emitted air is more buoyant than the ambient air and will rise until the emitted air reaches the same temperature as the ambient air. The effect that this situation has on dispersion of particulate matter is that it will result in the particulate matter traveling further downwind than it would if emitted at ambient temperature (Turner, 1985). Topography can have a strong effect on particulate matter dispersion as well; buildings can cause increased turbulent mixing causing a faster dispersion of the plume, or mountains and hills may force winds up or downslope altering the plume direction and speed (Plaza, 1997). Finally, the stack height or emissions source elevation will affect the settling time as well as dispersion of the plume (McRae, 1982).

2.5- Health Impacts of Particulate Matter

Increasing exposure to airborne particulate matter has been found to be associated with increasing incidences of morbidity and mortality in humans (Monn, 1999). It has been suggested that morbidity and mortality are the result of damage to lung tissues causing lung inflammation (Fujii, 2001). Inflammation of the lung may be the result of the chemical properties of the particulate- be that acidity, presence of metals, organic constituents and other biogenic materials (Monn, 1999). Damaged lung tissues will release cytokines (which are communicator proteins) into the blood stream resulting in a myriad of responses including the release of leukocytes and platelets from bone marrow (Fujii, 2001; Wan, 2000).

2.5.1-Mechanistic Explanation for Particulate Matter's Health Effects

Particulate matter's wide range of short and long term health effects can be explained by the reactive portions of the particulates. Specifically, the acidic, metallic, ionic and oxidative portions of the particulates have been found to damage lung tissues as well as cardiovascular tissues. Damaged tissues will then become inflamed and, depending on the severity and length of exposure, a percentage of exposed cells may die (Happo, 2008). Cell damage is not only limited to cell walls and organelles but has been shown to damage cell DNA resulting in the conclusion that particulate matter is genotoxic and a source of lung cancer (Upadhyay, 2003). As more and more lung tissue becomes damaged the lung's gas exchange regions become less efficient, resulting in lower oxygen levels in the blood, triggering an increased heart rate (Pope, 1999).

Cardiovascular tissues have also been found to constrict when exposed to particulate matter resulting in higher blood pressure and possibly the destabilization of susceptible plaques. Destabilized plaques may then be displaced and ultimately cause a blockage elsewhere in the cardiovascular system (Brook, 2002, Brook, 2004). Exposure to particulate matter has also been shown to increase blood coagulants such as fibrinogen, resulting in arterial thrombosis which is the clotting of blood while inside the arteries. This clotting in turn could lead to higher blood pressure or blocked arteries (Mutlu, 2007).

2.5.2-Testing Mechanisms

Determining the health effects of pollutants usually involves identifying the mechanistic source of the damage caused by the pollutant. Many studies employ the use of chamber studies, a method whereby willing individuals can be exposed to controlled pollution conditions. Unfortunately this system does not model sufficiently the mixtures of pollutants or temporal variations that are seen in real-world exposure (Brunekreef, 2002).

2.5.3-Dose-Effect

Health effects from exposure to particulate matter have been found to be dose dependent (Fujii, 2001). Many governmental health agencies including the World Health Organization (WHO), the California Air Resources Board (CARB) and Environment Canada have stated that there is no known safe threshold concentration for PM2.5 (Environment Canada, 2003; WHO, 1999). The overall mortality curve for exposure to particulate matter as well as cardiorespiratory mortality is a linear curve with no threshold (Schwartz, 2002; Daniels, 2000). Other sources of mortality, such as influenza and pneumonia, show little change in risk until particulate concentrations exceed 50μg/m3, indicating a threshold may be present (Daniels, 2000).

A recent study which plotted ambient PM2.5 levels in fifty-one cities and compared them to death statistics from a variety of causes concluded that the dose-response curve for exposure to PM2.5 is virtually linear. The researchers found that a 10μg/m3 increase in ambient PM2.5 concentrations results in a 4% increase in mortality from all tracked causes, a 6% increase in mortality from cardiopulmonary failure and an 8% increase in mortality from lung cancer (Pope, 2002).

2.5.4-Sensitivity to Particulate Matter

Elderly individuals have been found to be especially sensitive to exposure to ultra fine particulate matter. Specifically individuals over the age of 65 are at a greater risk of death from coronary events within the same day as they are exposed to elevated levels of PM2.5 (Forastiere, 2005). This pattern has also been observed in individuals who suffer from hypertension and chronic obstructive pulmonary disease, as well as those with reduced lung function such as asthmatics (Styer, 1995; Kodavanti, 2000). Asthmatic children also suffer reduced lung capacity and lung irritation during bouts of increased airborne particulate matter (Koenig, 1993). The length of the exposure and the number of consecutive days of exposure to elevated levels of particulate matter both result in an increase in the instances of hospitalizations for asthmatic children (Lin, 2002).

2.5.5-Short Term Exposure to PM2.5

Short term exposure to particulate matter can cause eye, throat, nasal and skin irritation in sensitive individuals (Feldman, 2004). Eyes may burn, tear, or foam during and after exposure to particulate matter and conjunctival epithelial cells have been observed to be damaged due to exposure. Short term exposure may also result in physical discomfort due to sweating, coughing, headaches or a difficulty concentrating. Medium term exposures, that is, over more than a few hours, can cause sleeplessness, sluggishness and changes in body skin temperature (Pan, 2000).

2.6-Montreal

The city of Montreal is the second largest city in Canada with a population of 1.62 million residents in 2006 according to Statistics Canada. The total area of metropolitan Montreal is 365.13 km^2 resulting in a population density of 4438.67/km^2. The Greater Montreal Area, which includes among other areas Longueil to the East and Laval to the North, has a population of 3.63 million residents and a density of 853.62/km^2.

2.6.1-Montreal Meteorology

Poor air quality episodes are much more common during the summer in Montreal than in the winters (Environmental Canada, 2003). Overall the air quality in Montreal is good and as such is only moderately burdened by air pollution (Goldberg, 2001). The formation of air pollutants during summers in Montreal is enhanced by the prevalence of clear, sunny days when sunlight is the most intense allowing for the formation of photochemical smog from VOCs, liquid fuels, solvents, organic chemicals and other components (Environment Canada, 2003). It should be mentioned that Montreal does not experience many extreme hot, humid days that are common in more southern North American cities (Goldberg, 2001). In the winter Montreal has also suffered from increases in particulate matter from wood burning used for heating (Environment Canada, 2000).

The mean concentration of ambient PM10 and PM2.5 in Montreal as well as Quebec has generally been decreasing yearly since 1975 largely due to reductions by industrial emitters and incineration. Conversely, during this time period there has been an increase in particulate matter from combustion sources (Developpement Durable Environnement et Parcs Quebec, 2002). The mean ambient concentration of PM2.5 over the past few years in Montreal has been around $10\mu g/m^3$ (Environment Canada, 2005). It should be noted however that daily fluctuations of particulate matter can be severe owing to changes in types of sources, source strengths, and number of sources (Goldberg, 2001).

Comparisons between historic concentrations of particulate matter and death rates have been conducted in Montreal. The results indicate that subjects with acute lower respiratory disease, congestive heart failure, and cardiovascular disease died at higher rates when ambient PM2.5 concentrations were higher. It was also found that elevated levels of PM2.5 also resulted in increased instances of cancer, chronic coronary artery disease, coronary artery disease and acute and chronic upper respiratory disease. The average death rates appear higher up to three days after a period of elevated PM2.5 concentration (Du Melle, 2001; Goldberg, 2001). Specifically a $100\mu g/m^3$ increase in average PM2.5 concentration was found to be associated with between a 6.3 and 25.3% increase in death rates (Goldberg, 2001).

2.6.2-Montreal Fireworks

Every summer La Ronde, an amusement park located on the island of Sainte-Helene to the East of Montreal, runs an international competition showcasing some of the most elaborate firework displays worldwide. The displays are largely held on weekends and number around ten a year. Each individual display lasts around 30 minutes beginning at 10pm regardless of weather conditions (The Gazette, 2006). Each event is different in the selection of fireworks used, the number detonated, the heights of detonation and the combination of detonations. It is estimated that each display uses around 2000 kilograms of fireworks in total, which is between 3,000 and 5,000 individual fireworks during the half-hour display (Brownstein, 1996). An image which shows the different types and altitudes of detonating fireworks as well as the particulate matter plume from a LaRonde fireworks event can be seen in Figure 2.1.

Figure 2.1: Image of LaRonde Firworks Event

Image Source: Meunier, Bruno. *La Ronde Fireworks.* ONLINE. Available at:http://www.brunomeunier.com/?paged=3

Chapter 3- Fireworks

3.1-Firework Chemistry

Pyrotechnic displays involve igniting powdered metals to produce colourful displays of varying styles and shapes. Individual fireworks can be composed of several components; a propellant or fuel to accelerate the firework to a target altitude; often gunpowder, oxidizing agents, colouring agents, smoke dyes, binding agents and other chemicals (Russell, 2000; Kosanke, 2004). Oxidizing agents are often used because of their tendency to produce high temperatures quickly allowing for metals to excite and thus produce their anticipated colour. This is achieved through the release of the oxygen from the oxidizer allowing for the combustion to take place at a high rate producing high temperatures. Some oxidizers are more explosive and therefore added for their propellant and sound properties. Popular oxidizing agents include: ammonium perchlorate (NH_4ClO_4), potassium chlorate ($KClO_2$), and potassium nitrate (KNO_3).

Colouring agents are chemicals whose desired properties may include oxidizing but are principally selected for the colour they produce when heated to a specific temperature. Pyrotechnic displays can attain a multitude of colours depending on the colouring agents present: red (strontium carbonate, $SrCO_3$), orange (calcium carbonate, $CaCO_3$), yellow (sodium bicarbonate, $NaHCO_3$), green (barium carbonate, $BaCO_3$), blue (copper arsenite, $CuHAsO_3$) (Kosanke, 2004).

Smoke dyes are coloured plumes of smoke that are created through the interaction of moisture in air with corrosive materials that hydrolyze into aerosol droplets. As with colouring agents there are a numerous colours available depending on the selection of chemical. A few examples include; auromine, indigo pure, oil red etc. (Kosanke, 2004).

Combustion agents make it possible for the oxidizing agent to become reduced and release the oxygen atoms resulting in combustion. Common combustion agents include charcoal, aluminum, and red phosphorus. Binding agents, as the name suggests, are designed to hold the mixture of colouring agents, oxidizing agents, combustion agents and other chemicals together in a paste like homogeneous mixture. Wheat flour and wheat starch are just two possible binding agents used in fireworks. There are several other chemicals that are often found in fireworks and are used for a variety of purposes; gallic acid is used for the whistling sound it produces when it reacts with potassium perchlorate, boron as a fire retardant, and boric acid to prevent moisture from corroding chemicals containing aluminum (Kosanke, 2004).

3.2- PM2.5 Episodes Caused by Firework Events

Celebrations and festivals throughout the world are often punctuated by copious fireworks displays, be they professional or amateur. Due to the numerous worldwide events in which fireworks are an integral part of celebrations, there is also a fair amount of evidence that these events can cause levels of ambient PM2.5 to surge many fold above normal ambient levels. During the Diwali festival in India in 1999, SO_2 was found to increase tenfold over normal ambient levels, TSP (total suspended particulates) increased around threefold and PM10 increased twofold over normal ambient levels (Ravindra, 2003).

During an air sampling exercise comparing air quality before and after the Lantern Festival of 2006 in Beijing, China, researchers measured airborne particles for a variety of chemical parameters. The researchers found that there were 18 different ions present in the captured PM2.5 including the anions Cl^-, $C_5H_6O_4^{2-}$, $C_3H_2O_4^{2-}$, $C_2O_4^{2-}$, $C_4H_4O_4^{2-}$, SO_4^{2-}, NO^-_3 and the cations K^+, Ca^{2+}, NH_4^+, Mg^+, Na^+ and that these ions were fivefold higher than prior to the lantern festival. Particulates were also found to be acidic with the larger PM10 fraction being 1 pH lower on average than the PM2.5 fraction. Particulate pH values ranged from 6.5 to 4.2 over the course of eight samples taken, four for PM10 and four for PM2.5. The pH results measured during this event are atypical in that PM2.5 is usually reported to be more acidic than PM10 and may be the result of specific feedstock or circumstance during this particular Beijing event. A variety of metals were also detected including potassium, magnesium, calcium, zinc and sodium as well as more toxic metals like strontium, manganese, copper, aluminum, lead and barium. These metals were in concentrations 3 times higher during the lantern festival than before the festival. In the sampled PM2.5, firework sources were responsible for 98% of the Pb present, 90% of the total mineral aerosol, 43% of total carbon, 28% of Zn, 8% of NO_3^-, and 3% of SO_4^{2-} (Wang, 2007).

On New Year's Eve 1999, there were firework celebrations throughout the world, including Leipzig, Germany where a particle sizer, used for measuring particle sizes as the name suggests, and two particle counters, which count the number of particles, were employed to measure plume characteristics. The results indicate that firework events produce the greatest number of particles in the PM2.5 fraction compared to PM10 fraction. Within the PM2.5 range the highest concentrations fall in the 80-120nm range when the particles are not assumed to be spherical, or in the 120-160nm range when they are assumed to be spherical. In both instances firework events will, at their maximum, increase levels one order of magnitude over regular ambient levels. For the non-spherical concentration estimations, regular ambient levels of 280nm particulates are around 46,000 particles per cm^{-3}, which increases to just below 46,000 particles per cm^{-3} on firework event days. For the spherical concentration estimations, regular ambient levels of 280nm particulates are around 280 particles per cm^{-3}, which increases to 1,000 particles per cm^{-3} on firework event days. Clearly firework events are responsible for large increases in the number of most particle sizes in the range of PM2.5 (Wehner, 2000).

In the United Kingdom each year on November 5th citizens celebrate 'bonfire night' on which fireworks are ignited as well as large open air fires. During one such event in 1994 researchers endeavoured to measure the changes in dioxin and furan levels over previous nights. The measured results were considered tenuous by the researchers but showed a pattern of greater quantities of dioxins and furans on bonfire night. The researchers also conceded that the actual source of the dioxins and furans were unknown and could not be limited to bonfires, fireworks or any other source (Dyke, 1997).

Laboratory tests have also indicated that firework plumes may contain dioxins and furans. The researchers found that prior to detonation or burning, fireworks contain dioxins and furans in the paper and cardboard containers which is a common result of the pulp and paper process. However, after detonation the quantities of dioxins and furans in the left-over shells are reduced leading to the conclusion that the dioxins and furans may have been released in the gaseous phase during firework explosion. Tested ash particles confirmed the presence of dioxins and furans after detonation of the fireworks; however, the researchers never clearly identify the size of the ash particles containing dioxins and furans thus making it difficult to determine the settling speed or inhalability of the present in the captured PM2.5 including the anions Cl^-, $C_5H_6O_4^{2-}$, $C_3H_2O_4^{2-}$, $C_2O_4^{2-}$, $C_4H_4O_4^{2-}$, SO_4^{2-}, NO^-_3 and the cations K^+, Ca^{2+}, NH_4^+, Mg^+, Na^+ and that these ions were fivefold higher than prior to the lantern festival. Particulates were also found to be acidic with the larger PM10 fraction being 1 pH lower on average than the PM2.5 fraction. Particulate pH values ranged from 6.5 to 4.2 over the course of eight samples taken, four for PM10 and four for PM2.5. The pH results measured during this event are atypical in that PM2.5 is usually reported to be more acidic than PM10 and may be the result of specific feedstock or circumstance during this particular Beijing event. A variety of metals were also detected including potassium, magnesium, calcium, zinc and sodium as well as more toxic metals like strontium, manganese, copper, aluminum, lead and barium. These metals were in concentrations 3 times higher during the lantern festival than before the festival. In the sampled PM2.5, firework sources were responsible for 98% of the Pb present, 90% of the total mineral aerosol, 43% of total carbon, 28% of Zn, 8% of NO_3^-, and 3% of SO_4^{2-} (Wang, 2007).

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In Valencia, Spain locals celebrate the festival of Las Fallas, which can last six days and involve elaborate firework displays. As with other firework events, the measured mass of particulate matter shows a several fold increase over normal ambient levels. NO levels, metal particles, and SO_2 were also measured rising dramatically, but less so than the levels of particulate matter. The researchers emphasized that the measured quantities of metal particles, metal species such as barium, lead, magnesium etc., as well as the size of the particles, around 1.2μm in size, were generally in agreement with other measurements from other worldwide firework events (Moreno, 2007).

Upon reviewing all the journal literature on particulate matter plumes from firework events, it becomes evident that there are many similarities between worldwide events, due to standard chemical properties, but also notable differences which can be attributed to local traditions and styles for firework displays (Moreno, 2007). One example of how traditions and customs for firework events vary worldwide is the use of open-pit bonfires on November 5th in the United Kingdom, which is a unique cultural event that ultimately affects the make-up and characteristics of the particulate matter plume.

Although firework events may be transitory in nature and therefore brief, and rare, the cumulative impact of the event should not be underestimated just as the localized health impacts should not be ignored. To illustrate this point, the United Kingdom produced a study through the UK Department of Environment, Food and Rural Affairs (DEFRA) that estimated the total quantity of metals released in the United Kingdom in

2002 from firework events. DEFRA calculated these quantities through two methods: based on the percentage of each individual firework's weight that is made up of metals and secondly through known emission rates of metals per ton of fireworks ignited (DEFRA, 2003). The results of the study can be seen in Table 3.1.

Table 3.1: DEFRA estimated quantities of metals released into the environment from firework sources in 2000/2002

Metal	Weight in tonnes (1500kg)*	Best estimate weight in tonnes (1500kg)*	% change in national inventory (2000)
Potassium	30-400	100	9.3%
Sodium	1.6-22	5.5	0.5%
Magnesium	22-290	73	7.6%
Barium	19-260	65	Not calculated
Strontium	2.9-39	9.9	Not calculated
Aluminum	26-340	86	Not calculated
Titanium	1.6-21	5.3	Not calculated
Copper	1-13.3	2.8	6%
Chromium	0.023-0.313	0.093	0.2%
Lead^	1-13.3	5.8	0.6%

*Based on a range of firework use between 2,250-30,000 tonnes each year (best estimate of 8,750 tonnes)
^Lead has not been used in fireworks in the U.K. since 1998 but was calculated to historic perspective on emission levels.
Source: DEFRA, 2003

In addition to the results in Table 3.1, DEFRA also concluded that PCBs (polychlorinated biphenyls) and dioxins/furans may be released in significant amounts from explosives used to propel fireworks into the air, as well as from the detonation of the firework itself. Clearly the results of DEFRA indicate that although firework events are small in scale and short in terms of time frame, cumulatively they can have meaningful impacts on the levels of environmental pollution (DEFRA, 2003).

3.3- Studies Linking Firework Events to Health Impairment

Although there is a fair amount of academic material concerning the effects firework events have on air quality there is much less information on how the reduced air quality from firework events specifically translates into impacts on community health. One researcher chronicled the air quality change in Honululu, Hawaii on New Year's Eve as fireworks were detonated and the subsequent effect it had on a few subjects with healthy and compromised respiratory systems. According to the author the concentration of respirable particles was measured to be in excess of 3800μg/m^3 during the event. Due to exposure to the plume, two male subjects who were already afflicted with chronic respiratory diseases suffered an average decrease of 26% in maximal midexpiratory flow, the maximum rate of airflow attained during a forced expiration, when compared to prior exposure. Three males without respiratory disease were also measured and showed a 4.7% decrease in maximal midexipiratory flow but this measurement was deemed to be close to, but not statistically significant. As a result, it was concluded that there was evidence that firework events clearly inhibited the respiratory health of compromised individuals but not that of healthy individuals (Smith, 1975). The relevance of these results should not be overestimated due to the age of the results, small sample size and lack of replication elsewhere.

Other academic results are based on disasters or serendipity. In May, 2000 a firework storage facility in Enschede, Netherlands exploded and in so doing consumed a large portion of the stocked fireworks. After rescue efforts had been completed, personnel and residents were interviewed concerning the effect the event had on their health. Many workers (35%), passers-by (45%) and rescue workers (23%) reported suffering from one or more acute symptoms from exposure. The symptoms most often reported were coughing and irritation of the throat, eyes, respiratory tract, and nose.

Other symptoms mentioned included earaches, tinnitus, shortness of breath, and vertigo. Although earaches and tinnitus were likely caused by exposure to acoustics from the firework detonation, shortness of breath and vertigo may have been due to impaired airways. More significant than these results was the revelation that rescue workers who wore facial protection or masks experienced far fewer acute symptoms (Van Kamp, 2006). Following the disaster the rescue workers' health was tracked electronically and it was found that respiratory problems increased the most dramatically in the second half of the year following the disaster. In addition to the increase in the second half of the year following the disaster, there was a continued increase from 7-12 months after the disaster. This seems to indicate there may have been a lag effect for respiratory illness in some rescue workers. Even up to two years following the disaster there were still a significant number of workers suffering from respiratory disorders when compared to the pre-disaster period (Dirkzwager, 2004). Results are summarized in Table 3.2.

Table 3.2: Percentage of rescue workers afflicted with respiratory health problems at specific intervals after the Enschede fireworks factory fire

6 Months *Pre*-Disaster	**1-6 Months *Post*-Disaster**	**7-12 Months *Post*-Disaster**	**13-18 Months *Post*-Disaster**	**19-24 Months *Post*-Disaster**
0.5% (n=5)	1.8% (n=19)	2.4% (n=25)	0.9% (n=9)	1.7% (n=18)

Source: Dirkzwager, 2004

The researchers did not explain why there appears to be a resurgence in respiratory health problems in the 19-24 month period.

Further anecdotal articles are available for review including the case of a Japanese man who confessed to being a habitual smoker. After exposure to firework smoke for 3 consecutive nights he was admitted to the hospital with persistent coughing, fever and shortness of breath. The doctor concluded that he was suffering from acute eosinophilic pneumonia whereby white blood cells coat the alveoli in the lung preventing oxygen transfer into the lung. The cause of the AEO was deemed to be due to prolonged exposure to smoke from fireworks (Hirai, 2000).

Based on the literature review of health effects caused by exposure to firework plumes it is clear that this area is lacking in the quantity and quality of studies that is present in the studies of firework plume characteristics discussed earlier.

Chapter 4: The AERMOD Dispersion Model

4.1-AERMOD History and Development

For many years Gaussian plume models have been a fundamental tool for modelling air pollution dynamics throughout the world. A Gaussian model is a steady state model which means that all inputted meteorology, pollutant source and type data are held constant during modelling. The output of a Gaussian model is a Gaussian plume which is composed of different concentrations that are normally distributed around the Y and Z axis (plume thickness and plume height). Thus a Gaussian plume will have the highest concentrations in the middle of the plume and lower concentrations at the edges of the plume.

Prior to the development of AERMOD, another dispersion model was widely used for air pollution modelling; the Industrial Source Complex Model (ISC). There have been several iterations of the ISC model each generally adding increased functionality as well as accuracy to the model. In 1991 a panel at the EPA was formed to investigate how the ISC could be improved and came up with the conclusion that a more complex model should include concepts and modules that factor in as many planetary boundary layer characteristics as possible. Part of the reason that ISC does not calculate or factor in many planetary boundary characteristics is that many of the mechanisms and processes associated with the layer were not well understood or documented until the early 1980s, and ISC updates had not kept pace with the growing breadth of understanding (Lakes Environmental, Smith 1984, Hayes 1986, Shulze 1999). The ISC model, although still used, was replaced due to its limited functionality, namely that the model could only make plume adjustments for limited terrain data, had inferior plume dispersion characterization compared to AERMOD, and did not include planetary boundary layer principles which are an integral part of AERMOD. When dispersion concentration measurements from both ISC and AERMOD were tested against real observations AERMOD was shown to be significantly superior at prediction than ISC. AERMOD is seen as a much more holistic dispersion modeler and a significant advance over ISC by regulatory agencies as well as private entities (EPA, 2005). As of December 2005 the EPA has instituted a policy that AERMOD or other more advanced models be used in all applications, ISC is no longer an acceptable diffusion modeler (EPA, 2005).

4.2-AERMOD's Build and Functionality

AERMOD is composed of three parts: a terrain preprocessor, a meteorological data preprocessor and a steady-state dispersion model. Each module has a separate function that is crucial for modelling the locations and quantities of emitted pollutants. The terrain processor will determine the position of receptors and sources in three dimensions (EPA 2004) as well as the influence terrain has on plume movement (Lakes Environmental, nd), the meteorological preprocessor is responsible for generating the planetary boundary layer (Lakes Environmental) and the steady-state dispersion model functions by modelling the non-stop constant rate emissions from one or more sources (EPA, 2005).

4.2.1-Planetary Boundary Layer (PBL) and Stable Boundary Layer (SBL)

The planetary boundary layer is the area on the planet where the atmosphere interacts directly with the surface of the earth and therefore the atmospheric processes in this area are very different than other parts of the atmosphere. There are a few forces and processes that are responsible for the pattern of circulation in the PBL; friction with the surface, uneven heating of the surface causing buoyancy and evaporation, turbulent air movement vertically and horizontally and differing wind speeds and temperatures by elevation (Inness, 2000). These processes are important to understand for modelling reasons because the PBL is where most air pollution is generated and spends most of its airborne life. In order to predict or model the behaviour of a pollutant in the PBL it is crucial that the model account for the forces and processes in the PBL. The PBL parameters are modelled using several algorithms that ascertain the wind speed profile, the wind direction profile, the potential for a temperature gradient and its profile, as well as a vertical and lateral turbulence profile (Lakes Environmental, nd).

Above the PBL lies the stable boundary layer (SBL). The SBL is much more stable than the PBL because there are no temperature inversions in the SBL resulting in strong stable stratification of air and little turbulent mixing (Lakes Environmental, nd).

4.2.2- Vertical and Horizontal Behaviour Calculations in the Stable Boundary Layer (SBL)

Using high altitude meteorological data, AERMOD calculates the distribution of plumes in both the vertical and horizontal direction of the SBL with a Gaussian model. The Gaussian model essentially calculates the statistical distribution of a plume based on diffusion, wind speed and atmospheric stability (Lakes Environmental, nd).

4.2.3- Vertical and Horizontal Plume Behaviour Calculations in the Convective Boundary Layer (CBL)

AERMOD calculates plume behaviour in the convective boundary layer (CBL) using a Gaussian model for the horizontal distributions and Bi-Gaussian p.d.f. (probability density function) for the vertical distributions. The difference between the two models is that under a Bi-Gaussian p.d.f. model the plume is affected by updrafts and downdrafts in the PBL which are not factored in a traditional Gaussian p.d.f. model. More specifically the model will calculate the statistical distribution of the updraft plume and the statistical distribution of the downdraft plume separately, then combine the two, hence the 'bi', to find the aggregated statistical plume (Lakes Environmental, nd; Wayson, 2003). The aggregated plume is also adjusted for instantaneous small-scale eddies that form in the CBL as the result of larger eddies. In order to calculate the probability density function AERMOD will take several factors into consideration: the plume rise, the displacement due to random convective velocities, the stack height, the mean wind speed, and the distance downwind where the plume is to be measured. When creating the aggregate plume AERMOD does not simply combine both the updraft and downdraft plumes at equal value, but rather it will weight the individual plumes based on the vertical velocity and standard deviation (Lakes Environmental, nd).

4.2.4- Pollutants Entering into the Stable Boundary Layer (SBL)

AERMOD is also capable of calculating the quantity of the emission which, in a buoyant situation, will exit the convective boundary layer (CBL) and enter into the stable boundary layer (SBL) and model its reemergence into the CBL at a later time and location (Lakes Environmental, nd).

Chapter 5- Model Boundaries and Inputs

5.1- Modelling

5.1.1- Number of Events

The years for which modelling was conducted include 1990 to 2004, from May to August on any dates where firework events took place at La Ronde, and meteorology conditions were favourable to modelling. A summary of all prospective dates can be seen in Table 5.1.

Table 5.1: Prospective dates of modelled firework events at La Ronde theme park in Montreal.

1990	1991	1992	1993	1994	1995	1996	1997
May 26	May 25	May 30	June 5	May 30	June 17	June 15	June 7
May 30	May 29	June 6	June 12	June 4	June 25	June 20	June 14
June 2	June 1	June 13	June 19	June 11	July 2	June 23	June 21
June 6	June 5	June 20	June 26	June 18	July 5	June 27	June 28
June 9	June 8	June 27	July 4	June 25	July 9	June 30	July 5
June 13	June 12	July 5	July 11	July 3	July 12	July 4	July 9
June 16	June 15	July 12	July 18	July 10	July 16	July 7	July 13
June 20	June 19	July 19	July 25	July 17	July 19	July 11	July 16
		July 26	August 1	July 24	July 23	July 14	July 20
		August 2		July 31		July 18	
1998	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	
June 6	June 19	June 17	June 20	June 15	June 21	June 12	
June 10	June 26	June 25	June 27	June 22	June 28	June 19	
June 13	July 3	July 2	June 30	June 29	July 5	June 26	
June 17	July 11	July 9	July 7	July 6	July 9	July 3	
June 20	July 14	July 12	July 11	July 13	July 12	July 10	
June 27	July 18	July 16	July 14	July 17	July 16	July 14	
July 5	July 21	July 19	July 18	July 21	July 19	July 17	
July 12	July 25	July 23	July 21	July 24	July 23	July 21	
July 19	July 28	July 26	July 25	July 28	July 26	July 24	
			July 28		July 30	July 28	

During each half-hour firework event it is estimated that 2,000 kilograms of fireworks are used (Brownstein, 1996). No data could be located that identify the quantity of products that are converted into PM2.5 during firework combustion so a conservative estimate of 25% of the 2,000kg weight was decided upon. This weight is the same as the PM2.5 value used by Environment Canada (EC) for 9 models EC produced of La Ronde's firework display in 2007 (Joly, 2007). Although each firework event uses a unique quantity of fireworks, 500kg was determined to be an acceptable, conservative average weight for the model inputs. Since each event lasts 30 minutes, the rate of emission is equal to 277.7 g/sec. However AERMOD cannot model half-hour events, the minimum length of time it can model is one-hour, thus it was necessary to divide the rate of emissions in half so that over one-hour of modelled time the quantity of emissions was equal to the actual emissions during a half-hour. As the result the emission rate entered into AERMOD was 138.8 g/sec.

5.1.2- Type of Emission Source

AERMOD is capable of modelling several types of emission sources; point, line and area sources. Line sources are generally meant to represent roads or other thin but lengthy emission sources. Area sources are usually considered expansive locations where emissions are non-point and variable in source. A good example of an area source would be a quarry emitting dust from excavation, transportation and processing activities. The final type of source is a point source such as a stack or flare. This source of emissions is the best suited for modelling firework events for a few reasons: point sources are located in a very precise geographic location which is appropriate for representing La Ronde's firework events which are staged from the same part of the island of Sainte-Helene for every event. Point sources, like stacks and flares, can be assigned an elevation parameter to reflect the height at which the stack or flare releases the pollutant. Fireworks are detonated at varying altitudes and as such the ability to set the height of an emission is a crucial tool for modelling a firework event.

5.1.3- Stack Height

Firework events are composed of a many different pyrotechnic units each with their own purpose and composition. Any single unit may be designed for a high altitude detonation or for a ground-level display. The high degree of variation among fireworks makes it difficult to gauge what is an appropriate elevation for modelling emissions. Any single event may contain a greater proportion of low, medium, or high altitude detonations making it impossible to completely capture the individual emission profiles for each event. The stack height for modelling purposes was entered as 250 metres which is a mid-range altitude for firework events in an attempt to capture the average height of detonations. Environment Canada modelled several firework events in Montreal in 2007 and also used 250 metres as the initial emission height (Joly, 2007).

5.1.4- Emission Temperature

One of the parameters that AERMOD uses to determine a plume's behaviour is its temperature relative to the ambient temperature. When an emission is warmer than the ambient temperature, that plume will be buoyant and rise, conversely a colder emission will be denser than the ambient air and tends to sink. Although fireworks detonations are exothermic reactions it is likely that the heat from this reaction would very quickly be lost due to the instantaneous mixing of ambient air and as such it is unlikely that the plume would be either more buoyant or denser than the ambient air. As a result, the emission temperature for the pollutant was entered as being equal to the ambient air temperature.

5.1.5- Gas Exit Velocity

The degree of plume rise in AERMOD is also controlled by the gas exit velocity which is the speed at which the emission is traveling over the threshold of the stack into the ambient air. This datum is more appropriate for modelling the emission of a traditional stack where the constrained volume of the stack restricts expansion causing increased pressure and therefore acceleration of the constrained gas (EPA AERMOD Implementation Guide, 2007). However there was a need to simulate the expansion of the plume due to the firing velocity and propulsion caused by the firework detonation. As the result a 1m/s input was used.

5.1.6- Stack Diameter

The diameter of a stack is another factor that will affect the plume rise, as smaller diameters will prevent the plume from expanding and therefore accelerate its speed. In order to avoid plume rise caused by a small stack diameter, the diameter for modelling purposes was set at 82 m. This diameter also loosely reflects the general area in which fireworks are expected to be generally detonated.

5.1.7- Receptors

The receptor network used by AERMOD is customizable meaning that the receptor grid size and number of receptors can be determined by the user. Most models were run with a 150x150 metre receptor cell size with the number of receptors being equal to the number necessary to cover a ten kilometer radius surrounding the island of Sainte-Helene. A few of the events had a lower resolution grid network due to their plumes being far larger and longer than most other events. This was done so that the computer was capable of calculating the entire size of the plume rather than a portion of the plume.

5.1.8- Input Meteorology

In order for AERMOD to model the atmospheric conditions present at the time of the fireworks event, it is necessary to input meteorology data into AERMOD. The meteorology data used for this project were supplied by Environment Canada and came from a meteorology station at Montreal's Pierre Elliote Trudeau International Airport located to 17km southwest of the island of Saint-Helene. The location of the station relative to the island of Saint-Helene can be seen in Figure 5.1.

Figure 5.1- Montreal Meteorology Station Relative to the Island of Saint-Helene

Prior to meteorology data being used in AERMOD it was first inspected for errors and suitability for modelling. Some meteorology data contained errors as the meteorology stations on occasion require maintenance and will return error data such as impossible values for windspeed and wind direction. Of all 137 firework event dates between 1990 and 2004, 42 were eliminated due to incompatible meteorology data. This process is further described in Section 5.2.

5.1.9- Number of Contour Intervals and Interval Size

AERMOD's outputted contour maps for concentration can be adjusted to display up to 100 different contour intervals. Given that PM2.5 has been shown to have no safe threshold (Schwartz, 2002) and several of the dates modelled had calculated concentrations up to 7000μg/m^3, the outputted maps were required to display a large range of concentrations in an effective fashion. A contour interval of 20μg/m^3 was selected such that the first contour mapped would be 20 μg/m^3 followed by 40 μg/m^3 continuing in this fashion to 1000μg/m^3 at which point any concentration equal to or greater than 1000 μg/m^3 would fall within the ≥1000 μg/m^3 contour. In practice this resulted in many maps where the ≥1000 μg/m^3 concentration area was clustered tightly in a small geographic area around the source point.

5.2- Model Validation

In order to verify the accuracy of the model it was necessary to compare the modelled results to in-situ measured concentrations taken by Environment Canada during seven fireworks events in 2007. The dates for which emissions were collected, locations and their concentrations can be seen in Table 5.2.

Table 5.2- Dates, locations and concentrations of firework events measured by Environment Canada for La Ronde firework events in 2007

Date	Type of Measurement	Location	Concentration (ug/m^3)
June 20, 2007	Predicted	-73.51990845 N, 45.51739109 W	66
June 27, 2007	Fixed	-73.52519134 N, 45.52787377 W	618
July 7, 2007	Fixed	-73.52519134 N, 45.52787377 W	840
July 7, 2007	Predicted	-73.52654631 N, 45.53040258 W	204
July 18, 2007	Fixed	-73.52519134 N, 45.52787377 W	319

July 21, 2007	Predicted	-73.53461349 N, 45.52109117 W	1152
July 25, 2007	Fixed	-73.52519134 N, 45.52787377 W	288
July 28, 2007	Predicted	-73.53763300 N, 45.52117500 W	1508

Several of the values recorded on dates above are fixed and several are considered predicted results. The fixed results are those where the sampling station did not move for the full hour. The predicted results are different in that the sampling station presumably did move during the event, likely to locate more centrally into the firework plume. The predicted measurements were not measured for a full hour but for about 50 minutes and thus the results are predicted for the full hour based on 50 minutes of measurement.

Test models were run in AERMOD for the same dates as Environment Canada measured. The results of these test models are compared to Environment Canada's results in Table 5.3.

Table 5.3- Comparison between Environment Canada's measured PM2.5 concentrations and AERMOD's predicted PM2.5 concentrations.

	Concentration (ug/m3)	
Date	Environment Canada	AERMOD Result
June 20, 2007	66 (predicted)	508
June 27, 2007	618 (measured)	Miss, No result
July 7, 2007	840 (measured)	700
July 7, 2007	204 (predicted)	1340
July 18, 2007	319 (measured)	55
July 21, 2007	1152 (predicted)	615
July 25, 2007	288 (measured)	10
July 28, 2007	1508 (predicted)	1900

Following modelling, some investigation was conducted to identify some of the possible reasons for the variation between Environment Canada's results and the AERMOD results. During a review of the meteorology data for the AERMOD models it was found that on one of the dates the wind direction changed dramatically from 9pm to

11pm. On July 18, 2007 over three hours the wind direction changed 179 degrees which may explain the large discrepancy between the Environment Canada result and the AERMOD result. This change was several-fold larger than the wind direction change on any other date. Consequently it was decided that AERMOD cannot model any date where the wind direction changes more than 100 degrees from 9pm to 11pm. The wind direction change for the three hours can be seen in Table 5.4.

Table 5.4- Wind direction change for validation events

	Wind Direction (degrees)			
	9pm	***10pm***	***11pm***	***Total Change***
20.06.2007	308	301	296	12
27.06.2007	13	58	33	70
7.07.2007	249	239	248	19
18.07.2007	181	295	0	179
21.07.2007	326	315	328	24
25.07.2007	222	218	211	11
28.07.2007	17	350	302	75

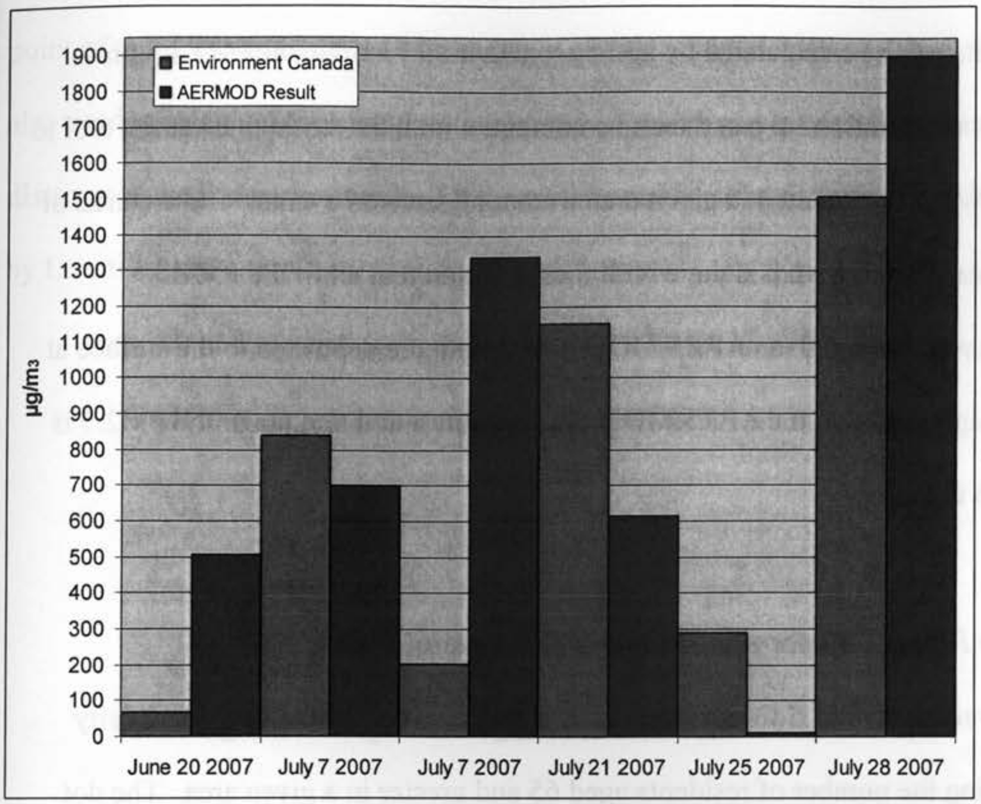
Wind direction change was also evaluated for the dates modelled and it was also found that one of the dates where there was a large discrepancy between Environment Canada's and AERMOD's results could be explained by a large change in wind velocity. On June 27, 2007 the windspeed dropped 4.1 m/s over three hours. This change in wind speed was quite large compared to all the other dates, with the exception of July 7 which was the other date eliminated due to a large change in wind speed. Due to the large discrepancy between Environment Canada's result and AERMOD's for the July 7 date, it was concluded that AERMOD cannot accurately model dates where the windspeed changes more than 2.5m/s over the three hours surrounding the firework event. The windspeed changes can be seen in Table 5.5.

Table 5.5- Windspeed change for validation events

	Windspeed (m/s)			
	9pm	*10pm*	*11pm*	*Total Change*
20.06.2007	2.6	3.1	3.1	0.5
27.06.2007	7.7	4.1	3.6	4.1
7.07.2007	3.6	3.1	3.1	0.5
18.07.2007	2.1	2.1	0	2.1
21.07.2007	2.1	3.1	2.6	1.5
25.07.2007	1	2.1	2.6	1.6
28.07.2007	3.1	2.6	2.6	0.5

After eliminating the two dates due to meteorology limitations the Environment Canada results and AERMOD results were put to a simple correlation test to determine the quantity of correlation. The correlation coefficient between the two results was found to be 0.534. These results were deemed to be acceptable due to the limited number of events measured by Environment Canada, the fact that all events measured by Environment Canada were from the same year and the fact that several of Environment Canada's results were predicted. A side-by-side comparison of the results can be seen in Figure 5.2.

Figure 5.2- Comparison of Environment Canada's measured/predicted particulate matter concentrations and AERMOD's predicted results



5.3- Model Results

5.3.1- Averaged PM2.5 Concentration Map

The Averaged PM2.5 Concentration Map was produced in ArcMap by rasterizing each individual concentration map. Using the ArcMap raster calculator, the values on each map were added together and the sum divided by 93 which is the total number of events. This map was later combined with a layer produced by *CanMap RouteLogistics* in 2008 of hospitals and health clinics.

5.3.2- Gross Concentration Map

The gross weight of PM2.5 deposited in a 10km radius from La Ronde from all fireworks events can be calculated by adding together all 93 individual PM2.5 plumes. This Gross Concentration Map can then be combined with the ArcMap measuring tool to calculate the PM2.5 deposited in a given area from all fireworks events. The creation of the Gross Concentration Map is done with the assumption that all of the PM2.5 concentrations represented in an AERMOD plume output are deposited to the surface at the locations represented in the AERMOD plume outputs and that none of the PM2.5 is resuspended to the air.

5.3.3- Average PM2.5 Concentration Map and Dot Density Map

The Average PM2.5 Concentration Map was also combined with a dot density map representing the number of residents aged 65 and greater in a given area. The dot density map was created from the results of the 2006 Canada Census at the dissemination area scale. A dissemination area is a socially and economically uniform area with a population of between 400-700 people. The dissemination areas in the Montreal area are small and densely packed since 700 people can be found in one high-rise residential building. In order to calculate the number of individuals over 65, several columns of census data needed to be added together. The columns that were added include the population of males ages 65-69, 70-74, 75-79, 80-84, and 85 plus, and their female population counterparts. These results were then mapped in a 10km radius from the point of La Ronde's fireworks events. The population density was displayed using a dot density map which is a map that represents a certain number of individuals by a single dot. The map that was produced uses a single dot to represent 7 individuals aged 65 and over. The area displayed by the map is approximately equal to a 3km radius from the point of the fireworks events. In addition to the outputted dot density map, ArcMap was also used to calculate the number of individual aged 65 and over within a given buffer distance of the fireworks events. This was achieved by using ArcMap's 'Select Feature by Location' tool.

Chapter 6- Results and Observations

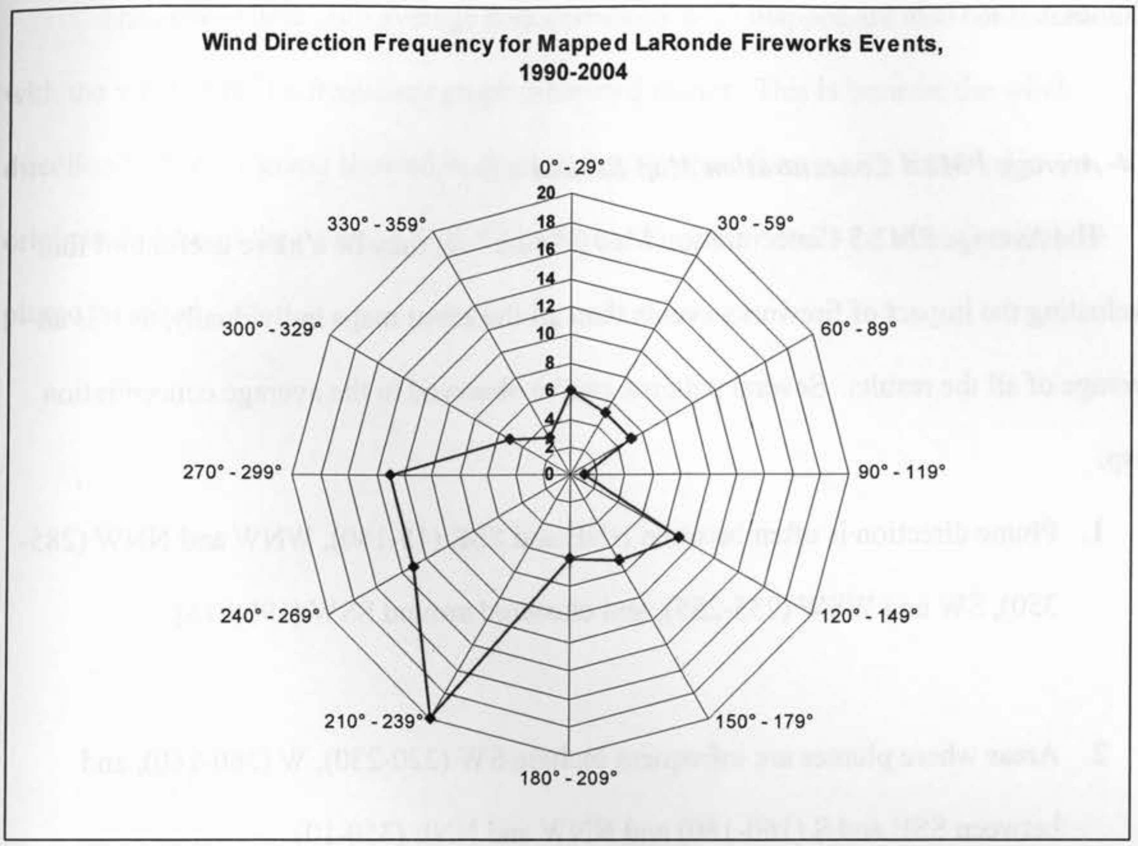
6.1- Overview

A cursory examination of the model outputs indicate that PM2.5 concentrations on the island of Sainte-Helene during fireworks events in the summer nearly always exceed 1000μg/m^3 for a portion of the island. This central concentration area is surrounded by many closely packed concentration gradients where the concentration decreases precipitously over a short distance, often less than 2km in the direction of the prevailing winds, and less than 0.5km in the directions perpendicular to the prevailing winds as well as in the direction opposite to the prevailing winds (180degrees). Beyond the area of precipitous declining concentration gradients is an area where the gradients gradually decrease in concentration but increase in area. Although the outermost concentration gradient is 20μg/m^3 all the models calculated some concentration of PM2.5 from the event in all of the receptor quadrants. The map results for all events can be found in Appendix A.

6.2-Wind Direction and Frequency

In each meteorology file there is a measurement of wind direction in degrees. The listed wind direction in the meteorology files is based on a 360 degree spectrum with 0 degrees representing wind from directly north, 90 degrees from directly east, 180 degrees from directly south and 270 degrees from directly west. A histogram (Figure 6.1) of all fireworks events that were not eliminated reveals that the wind direction was blowing from between 210° and 299° for many events, and between 330° and 359° as well as 60° and 119° for very few events.

Figure 6.1- Wind direction frequency for mapped La Ronde fireworks events, 1990-2004



These results are further discussed in Section 6.3.

6.3-Plume Lengths

Most of the plumes' 20 $\mu g/m^3$ gradient fell within a few kilometers of the 10km radius of the base map, although there were some anomalies such as June 16, 2003 where the plume barely reached 5km in length and June 28, 1999 where the plume was modelled to have exceeded 40km during the course of one hour. The latter is likely an inaccurate result as the windspeed during this event was 2.1 m/s which should result in a plume of around 7.5km. Despite the questionable accuracy of a few models, it is clear that the wind speed for the majority of the models directly affects the length of the plume; stronger wind speeds result in longer plumes and weaker wind speeds result in shorter plumes.

6.4- Average PM2.5 Concentration Map Results

The Average PM2.5 Concentration Map (Figure 6.2) may be a more useful tool for evaluating the impact of fireworks events than all the event maps individually, as it is an average of all the results. Several patterns can be observed in the average concentration map:

1. Plume direction is often between NNE and SSE (15-160), WNW and NNW (285-350), SW and WSW (235-255), and clustered around SSW (190-215).

2. Areas where plumes are infrequent include SW (220-230), W (260-280), and between SSE and S (160-180) and NNW and NNE (350-10).

3. The areas listed under point 1 are where the prevailing winds are more common and, as a result, these areas are also where PM2.5 concentrations are, on average, the highest during the hour of the event.

4. The areas listed under point 2 are where the prevailing winds are uncommon and, as a result, these areas are where PM2.5 concentrations are, on average, the lowest during the hour of the event.

5. The areas to the east of Sainte-Helene Island are impacted the most on average by fireworks plumes (Longueuil).

The areas where high average concentrations were mapped are also consistent with the wind direction frequency graph presented earlier. This is because the wind direction frequency graph showed in degrees the direction from which the wind originated whereas the Average PM2.5 Concentration Map details the direction that the plume travelled.

Averaged One Hour PM2.5 Concentration
For All Mapped Fireworks Events

Deon Bridge
UTM 1983, Zone 18
March, 2009

Figure 6.2- Average PM2.5 Concentration Map

6.4- Health Clinics

There are several health clinics located near La Ronde and, according to the Average PM2.5 Concentration Map, within areas of elevated concentrations of PM2.5 during fireworks events. A summary of clinics is found in Table 6.1 and the average PM2.5 Concentration Map with the health centres can be seen below in Figure 6.3.

Table 6.1: Health clinics proximal to La Ronde and their average PM2.5 concentration

Name	*µg/m3*	*Distance (km)*	*Service*
LES CENTRES JEUNESSE DE LA MONTEREGIE	50-74	1.44	Child Protection/Troubled Youth
CHSLD LE MANOIR TRINITE	30-39	3.04	Nursing home/24 hour care
CHSLD CHEVALIER DE LEVIS	30-39	2.77	Nursing home/24 hour care
CHSLD ST-FELIX DE LONGUEUIL	30-39	2.85	Nursing home/24 hour care
CENTRE D'ACCUEIL ST LAURENT ENR	30-39	2.42	Nursing home/24 hour care
CENTRE D'HÉBERGEMENT MAISON-NEUVE	20-29	2.45	Nursing home/24 hour care
CENTRE D'HÉBERGEMENT J-HENRI-CHARBONNEAU	20-29	2.46	Nursing home/24 hour care
RESIDENCE ARMAND LAVERGNE	20-29	2.31	Nursing home/24 hour care
CLSC CENTRE-SUD	20-29	2.07	Mental Health

Figure 6.3- Averaged one hour PM2.5 concentration for all mapped firework events and health centre locations

As displayed in Table 6.1, there are 7 nursing and permanent care residences within 3km of the staging area for La Ronde's fireworks events. All these residences are in areas where plumes are more commonly observed and, as a result, they are areas exposed to elevated levels of PM2.5. The residents in these homes are often individuals with serious respiratory or cardiovascular illness and are therefore highly susceptible to adverse reactions from exposure to PM2.5. Since these locations are long-term care locations, it is reasonable to conclude that the majority of residents at any given time will be at the location of the residence where exposure could occur if the resident is outside or in a room with an open window. There are also two centres in Table 6.1 that deal with mental health, one of which is dedicated to treating children. Although not a direct focus of this paper, it may be the case that some residents in these mental health institutions are more sensitive to loud noises, due to posttraumatic stress or schizophrenia, and thus prone to startling or stress due to the acoustic effects of the display. The mental health institution for children can be considered a location with a susceptible population as asthmatic children are more sensitive to the adverse effects of PM2.5 exposure.

In addition to the long term care centres in close proximity to the fireworks events, as listed in Table 6.1, there are also several hospitals within a 10 kilometer radius of La Ronde. These locations are summarized in Table 6.2.

Table 6.2- Hospitals proximal to La Ronde and their average PM2.5 concentration

Name	*Ug/m3*	*Distance*
HÔPITAL SANTA CABRINI	1-4	6.
HÔPITAL CHARLES LEMOYNE	20-29	4.
HOPITAL ST-DENIS (1980) INC	10-14	4.
HÔPITAL JEAN-TALON	1-4	6.
HOPITAL SAINT-LUC	15-19	2.
GRACE DART HOSPITAL	1-4	5.
HÔPITAL LOUIS-H LAFONTAINE	1-4	6.
HÔPITAL MAISONNEUVE-ROSEMONT	1-4	5.
HÔPITAL STE-JEANNE D'ARC	5-9	3.
LINDSAY REHABILITATION HOSPITAL	1-4	7.
MONTREAL CHINESE HOSPITAL	15-19	2.
ST MARY'S HOSPITAL CENTER	1-4	7.
SHRINERS HOSPITAL FOR CHILDREN	1-4	5.
SIR MORTIMER B DAVIS JEWISH GENERAL HOSPITAL	1-4	7.
HÔPITAL NOTRE-DAME	10-14	2.
MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL CHILDREN'S HOSPITAL	1-4	5.
MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL CHEST INSTITUTE	5-9	3.
MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL CHILDREN'S HOSPITAL	1-4	5.

The hospitals listed in Table 6.2 above are areas where a high density of infirm individuals are located, possibly for long periods of time. In total there are over 133 hospitals, emergency care and long-term care facilities within a 10 km radius of the fireworks events.

6.5- Individual Plume Maps and Health Centres

Each individual plume map was also overlayed with the locations of all health centres within a 10 km radius of the island of Saint-Helene. This made it possible to count the number of health facilities that were located anywhere within the boundaries of each of the individual fireworks plumes. The results of this process can be seen in Table 6.3.

Table 6.3: Number of health facilities located within each individual plume

Date of Event	Number of Health Facilities	Date of Event	Number of Health Facilities
900526	5	920726	18
900530	1	920802	3
900602	4	930605	11
900606	32	930612	5
900613	18	930626	4
900620	36	930704	6
000625	3	930711	8
000712	5	930718	2
000719	3	930725	26
000726	11	930801	5
010620	3	940530	5
010627	3	940604	20
010711	9	940618	1
010714	5	940703	9
010718	29	940710	3
010721	3	940717	11
010725	6	940724	17
020622	15	950702	8
020629	6	950705	20
020721	3	950712	3
030621	5	950719	3
030628	5	950723	7
030705	4	960620	17
030709	15	960623	26
030712	3	960627	4
030716	4	960704	2
030719	4	960714	21
030723	20	960718	17
040612	18	970607	8
040619	5	970614	7
040626	8	970621	4
040710	31	970628	6
040714	8	970713	22
040717	21	970720	7
040721	15	980606	4
910529	4	980610	30
910601	5	980617	0
910605	3	980627	28
910608	10	980705	6
910612	2	980712	18
910615	31	980719	14
910619	6	990703	16
920530	1	990711	6
920606	1	990714	15

920613	4	990721	4
920620	5	990728	6

Table 6.3 demonstrates that there is large variability in the number of health centers exposed directly to the fireworks plume of any single fireworks event. The largest number of health centers impacted by a single event was 36 and the lowest was 0. The respective plumes and health facilities are presented below in Table 6.4 and Figures 6.4 and 6.5.

Table 6.4: List of health facilities impacted by the June 20, 1990 fireworks plume

3	Point	INSTITUT UNIVERSITAIRE DE GERIATRIE DE MONTREAL - PAVILLON ALFRED-DESROCHERS
4	Point	INSTITUT UNIVERSITAIRE DE GERIATRIE DE MONTREAL - PAVILLON ALFRED-DESROCHERS
7	Point	MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL CHEST INSTITUTE
8	Point	MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL CHILDREN'S HOSPITAL
183	Point	LES CENTRES JEUNESSE DE LA MONTEREGIE
216	Point	RÉSIDENCE ST-CHARLES-BORROMÉE
217	Point	CHSLD CENTRE-VILLE DE MONTREAL - MANOIR L'AGE-D'OR
223	Point	CLSC CENTRE-SUD
224	Point	CLSC CENTRE-VILLE
226	Point	CLSC METRO
227	Point	CLSC NOTRE-DAME-DE-GRACE MONTREAL-OUEST
237	Point	CENTRE D'ACCUEIL HERITAGE INC
244	Point	CENTRE D'HEBERGEMENT ST GEORGES INC
246	Point	CENTRE HOSPITALIER JACQUES VIGER
247	Point	CENTRE HOSPITALIER RICHARDSON/CENTRE D'ACCUEIL HENRI BRADET (CHSLD)
252	Point	MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL NEUROLOGICAL HOSPITAL
259	Point	MCGILL UNIVERSITY HEALTH CENTRE - ROYAL VICTORIA HOSPITAL
260	Point	ST ANDREW PRESBYTERIAN HOMES INC
545	Point	ST MARGARET'S HOME
649	Point	CATHERINE BOOTH HOSPITAL CENTRE
650	Point	CHSLD RESIDENCES MANCE-DECARY
663	Point	CENTRE HOSPITALIER RICHARDSON
664	Point	HOPITAL SAINT-LUC
665	Point	CENTRE HOSPITALIER DE L'UNIVERSITÉ DE MONTRÉAL (CHUM) - HÔTEL-DIEU (SIÈGE SOCIAL)
670	Point	FULFORD RESIDENCE
681	Point	HÔPITAL STE-JEANNE D'ARC
704	Point	INSTITUT RAYMOND-DEWAR
707	Point	JEWISH ELDERCARE CENTRE
708	Point	JEWISH NURSING HOME
711	Point	MAISON SAINTE-ELIZABETH
713	Point	MANOIR COTE DES NEIGES
716	Point	MONTREAL CHINESE HOSPITAL
718	Point	MCGILL UNIVERSITY HEALTH CENTRE - MONTREAL GENERAL CAMPUS
719	Point	PORTAGE PROGRAM FOR DRUG DEPENDENCIES INC
725	Point	ST MARY'S HOSPITAL CENTER
726	Point	SHRINERS HOSPITAL FOR CHILDREN
727	Point	SIR MORTIMER B DAVIS JEWISH GENERAL HOSPITAL
728	Point	VILLA MÉDICA INC

Health Facilities Impacted by the June 20, 1990 LaRonde Fireworks Plume

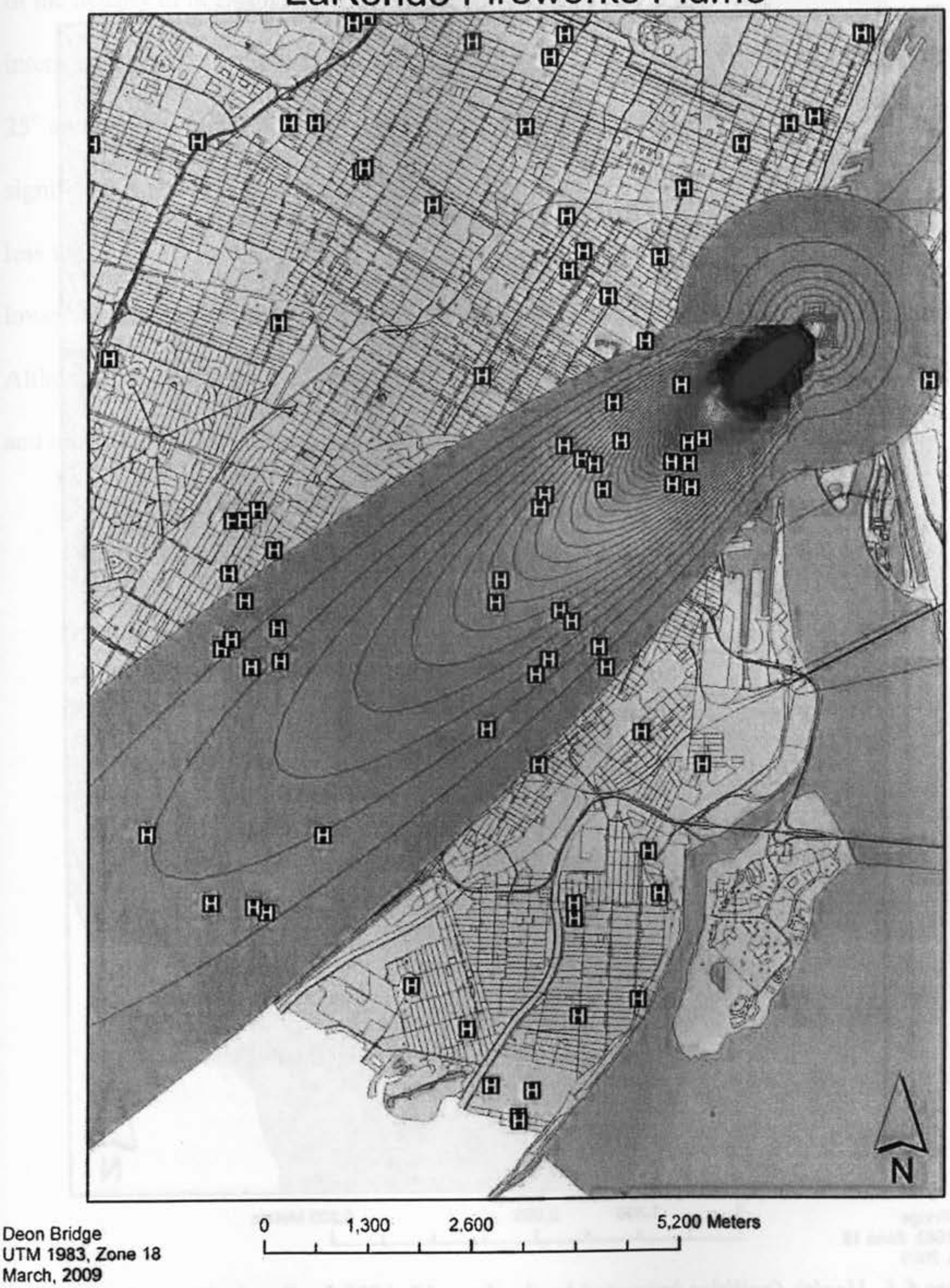
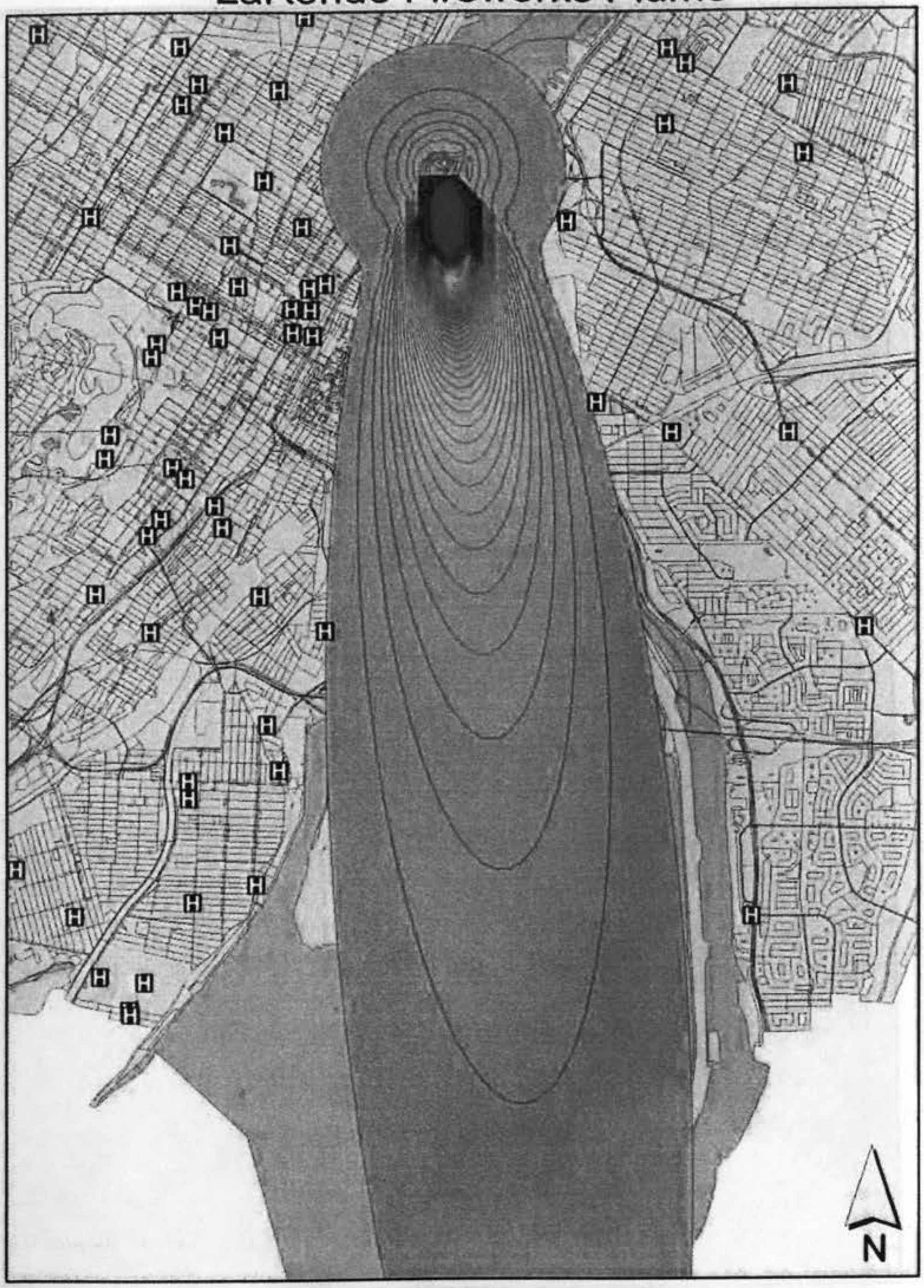


Figure 6.4- Health facilities impacted by the June 20, 1990 La Ronde fireworks plume

Health Facilities Impacted by the June 17, 1998 LaRonde Fireworks Plume



Deon Bridge
UTM 1983, Zone 18
March, 2009

0 1,300 2,600 5,200 Meters

Figure 6.5- Health facilities impacted by the June 17, 1998 La Ronde fireworks plume

The number of health facilities impacted by the June 20, 1990 plume is illustrative of the density of health facilities on the island of Montreal. Of the 15 plumes that intersected with 20+ health centers, 11 were the result of wind from the direction of 78° - 25° and only 4 from 156° - 123°. The number of health centers on the Longueuil shore is significantly less which explains why the vast majority of plumes to the west intersect less than 5 health centers. Plumes travelling towards the west intersect with areas of lower density and lower total population than plumes travelling westward over Montreal. Although plumes are less common over Montreal, they present a higher risk of morbidity and mortality due to the high population density.

Chapter 7- Discussion and Recommendations

7.1- PM2.5 and Public Health

Given that there are roughly 2 million spectators yearly at risk of exposure to high levels of PM2.5 there is a necessity that the population be informed of the risk they are facing. Currently there is little awareness in the general public of the risk posed by exposure to PM2.5 and likely even less knowledge of the risk posed by fireworks events as sources of PM2.5. It would be prudent for La Ronde to communicate the risk posed by the fireworks events to ticket holders and spectators and even offer personal protective equipment such as disposable face masks prior to the event. Face masks have been found to limit some of the health effects caused by exposure to PM2.5 (Van Kamp, 2006, Langrish, 2009) La Ronde workplace policy should also require that all staff use face masks during the events.

Many of the fireworks event spectators are not inside La Ronde itself but in public places surrounding the venue. These individuals should also be made aware of the risks posed by exposure to high concentrations of PM2.5. An effective public health campaign could be one of the mechanisms for informing individuals who intend to witness the event from outside the park's perimeter. A public health campaign would also be beneficial to residents of the Montreal area who may be at additional risk from exposure to PM2.5, such as the elderly or infirm, even though they may not be attending the events or plan to be in the near vicinity of the event. Since many of the events take place during hot weather, many residents who live far from the event may still be exposed through open windows or during outdoor activities as the plume travels downwind.

The results of the modelling should also be used in conjunction with health data collected from 1990 to 2004 in order to confirm and quantify the nature and strength of the relationship between firework plumes and morbidity and mortality for Montreal and Longueuil.

7.2- Fireworks and the Elderly Population of Montreal

The dot density map (Figure 7.1) reveals that there is a large population of elderly aged 65 and over within close proximity to La Ronde. These elderly are located in areas that experience a range of PM2.5 concentrations, from elevated to extremely high. The outside border of the map contains the largest density of dots and this is also the areas of lowest average concentrations. However there are many examples of densely populated elderly areas (Figure 7.2) in the 20-29μg/m^3 gradient on the Montreal (west) side of the map, in the 30-39μg/m^3 gradient on the (east) Longueuil side of the map and a large cluster of elderly located in the 75-99μg/m^3 gradient on the Longueuil side of the map. This latter cluster is populated by 615 65+ individuals. There are also two very densely packed dissemination areas in the 100-149μg/m^3 on the west side of the map. These two clusters alone contain 130 and 100 individuals aged 65+ respectively.

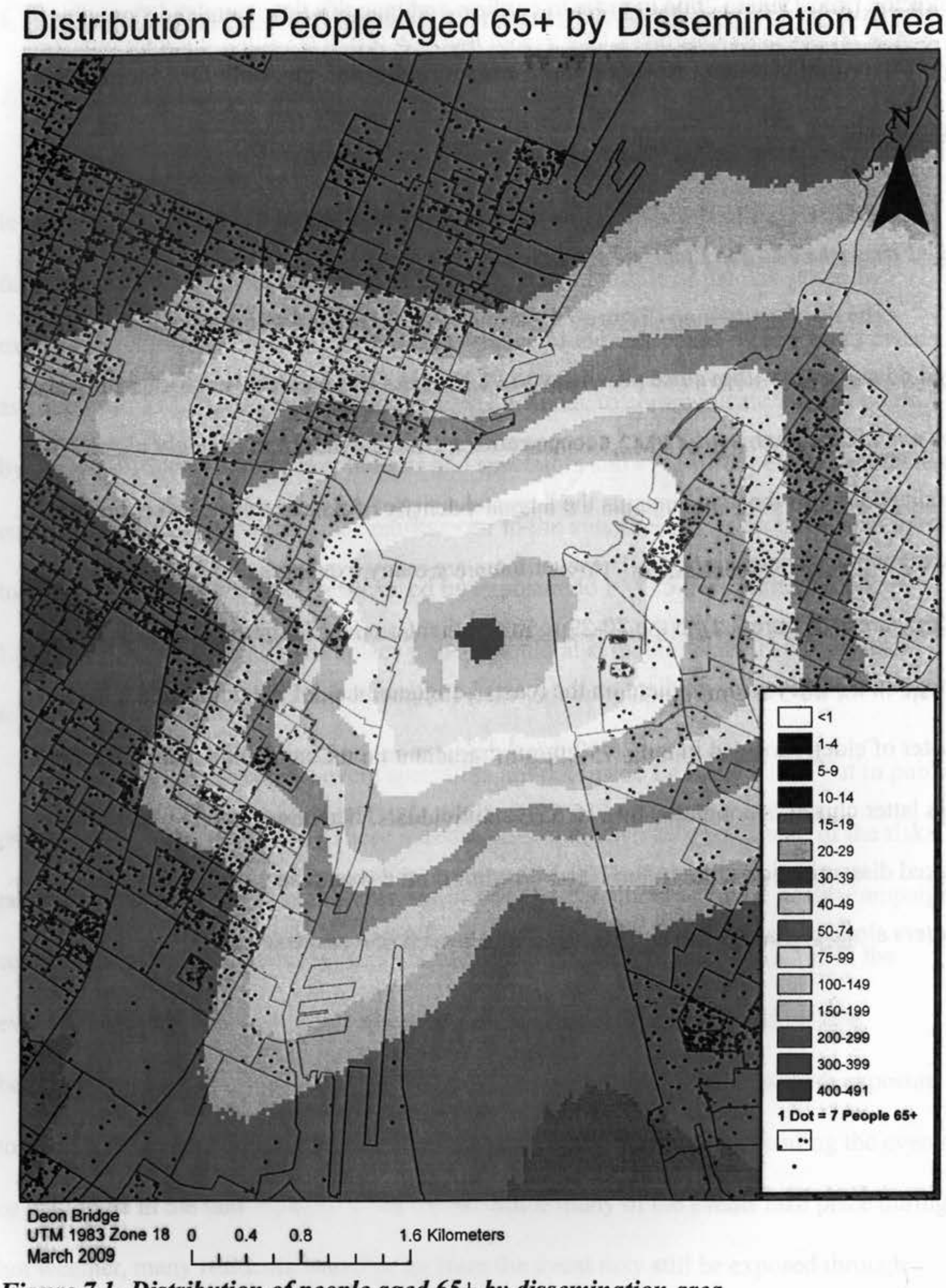


Figure 7.1- Distribution of people aged 65+ by dissemination area

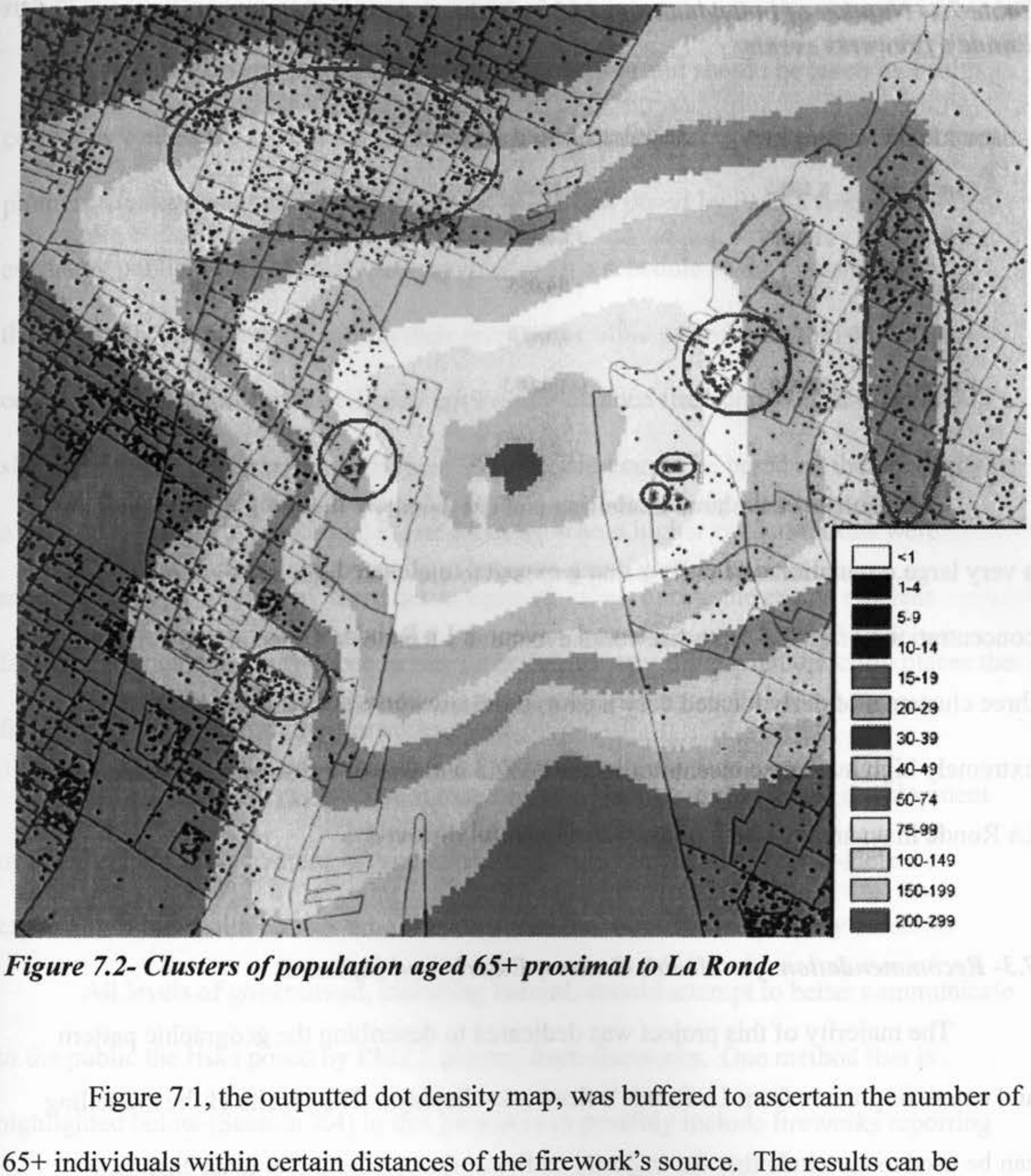


Figure 7.2- Clusters of population aged 65+ proximal to La Ronde

Figure 7.1, the outputted dot density map, was buffered to ascertain the number of 65+ individuals within certain distances of the firework's source. The results can be found in Table 7.1.

Table 7.1- Number of individuals aged 65+ within a certain distance of the source of La Ronde's fireworks events

Buffer Radius	Elderly 65+	Additional Elderly per Buffer Zone
2km	8,190	8,190
3km	21,650	13,460
4km	35,685	14,035
5km	53,695	18,010
10km	194,780	141,085

The results of the plume modelling and dot density mapping indicate that there is a very large population of elderly being exposed to elevated, high and extremely high concentrations of PM2.5 from fireworks event at La Ronde. Of special concern are the three clusters of elderly located very near to the fireworks site as these areas have extremely high average concentrations for PM2.5 and two of the areas are located east of La Ronde in an area where plumes are frequently observed.

7.3- Recommendations for Health Centres, Elderly and Infirmed

The majority of this project was dedicated to describing the geographic pattern and extent of plumes from La Ronde's fireworks displays. The results of the modelling can be used to conclude that the majority of fireworks plumes travel in an eastward direction toward Longueuil and away from the most densely populated parts of Montreal. The greatest number, and highest density of health centers is also located within the Montreal city area as compared to Longueuil and thus plumes that travel east would not be exposing the highly susceptible residents of these areas to PM2.5. However as shown in several maps there are clusters of elderly in both Montreal and Longueuil who are at risk of adverse reaction to exposure to PM2.5.

There are several preventative measures that can and should be taken by health centers as well as the general public in order to reduce the risk of exposure to PM2.5 plumes. Health centers should be informed of the risk posed by PM2.5 from fireworks events by public health officials and provided with a schedule of the planned events so that they may appropriately inform their most susceptible patients of the risk. The health centre administration can then decide prior to the planned fireworks events if patients should be restricted to indoor activities. This decision could be based on the proximity of a particular facility to La Ronde; closer facilities where higher concentrations were modelled may not allow any activities or open windows during the events whereas facilities further away may chose to restrict activities only if the wind direction places the facilities downwind from the fireworks event.

From a planning perspective it may be good practice to restrict the development of new health centers to areas several kilometers from the island of Sainte-Helene, especially if the health centers are for elderly, cardiovascular or respiratory care.

All levels of government, including federal, should attempt to better communicate to the public the risks posed by PM2.5 plumes from fireworks. One method that is highlighted below (Section 7.4) in this project is to possibly include fireworks reporting on the NPRI. Presently by not requiring the input, it sends a message that fireworks are not a significant source of PM2.5 and that it is not necessary to track fireworks as sources of particulate matter.

7.4- Environment Canada's National Pollutant Release Inventory (NPRI)

Each year Environment Canada requires that companies that manufacture, process or otherwise use certain substances deemed a risk to the environment disclose how they are transferred or disposed. PM2.5 is listed under Part 4 Criteria Air Contaminants (CAC) in the NPRI substance list (Environment Canada, 2007). Currently fireworks events are exempt from report under the NPRI under the grounds that employees at the events do not exceed 20,000 hours of employment during the calendar year and stationary combustion equipment is not operated at the facility (Environment Canada, Guide for Reporting to the National Pollutant Release Inventory, 2007). However each individual firework event likely exceeds the NPRI threshold for reporting PM2.5 which is set to 0.3 tonnes annually whereas a single firework event is estimated to release around 500 kg of PM2.5.

As the modelling results have shown, cumulatively, the firework events are responsible for high levels of particulate matter which may contain high concentrations of metals, dioxins and furans, perchlorate, and other highly toxic environmental pollutants. The NPRI is designed as a tool for informing the public of significant sources of pollutants in their environment. Firework events should qualify for mandatory reporting on Canada's NPRI.

7.5- Aquatic Effects of Fireworks Displays

A large quantity of the PM2.5 from La Ronde's fireworks displays is dispersed and deposited over portions of the St. Lawrence River. In addition to the plumes themselves that deposit directly onto the St. Lawrence River, there would also be large quantities of run-off from the events that would undoubtedly reach the St. Lawrence. Using the Gross PM2.5 Concentration Map, a 1km buffer was drawn around the central fireworks location on the island of Sainte-Helene, and the total quantity of particulate from all plumes entering into the St. Lawrence was calculated. The calculations can be found in Table 7.2.

Table 7.2- Total PM2.5 deposition into St. Lawrence based on Gross PM2.5 Concentration Map

Area (sq m)	Concentration Range (ug/m3)	Midpoint	Total ug/m2
574000	10,020-15,000	12510	7180740000
353000	15,020-20,000	17510	6181030000
188000	20,020-25,000	22510	4231880000
127000	25,020-30,000	27510	3493770000
34000	30,040-35,000	32510	1105340000
20000	35,200-40,000	37510	750200000
4000	40,020-45,700	42860	171440000
		Total ug	23114400000
		Total kg	23.11

The calculation in Table 7.2 is based on the assumption that all PM2.5 in a cubic meter at the surface settles onto a square meter of surface area. The resultant calculation indicates that, due to all 93 fireworks events, the St. Lawrence directly received 23kg of particulate matter within 1km of La Ronde. This quantity of particulate matter is significant given that a large composition of PM2.5 is made up of metals, perchlorate, and reactive ions. Although there is little information on how fireworks impact water quality, the result of what little research there is suggests water quality can be adversely affected by perchlorates (Wilkin, 2007). The effects that La Ronde fireworks displays have on the St. Lawrence's water quality are not known; however, the modelling results presented above indicate that the cumulative effects of all the events may be large enough to affect water quality and warrant further investigation.

7.6- Reducing Ground Level PM2.5

Currently both private industry and the United States military are researching and developing low and reduced smoke pyrotechnics. Conventional fireworks are accelerated to their objective altitude by combusting black powder; however other means of launching fireworks are being investigated including the use of compressed air which would produce no particulate matter during launching at all. The elimination of black powder would not eliminate all PM2.5 produced during fireworks events as the combustion and reaction of the fireworks themselves produce large quantities of PM2.5. The use of compressed air would eliminate a large source of the ground-level particulate matter that fireworks technicians, La Ronde employees and spectators are exposed to. Although there are likely costs associated with migrating to a compressed air system, other venues, including Disneyland in California have already adopted compressed air as the projection mechanism for their events (Hills 2006 and Halford, 2008).

La Ronde should be encouraged to migrate their fireworks system to an air-compression system as used at other venues. It may be possible to allocate some funding from one or several levels of government to help offset the cost of migrating to the lower impact system.

7.7- AERMOD Suitability for Modelling Fireworks Events

Lakes Environmental's commercial AERMOD software package proved to be a good preliminary tool for modelling fireworks events. Although the use of a stack to simulate a fireworks event is not an ideal solution for simulating the emissions from a firework event, the use of a stack proved to be a sufficiently reliable tool once the stack parameters were adapted to the task. The key limitation with using AERMOD was that it required a continuous, one-hour emission from the stack. Fireworks events do not function as continuous emission events but rather they are more akin to a series of intermittent bursts of pollutants separated by varying time periods where the emission of pollutants is very low or stops entirely. Furthermore the La Ronde fireworks events do not last a full hour but seem to vary between 30 minutes and 40 minutes.

If more accurate results were sought in the future, it would be ideal to use a model capable of simulating puffs of pollutants as opposed to continuous emission. In addition to AERMOD, Lakes Environmental also sells a commercial product capable of simulating puff emissions; CALPUFF. CALPUFF is a non-steady state modeler meaning it can model emissions as intermittent events or 'puffs'. Similarly CALPUFF is also able to model meteorology conditions that vary spatially and temporally. In practice, this means that each puff is independent of other puffs and will likely have its own unique plume trajectory and dispersion characteristics. CALPUFF, unlike AERMOD, also has the capability to model the dry and wet deposition of pollutants. If CALPUFF were to be used to model the fireworks events at La Ronde, more data would be needed to run the model including; a data file on the varying emissions rate in order to model the puffs and pauses, extended meteorology information including precipitation data, humidity, and short-wave solar radiation. If CALPUFF were to be used, it would also be beneficial to model the building sizes and shapes that are proximal to La Ronde in order to permit the model to simulate the small scale changes in meteorology that are common in urban areas. Although AERMOD is capable of modelling building features, it would be a far more useful and appropriate exercise with a puff modeler.

Although CALPUFF is a more capable package for simulating the intricacies of fireworks events, it is also significantly more expensive and likely would not prove to be significantly more accurate without more precise input data. The stack parameters used to simulate all events were uniform and based on the best available data. Ideally each event would have stack inputs which would have been tailored to suit the mix of different fireworks used as well as the pace of emissions. If future work were to be done modelling La Ronde fireworks events, it would be valuable to collect more specific information on the area where fireworks are ignited, the weight of fireworks used, the different altitudes of firework detonation, and finally the length of the event with pauses in activity noted.

7.8- Final Remarks

AERMOD and ArcMap, when used together, are powerful tools for modelling and mapping PM2.5 plumes from fireworks events. Although there were noted limitations to what is capable using these tools, the majority of results are a useful, quantitative measure of the impact of fireworks on urban air quality in Montreal. When the events are examined cumulatively, the evidence suggests that fireworks events are significant sources of particulate matter and these results should be a starting point leading to more research and greater understanding into impacts of firework plumes on human health and the environment. Ideally, further research would be done with more specific input data and possibly the use of more powerful modelling software.

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APPENDIX A: Meteorology Evaluation

LEGEND

- Eliminated date
- Datum causing elimination

YYMMDD	Time	Wind Direction (°)	Wind Speed (m/s)	Wind Direction Change (°)	Wind Speed Change (m/s)
900526					
	9pm	238	1.00	79	0.5
	10pm	299	0.50		
	11pm	317	0.50		
900530					
	9pm	282	4.10	10	0.5
	10pm	290	4.10		
	11pm	288	3.60		
900602					
	9pm	225	4.10	22	1.5
	10pm	231	3.60		
	11pm	215	2.60		
900606					
	9pm	55	1.50	73	1.5
	10pm	64	0.50		
	11pm	360	1.00		
900609					
	9pm	6	3.10	78	2.7
	10pm	48	1.50		
	11pm	84	2.60		
900613					
	9pm	158	2.60	1	2
	10pm	157	3.10		
	11pm	157	4.60		
900616					
	9pm	137	2.10	170	1.1
	10pm	47	1.00		
	11pm	127	1.00		
900620					
	9pm	28	2.10	88	1.6
	10pm	51	2.10		
	11pm	116	0.50		
910525					
	9pm	0	0.00	84	5.1
	10pm	73	4.60		
	11pm	62	4.10		
910529					
	9pm	236	1.50	81	1.5
	10pm	209	0.50		

	11pm	155	1.00		
910601					
	9pm	290	2.10	24	1.5
	10pm	296	2.60		
	11pm	314	3.60		
910605					
	9pm	359	1.00	26	1
	10pm	339	0.50		
	11pm	333	1.00		
910608					
	9pm	9	4.60	2	2.5
	10pm	10	3.10		
	11pm	9	4.10		
910612					
	9pm	271	5.10	36	0.6
	10pm	296	5.10		
	11pm	307	5.70		
910615					
	9pm	70	4.10	29	2.5
	10pm	65	3.10		
	11pm	41	4.60		
910619					
	9pm	226	2.10	22	2.5
	10pm	246	4.10		
	11pm	244	3.60		
920530					
	9pm	201	5.10	22	2.5
	10pm	215	4.60		
	11pm	207	2.60		
920606					
	9pm	152	0.50	69	1
	10pm	208	1.50		
	11pm	221	1.50		
920613					
	9pm	226	5.70	12	2.1
	10pm	237	4.60		
	11pm	238	3.60		
920620					
	9pm	247	4.10	13	1.5
	10pm	241	4.60		
	11pm	248	3.60		
920627					

	9pm	276	2.10	200	2.6
	10pm	204	2.60		
	11pm	332	0.50		
920705					
	9pm	212	3.60	36	2.7
	10pm	225	1.50		
	11pm	248	2.10		
920712					
	9pm	308	0.50	109	2.6
	10pm	29	3.10		
	11pm	57	3.10		
920719					
	9pm	115	1.00	50	0.5
	10pm	121	1.50		
	11pm	165	1.50		
920726					
	9pm	186	2.10	34	1
	10pm	178	3.10		
	11pm	204	3.10		
920802					
	9pm	237	6.20	20	1.6
	10pm	227	5.70		
	11pm	237	4.60		
930605					
	9pm	119	3.60	54	1.5
	10pm	89	3.60		
	11pm	113	5.10		
930612					
	9pm	241	3.10	26	1
	10pm	226	2.60		
	11pm	237	2.10		
930619					
	9pm	196	2.10	256	2.1
	10pm	226	1.50		
	11pm	0	0.00		
930626					
	9pm	233	5.10	4	2
	10pm	230	3.60		
	11pm	229	4.10		
930704					
	9pm	285	3.10	58	2.1
	10pm	274	1.50		

	11pm	227	1.00		
930711					
	9pm	240	2.10	21	3
	10pm	252	3.60		
	11pm	243	2.10		
930718					
	9pm	221	1.50	32	0.6
	10pm	225	1.50		
	11pm	197	2.10		
930725					
	9pm	82	2.60	11	0
	10pm	78	2.60		
	11pm	71	2.60		
930801					
	9pm	236	2.60	30	0.5
	10pm	237	2.10		
	11pm	208	2.10		
940530					
	9pm	232	5.10	20	0.6
	10pm	240	5.10		
	11pm	228	5.70		
940604					
	9pm	139	3.10	19	1.6
	10pm	155	2.10		
	11pm	152	1.50		
940611					
	9pm	128	0.50	173	1
	10pm	70	0.50		
	11pm	185	1.50		
940618					
	9pm	18	4.10	61	1.5
	10pm	350	3.60		
	11pm	317	2.60		
940625					
	9pm	115	1.00	589	2
	10pm	352	1.50		
	11pm	0	0.00		
940703					
	9pm	236	3.60	19	1.5
	10pm	255	2.60		
	11pm	255	2.10		
940710					

	9pm	294	3.10	27	1
	10pm	279	4.10		
	11pm	291	4.10		
940717					
	9pm	122	1.50	30	1.6
	10pm	130	1.00		
	11pm	108	2.10		
940724					
	9pm	35	1.50	7	1
	10pm	34	1.00		
	11pm	40	0.50		
940731					
	9pm	208	4.10	19	2.6
	10pm	227	1.50		
	11pm	227	1.50		
950617					
	9pm	245	6.70	8	2.6
	10pm	245	5.70		
	11pm	253	4.10		
950625					
	9pm	25	3.10	8	3.7
	10pm	32	1.50		
	11pm	31	3.60		
950702					
	9pm	253	4.10	11	1.5
	10pm	249	3.60		
	11pm	256	2.60		
950705					
	9pm	151	2.60	55	1
	10pm	156	2.60		
	11pm	206	3.60		
950709					
	9pm	251	3.60	17	1.5
	10pm	264	4.10		
	11pm	260	5.10		
950712					
	9pm	228	3.10	16	1
	10pm	223	4.10		

YYMMDD	Time	Wind Direction (°)	Wind Speed (m/s)	Wind Direction Change (°)	Wind Speed Change (m/s)
950617					
	9pm	245	4.1	2	1.5
	10pm	245	5.1		
	11pm	243	4.6		
950625					
	9pm	5	2.6	98	2.1
	10pm	52	3.1		
	11pm	1	1.5		
950702					
	9pm	263	3.6	29	1.5
	10pm	269	3.1		
	11pm	246	2.1		
950705					
	9pm	151	2.1	15	0.5
	10pm	156	2.6		
	11pm	166	2.6		
950709					
	9pm	261	5.7	13	3.6
	10pm	254	3.1		
	11pm	260	4.1		
950712					
	9pm	238	2.6	34	0.5
	10pm	223	2.6		

	11pm	212	4.10		
950716					
	9pm	36	3.10	19	1.5
	10pm	39	4.10		
	11pm	55	3.60		
950719					
	9pm	230	4.60	22	1.7
	10pm	226	5.70		
	11pm	244	5.10		
950723					
	9pm	299	2.10	64	1.6
	10pm	259	1.00		
	11pm	283	1.50		
960615					
	9pm	27	3.60	30	2
	10pm	17	3.10		
	11pm	37	4.60		
960620					
	9pm	137	2.60	49	1.7
	10pm	111	1.50		
	11pm	88	2.10		
960623					
	9pm	31	2.10	11	2.2
	10pm	28	1.00		
	11pm	36	2.10		
960627					
	9pm	226	3.60	20	0.5
	10pm	234	3.60		
	11pm	222	3.10		
960630					
	9pm	140	4.10	13	1
	10pm	135	3.60		
	11pm	143	3.10		
960704					
	9pm	301	4.10	15	1
	10pm	296	3.60		
	11pm	286	3.10		
960707					
	9pm	121	3.60	63	2.1
	10pm	88	2.10		
	11pm	118	1.50		
960711					

	11pm	242	3.1		
950716					
	9pm	16	2.6	301	2
	10pm	239	2.1		
	11pm	75	3.6		
950719					
	9pm	240	4.1	14	0.5
	10pm	246	4.1		
	11pm	254	4.6		
950723					
	9pm	319	1.5	56	0.6
	10pm	279	1.5		
	11pm	263	2.1		
960615					
	9pm	-9	-999.9	0	0
	10pm	-9	-999.9		
	11pm	-9	-999.9		
960620					
	9pm	147	2.1	23	0.6
	10pm	141	2.1		
	11pm	158	1.5		
960623					
	9pm	11	2.6	19	2
	10pm	28	3.1		
	11pm	26	4.6		
960627					
	9pm	226	3.1	10	1
	10pm	234	3.1		
	11pm	232	2.1		
960630					
	9pm	160	4.6	23	3.5
	10pm	155	2.6		
	11pm	173	4.1		
960704					
	9pm	351	3.1	35	0.5
	10pm	326	2.6		
	11pm	316	2.6		
960707					
	9pm	-9	-999.9	0	0
	10pm	-9	-999.9		
	11pm	-9	-999.9		
960711					

	9pm	238	5.10	14	5
	10pm	243	2.60		
	11pm	252	5.10		
960714					
	9pm	89	1.50	43	1.6
	10pm	123	2.60		
	11pm	132	3.10		
960718					
	9pm	140	1.50	12	2.1
	10pm	136	2.60		
	11pm	144	3.60		
970607					
	9pm	12	1.00	7	2.1
	10pm	8	2.10		
	11pm	11	3.10		
970614					
	9pm	316	3.10	48	1
	10pm	307	2.60		
	11pm	268	2.10		
970621					
	9pm	147	3.10	101	0
	10pm	211	3.10		
	11pm	248	3.10		
970628					
	9pm	236	5.10	30	2
	10pm	244	3.60		
	11pm	222	4.10		
970705					
	9pm	241	4.60	25	4.7
	10pm	226	6.70		
	11pm	216	4.10		
970709					
	9pm	311	2.60	39	2.5
	10pm	334	3.60		
	11pm	350	2.10		
970713					
	9pm	138	2.10	11	0
	10pm	129	2.10		
	11pm	127	2.10		
970716					
	9pm	216	4.60	17	0.5
	10pm	229	4.60		

	9pm	238	2.6	94	3.1
	10pm	243	3.1		
	11pm	332	0.5		
960714					
	9pm	69	0.5	113	1.6
	10pm	143	2.1		
	11pm	182	2.1		
960718					
	9pm	170	1.5	42	0
	10pm	146	1.5		
	11pm	164	1.5		
970607					
	9pm	12	1.5	11	0
	10pm	8	1.5		
	11pm	1	1.5		
970614					
	9pm	316	3.6	38	1.5
	10pm	307	2.1		
	11pm	278	2.1		
970621					
	9pm	207	3.6	57	1
	10pm	251	3.1		
	11pm	238	2.6		
970628					
	9pm	236	5.1	30	1
	10pm	244	4.1		
	11pm	222	4.1		
970705					
	9pm	231	4.1	25	1
	10pm	226	5.1		
	11pm	246	5.1		
970709					
	9pm	-9	-999.9	0	0
	10pm	-9	-999.9		
	11pm	-9	-999.9		
970713					
	9pm	158	2.1	13	0.5
	10pm	169	2.1		
	11pm	167	2.6		
970716					
	9pm	226	4.1	9	2.7
	10pm	229	5.7		

	11pm	225	5.10		
970720					
	9pm	265	2.10	22	1.6
	10pm	271	2.60		
	11pm	255	1.50		
980606					
	9pm	295	3.60	15	1.5
	10pm	284	3.10		
	11pm	280	4.10		
980610					
	9pm	77	3.10	59	2.5
	10pm	70	2.60		
	11pm	122	4.60		
980613					
	9pm	38	2.10	129	1.6
	10pm	117	1.00		
	11pm	67	1.50		
980617					
	9pm	325	2.60	78	0
	10pm	355	2.60		
	11pm	43	2.60		
980620					
	9pm	0	0.00	242	2
	10pm	121	1.00		
	11pm	0	0.00		
980627					
	9pm	43	4.10	10	0.5
	10pm	38	3.60		
	11pm	43	3.60		
980705					
	9pm	301	1.50	35	1.7
	10pm	326	2.10		
	11pm	336	1.00		
980712					
	9pm	168	4.10	44	1.5
	10pm	183	2.60		
	11pm	212	2.60		
980719					
	9pm	140	3.10	28	2
	10pm	166	3.60		
	11pm	164	2.10		
990619					

	11pm	235	4.6		
970720					
	9pm	295	2.6	48	0.5
	10pm	261	2.6		
	11pm	275	3.1		
980606					
	9pm	285	3.6	23	1.5
	10pm	294	4.1		
	11pm	280	3.1		
980610					
	9pm	147	4.1	11	2
	10pm	150	2.6		
	11pm	142	3.1		
980613					
	9pm	68	2.6	9	2.1
	10pm	77	1		
	11pm	77	1.5		
980617					
	9pm	45	2.6	38	1.1
	10pm	25	2.1		
	11pm	43	1.5		
980620					
	9pm	88	1.5	52	0
	10pm	81	1.5		
	11pm	36	1.5		
980627					
	9pm	43	3.6	10	0.5
	10pm	48	3.1		
	11pm	53	3.1		
980705					
	9pm	321	0.5	5	1
	10pm	316	1		
	11pm	316	0.5		
980712					
	9pm	148	3.1	44	1
	10pm	173	2.6		
	11pm	192	2.1		
980719					
	9pm	150	1.5	22	0.6
	10pm	146	1.5		
	11pm	164	2.1		
990619					

	9pm	156	4.10	148	3.1
	10pm	146	3.10		
	11pm	284	1.00		
990626					
	9pm	253	2.10	4	3.5
	10pm	250	5.10		
	11pm	249	4.60		
990703					
	9pm	136	1.00	59	1.1
	10pm	145	1.50		
	11pm	195	2.10		
990711					
	9pm	220	2.10	41	2.5
	10pm	242	3.10		
	11pm	223	4.60		
990714					
	9pm	215	3.10	49	1
	10pm	186	4.10		
	11pm	206	4.10		
990718					
	9pm	261	2.10	96	1.7
	10pm	285	1.50		
	11pm	357	2.60		
990721					
	9pm	176	3.10	42	1
	10pm	205	3.10		
	11pm	218	4.10		
990725					
	9pm	12	1.50	73	2.6
	10pm	38	3.10		
	11pm	351	2.10		
990728					
	9pm	317	2.10	75	1.7
	10pm	270	1.50		
	11pm	242	2.60		
000617					
	9pm	268	5.10	49	4
	10pm	310	2.10		
	11pm	317	3.10		
000625					
	9pm	213	4.10	32	2
	10pm	210	3.60		

	9pm	216	1	108	2.2
	10pm	166	2.1		
	11pm	224	1		
990626					
	9pm	313	1	82	1.6
	10pm	240	2.6		
	11pm	249	2.6		
990703					
	9pm	166	2.6	59	1
	10pm	215	2.1		
	11pm	225	2.6		
990711					
	9pm	210	1.5	33	1.6
	10pm	222	2.6		
	11pm	243	3.1		
990714					
	9pm	235	1.5	49	1.6
	10pm	206	2.6		
	11pm	186	3.1		
990718					
	9pm	-9	-999.9	0	0
	10pm	-9	-999.9		
	11pm	-9	-999.9		
990721					
	9pm	206	2.6	4	0.5
	10pm	205	2.1		
	11pm	208	2.1		
990725					
	9pm	12	1.5	7	1.6
	10pm	8	1		
	11pm	11	2.1		
990728					
	9pm	257	3.1	59	1.5
	10pm	230	2.1		
	11pm	262	2.6		
000617					
	9pm	278	3.1	49	1
	10pm	310	2.6		
	11pm	327	3.1		
000625					
	9pm	213	3.1	18	0.5
	10pm	230	2.6		

	11pm	239	2.10		
000702					
	9pm	246	7.70	11	1.1
	10pm	245	7.70		
	11pm	255	8.80		
000709					
	9pm	144	3.10	57	1.5
	10pm	189	2.10		
	11pm	201	2.60		
000712					
	9pm	288	2.60	13	0.5
	10pm	289	2.60		
	11pm	277	2.10		
000716					
	9pm	102	5.70	40	2.1
	10pm	120	4.60		
	11pm	98	3.60		
000719					
	9pm	265	1.50	20	0
	10pm	281	1.50		
	11pm	285	1.50		
000723					
	9pm	255	2.10	27	1
	10pm	234	2.60		
	11pm	240	3.10		
000726					
	9pm	146	4.10	34	1.6
	10pm	138	4.60		
	11pm	164	5.70		
010620					
	9pm	248	2.10	32	0.6
	10pm	231	2.10		
	11pm	246	1.50		
010627					
	9pm	303	3.60	30	2
	10pm	278	4.10		
	11pm	273	2.60		
010630					
	9pm	209	4.60	48	6.2
	10pm	222	6.70		
	11pm	187	2.60		
010707					

	11pm	229	2.6		
000702					
	9pm	246	6.7	1	4.1
	10pm	245	3.6		
	11pm	245	4.6		
000709					
	9pm	104	1	127	0.5
	10pm	189	1		
	11pm	231	0.5		
000712					
	9pm	288	2.6	3	0
	10pm	289	2.6		
	11pm	287	2.6		
000716					
	9pm	92	3.6	14	3
	10pm	80	2.1		
	11pm	78	3.6		
000719					
	9pm	255	2.1	20	1
	10pm	261	2.6		
	11pm	275	2.1		
000723					
	9pm	-9	-999.9	0	0
	10pm	-9	-999.9		
	11pm	-9	-999.9		
000726					
	9pm	166	3.6	22	1
	10pm	148	2.6		
	11pm	144	2.6		
010620					
	9pm	248	2.1	18	0
	10pm	261	2.1		
	11pm	266	2.1		
010627					
	9pm	283	3.6	30	0.5
	10pm	268	3.1		
	11pm	283	3.1		
010630					
	9pm	229	1.5	38	2.1
	10pm	242	3.1		
	11pm	217	3.6		
010707					

	9pm	179	4.10	21	3
	10pm	179	5.10		
	11pm	158	3.10		
010711					
	9pm	280	2.60	37	0
	10pm	252	2.60		
	11pm	243	2.60		
010714					
	9pm	305	3.10	21	2.5
	10pm	306	4.10		
	11pm	286	2.60		
010718					
	9pm	41	3.60	22	0
	10pm	55	3.60		
	11pm	47	3.60		
010721					
	9pm	216	5.10	16	1.6
	10pm	225	4.60		
	11pm	218	5.70		
010725					
	9pm	332	3.10	47	0.5
	10pm	318	3.10		
	11pm	351	3.60		
010728					
	9pm	187	4.10	35	2.6
	10pm	200	2.60		
	11pm	222	1.50		
020615					
	9pm	80	7.70	9	3
	10pm	85	6.20		
	11pm	81	7.70		
020622					
	9pm	129	4.10	5	2
	10pm	132	3.10		
	11pm	134	4.10		
020629					
	9pm	219	1.00	91	1.6
	10pm	252	1.00		
	11pm	194	2.60		
020706					
	9pm	122	2.10	220	1
	10pm	215	2.60		

	9pm	169	1.5	49	1.1
	10pm	159	1.5		
	11pm	198	2.6		
010711					
	9pm	270	2.6	11	1
	10pm	272	3.1		
	11pm	263	2.6		
010714					
	9pm	285	3.1	31	0.5
	10pm	296	3.1		
	11pm	276	2.6		
010718					
	9pm	41	2.1	26	1.2
	10pm	65	1.5		
	11pm	67	2.1		
010721					
	9pm	226	4.1	26	1.5
	10pm	245	3.1		
	11pm	238	3.6		
010725					
	9pm	342	2.6	9	1
	10pm	348	2.1		
	11pm	351	2.6		
010728					
	9pm	187	1	35	1
	10pm	210	1.5		
	11pm	222	1		
020615					
	9pm	80	4.6	9	1
	10pm	85	5.1		
	11pm	81	4.6		
020622					
	9pm	169	2.6	15	1.7
	10pm	162	1.5		
	11pm	154	2.1		
020629					
	9pm	239	1.5	19	0
	10pm	222	1.5		
	11pm	224	1.5		
020706					
	9pm	172	1.5	280	2.6
	10pm	45	0.5		

	11pm	88	3.10		
020713					
	9pm	268	1.50	268	1.5
	10pm	259	1.00		
	11pm	0	0.00		
020717					
	9pm	92	1.00	86	2.1
	10pm	140	2.60		
	11pm	178	2.10		
020721					
	9pm	206	2.60	16	1
	10pm	215	3.10		
	11pm	208	2.60		
020724					
	9pm	95	2.60	95	2.6
	10pm	94	1.00		
	11pm	0	0.00		
020728					
	9pm	167	6.20	45	0
	10pm	180	6.20		
	11pm	212	6.20		
030621					
	9pm	257	2.60	63	1
	10pm	241	3.60		
	11pm	288	3.60		
030628					
	9pm	226	2.60	30	0
	10pm	204	2.60		
	11pm	212	2.60		
030705					
	9pm	231	4.10	15	2.1
	10pm	236	4.10		
	11pm	246	6.20		
030709					
	9pm	31	3.60	23	2.1
	10pm	14	2.10		
	11pm	20	1.50		
030712					
	9pm	228	8.80	16	1.6
	10pm	233	7.70		
	11pm	222	8.20		
030716					

	11pm	198	2.1		
020713					
	9pm	258	2.1	17	0.6
	10pm	249	1.5		
	11pm	257	1.5		
020717					
	9pm	42	1	150	2.1
	10pm	190	2.6		
	11pm	188	2.1		
020721					
	9pm	186	2.6	36	1
	10pm	215	3.6		
	11pm	208	3.6		
020724					
	9pm	95	1	455	2
	10pm	0	0		
	11pm	360	1		
020728					
	9pm	147	4.1	145	3.1
	10pm	180	3.6		
	11pm	292	6.2		
030621					
	9pm	237	1.5	33	1.6
	10pm	231	2.1		
	11pm	258	3.1		
030628					
	9pm	196	1	70	0.5
	10pm	184	1.5		
	11pm	242	1.5		
030705					
	9pm	271	4.6	45	2
	10pm	236	2.6		
	11pm	246	2.6		
030709					
	9pm	11	1.5	23	0.6
	10pm	354	1.5		
	11pm	360	2.1		
030712					
	9pm	218	5.1	26	0.5
	10pm	233	4.6		
	11pm	222	4.6		
030716					

	9pm	236	7.20	19	0
	10pm	239	7.20		
	11pm	255	7.20		
030719					
	9pm	250	5.10	32	2.5
	10pm	236	5.10		
	11pm	254	2.60		
030723					
	9pm	39	3.10	24	2
	10pm	29	4.10		
	11pm	43	3.10		
030726					
	9pm	239	12.40	32	8.8
	10pm	240	6.20		
	11pm	209	3.60		
030730					
	9pm	0	0.00	127	1
	10pm	0	0.00		
	11pm	127	1.00		
040612					
	9pm	178	3.60	11	0.5
	10pm	177	3.10		
	11pm	187	3.10		
040619					
	9pm	308	4.60	22	1.5
	10pm	301	3.60		
	11pm	286	4.10		
040626					
	9pm	253	3.10	20	1.6
	10pm	268	2.60		
	11pm	273	1.50		
040703					
	9pm	215	3.60	233	3.6
	10pm	224	1.50		
	11pm	0	0.00		
040710					
	9pm	60	2.60	19	1.5
	10pm	42	3.10		
	11pm	43	2.10		
040714					
	9pm	129	5.70	15	1.1
	10pm	123	5.70		

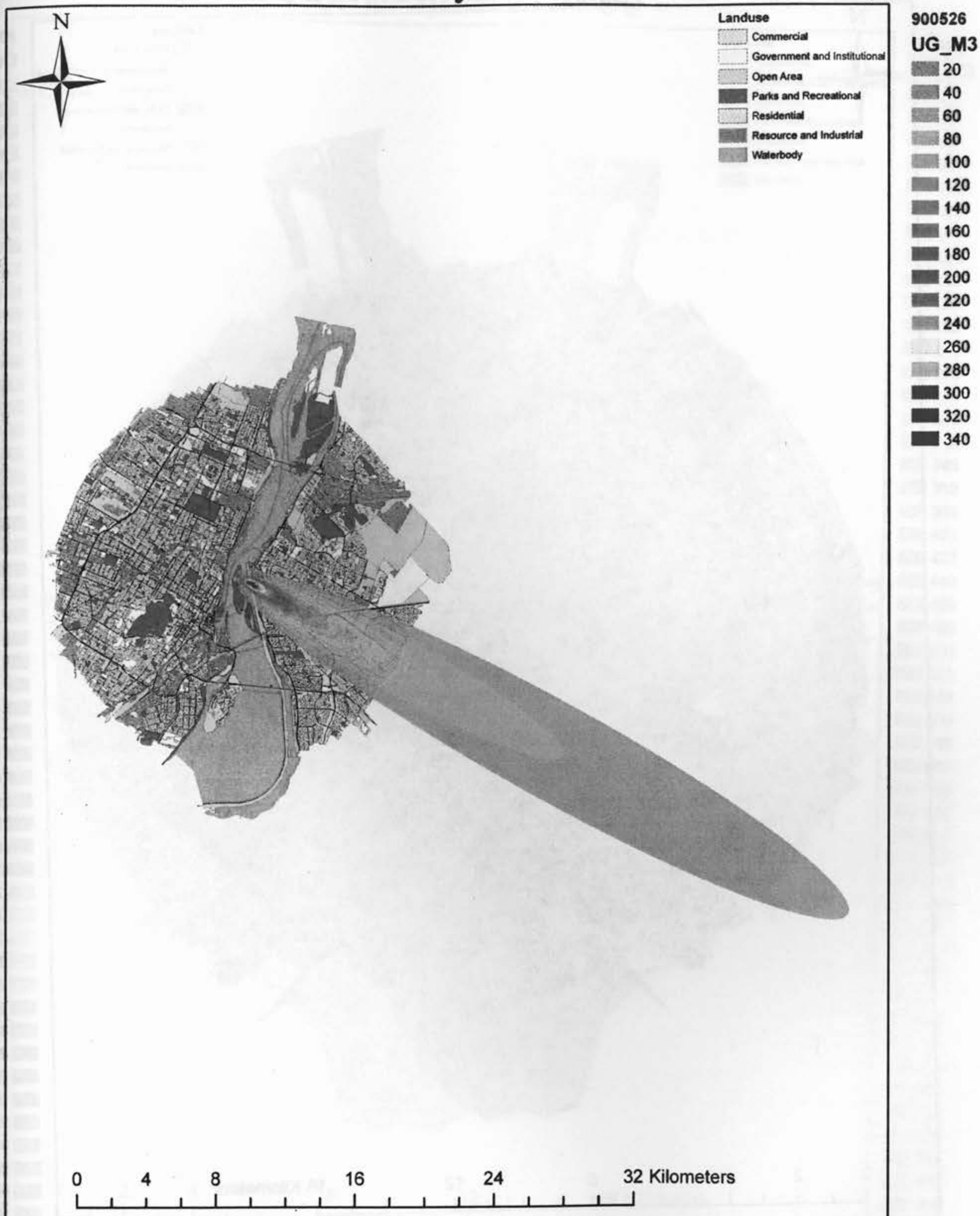
	9pm	246	4.1	17	0.5
	10pm	249	4.1		
	11pm	235	3.6		
030719					
	9pm	240	3.1	14	1
	10pm	246	3.1		
	11pm	254	2.1		
030723					
	9pm	49	1	36	1.7
	10pm	19	2.1		
	11pm	13	1.5		
030726					
	9pm	249	5.7	20	4.1
	10pm	230	6.7		
	11pm	229	3.6		
030730					
	9pm	241	1	76	0
	10pm	166	1		
	11pm	167	1		
040612					
	9pm	168	2.1	29	0.6
	10pm	187	2.1		
	11pm	177	1.5		
040619					
	9pm	288	3.6	28	0.5
	10pm	301	3.6		
	11pm	286	3.1		
040626					
	9pm	243	3.1	10	0.5
	10pm	238	3.1		
	11pm	243	2.6		
040703					
	9pm	235	2.1	44	0.5
	10pm	204	2.1		
	11pm	217	2.6		
040710					
	9pm	70	2.1	19	0.6
	10pm	52	1.5		
	11pm	53	1.5		
040714					
	9pm	119	4.1	17	2.5
	10pm	113	2.6		

	11pm	132	4.60		
040717					
	9pm	341	1.00	86	1.6
	10pm	25	1.50		
	11pm	67	2.60		
040721					
	9pm	159	3.60	43	1.5
	10pm	175	4.10		
	11pm	202	3.10		
040724					
	9pm	172	2.10	264	2.1
	10pm	218	1.50		
	11pm	0	0.00		
040728					
	9pm	0	0.00	355	1.5
	10pm	340	1.00		
	11pm	325	1.50		

	11pm	102	3.6		
040717					
	9pm	51	1.5	62	1.6
	10pm	65	1		
	11pm	17	2.1		
040721					
	9pm	169	2.1	7	0.6
	10pm	165	2.1		
	11pm	162	1.5		
040724					
	9pm	142	1.5	191	0
	10pm	118	1.5		
	11pm	311	1.5		
040728					
	9pm	68	0.5	203	0.5
	10pm	320	0.5		
	11pm	225	1		

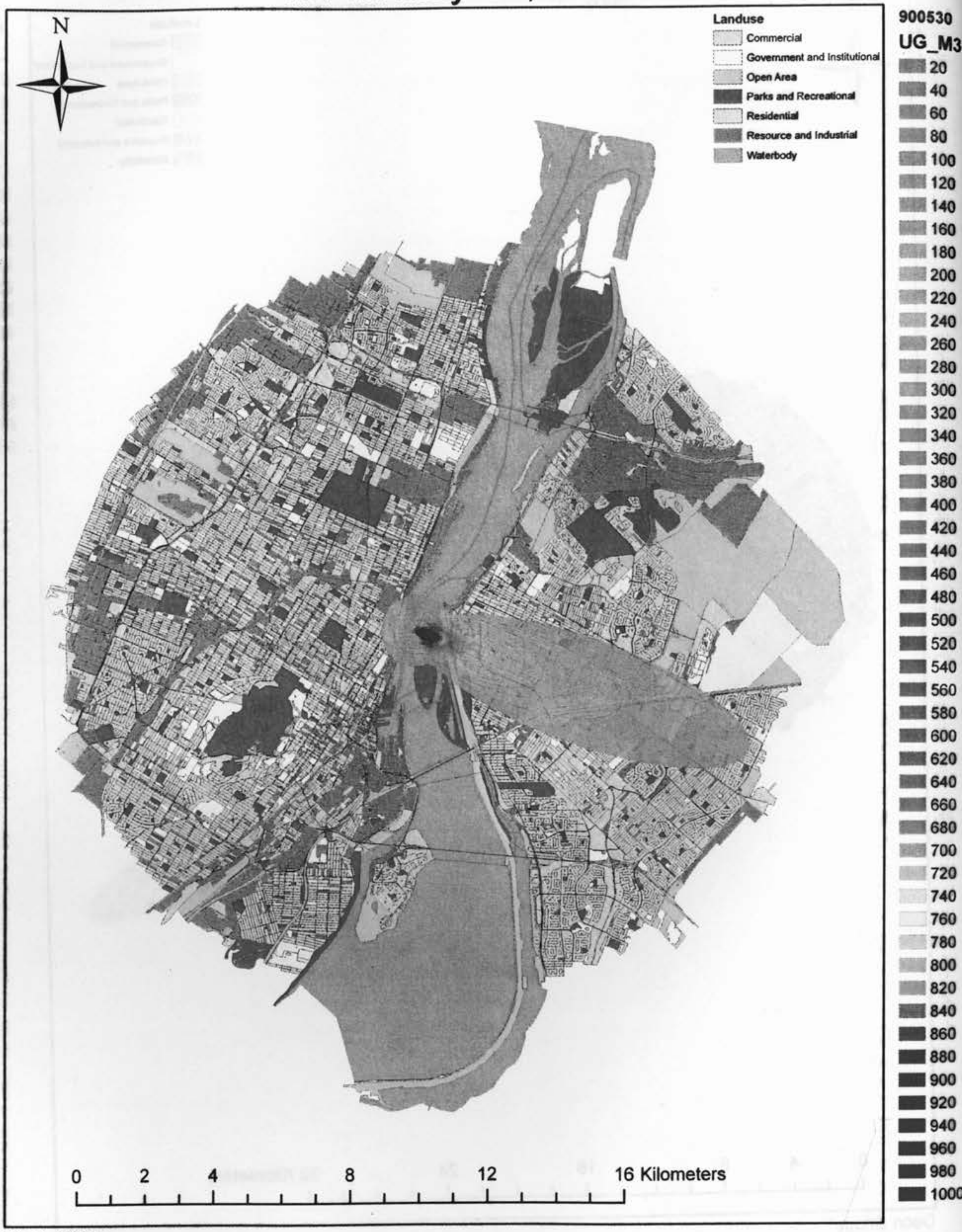
APPENDIX B- Individual Firework Event Maps

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM May 26, 1990



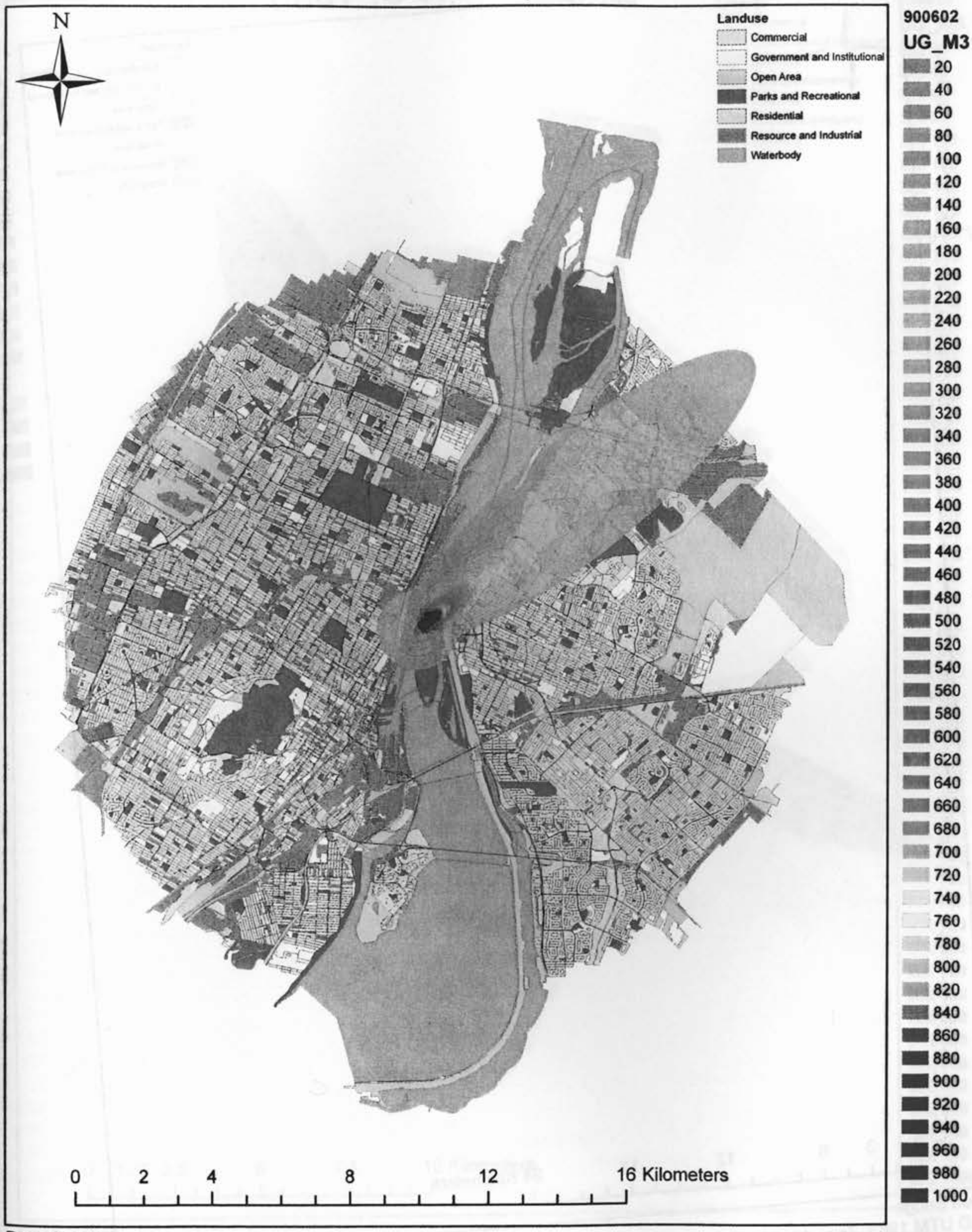
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM May 30, 1990



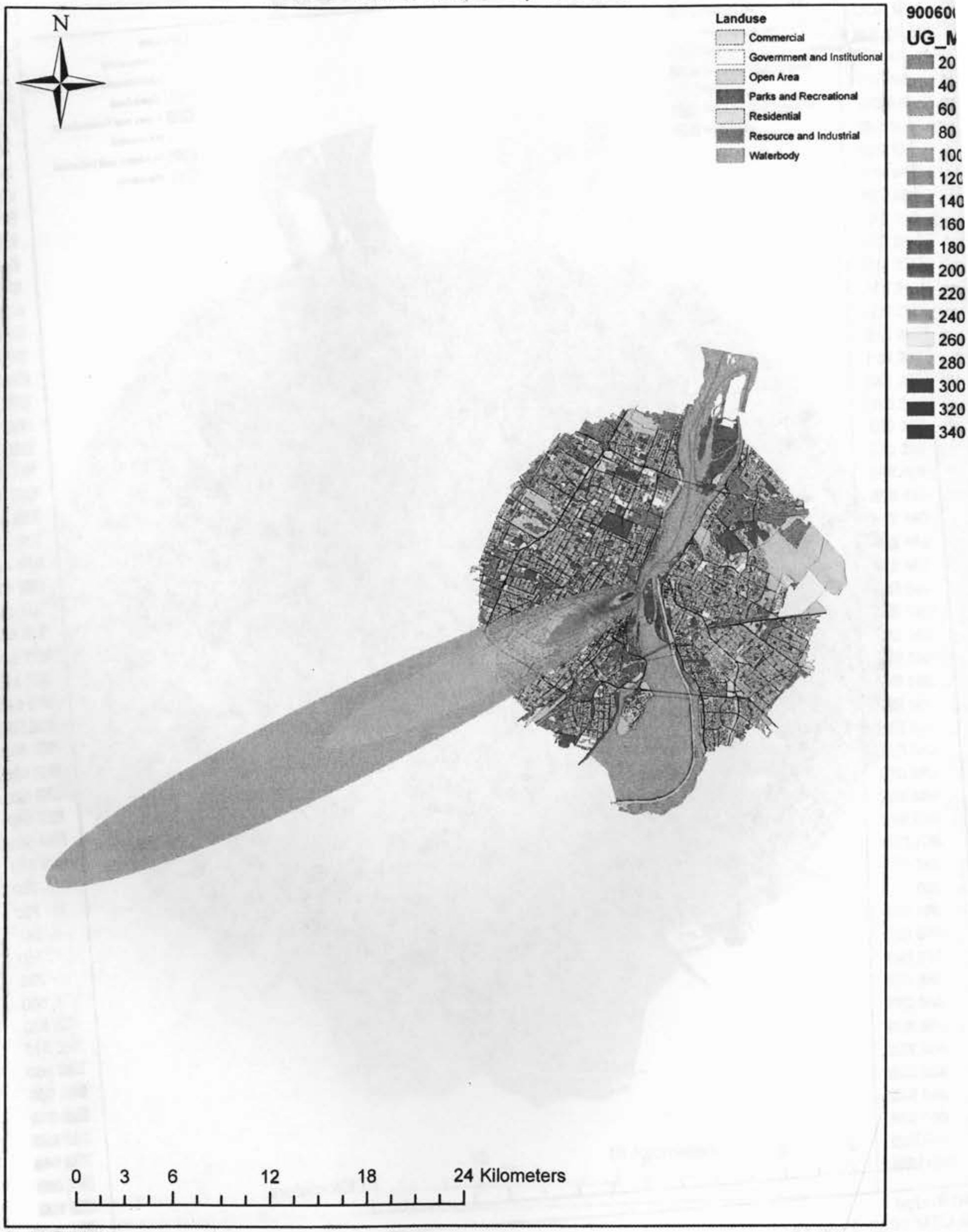
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 2, 1990



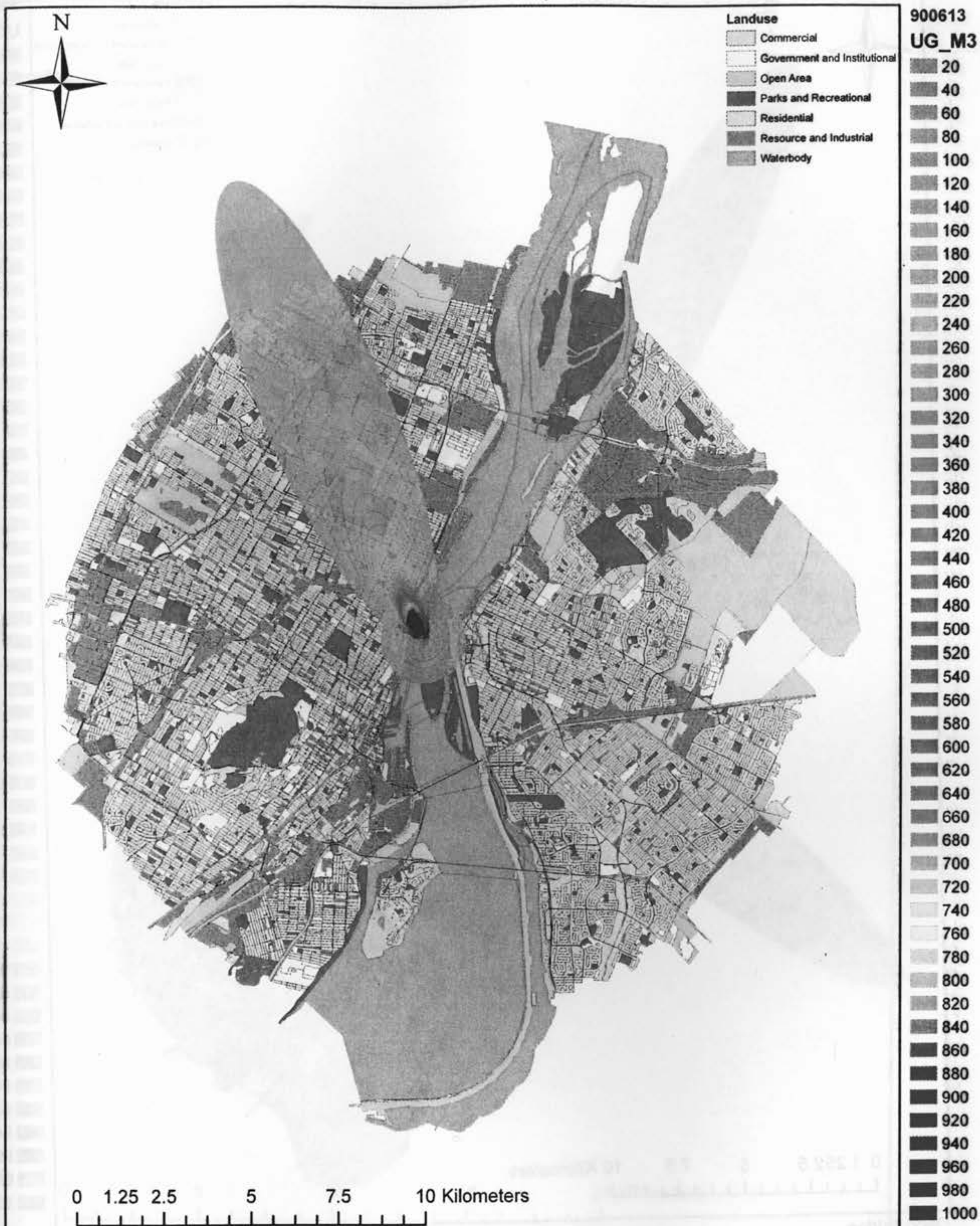
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 6, 1990



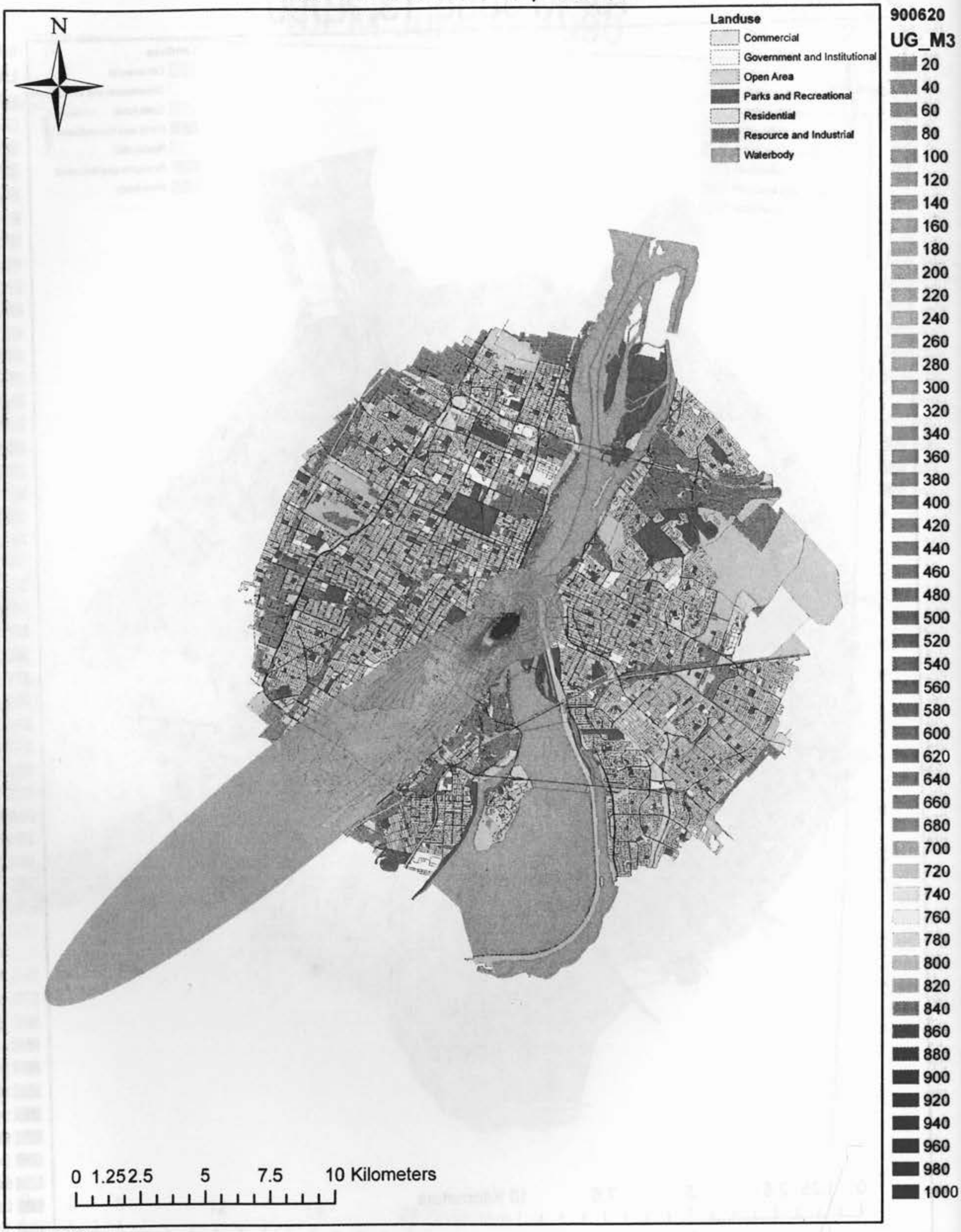
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 13, 1990



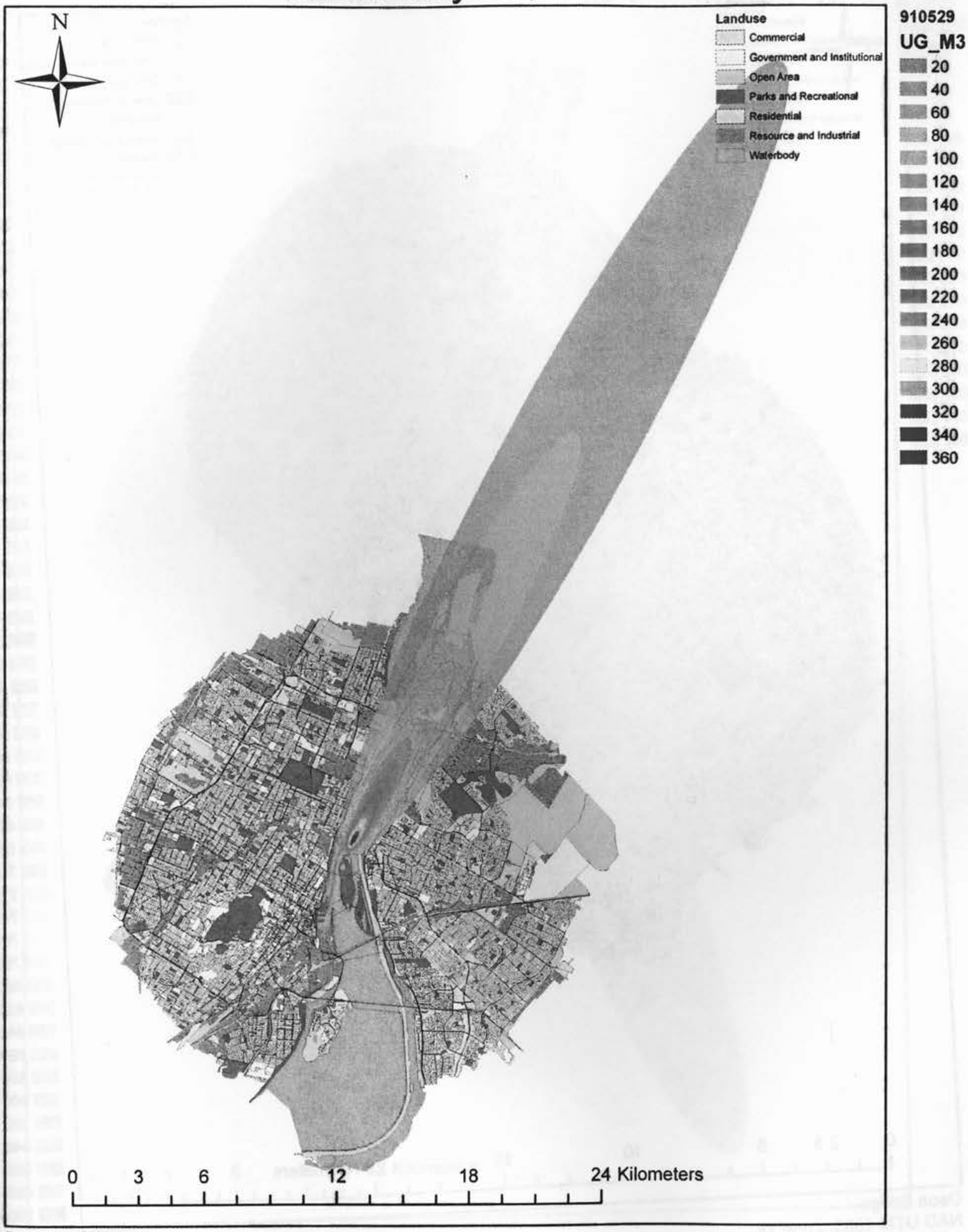
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 20, 1990



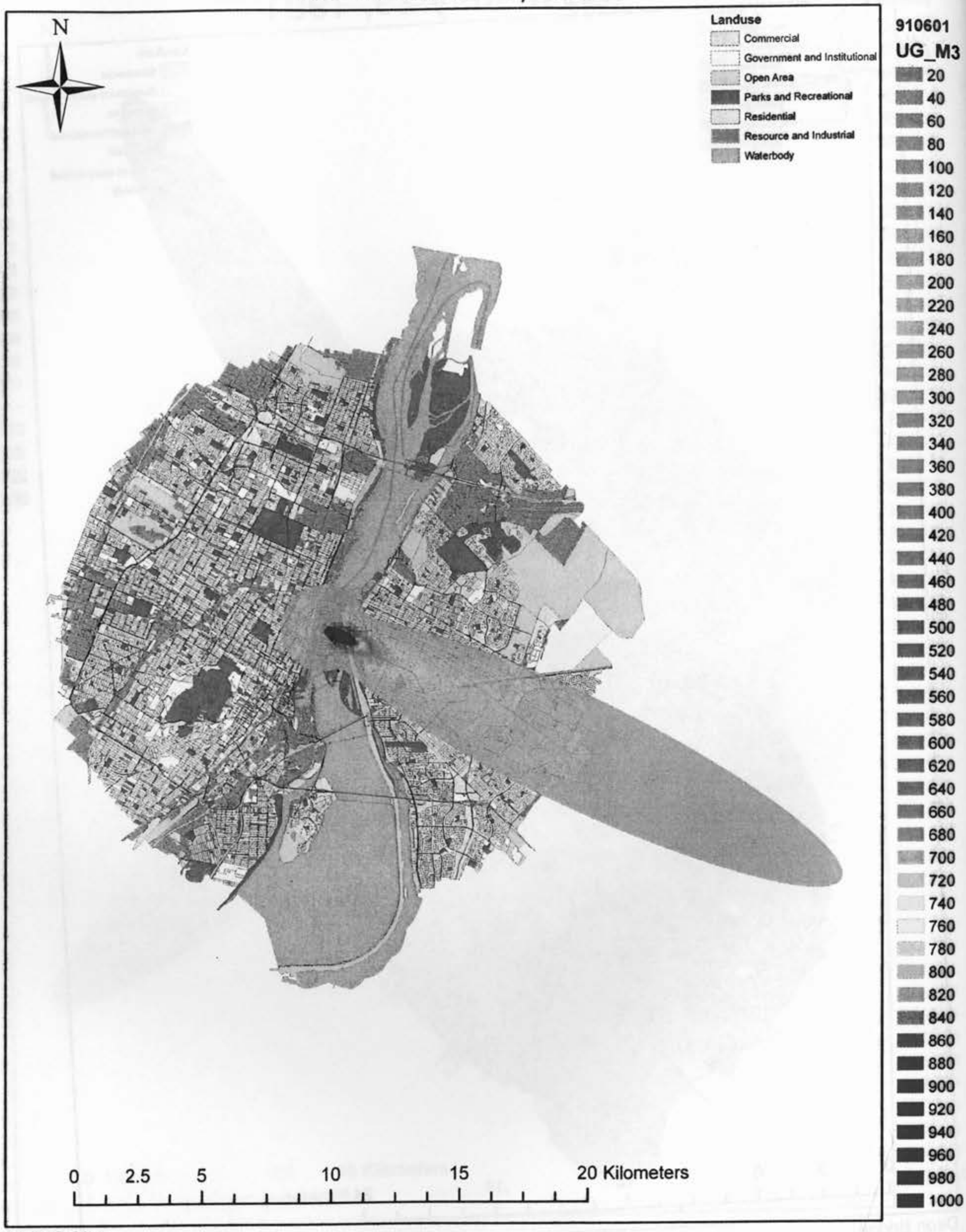
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM May 29, 1991



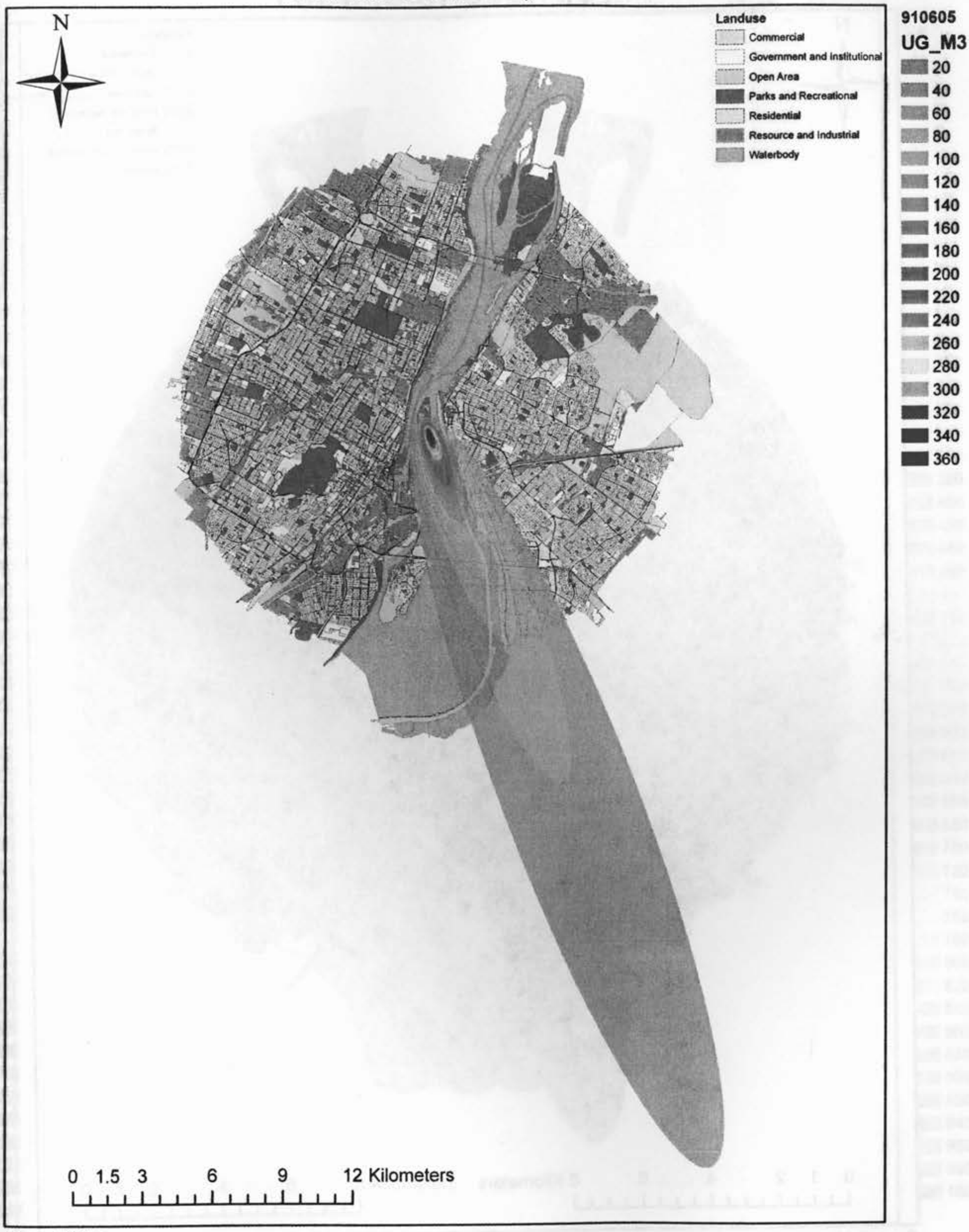
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 1, 1991



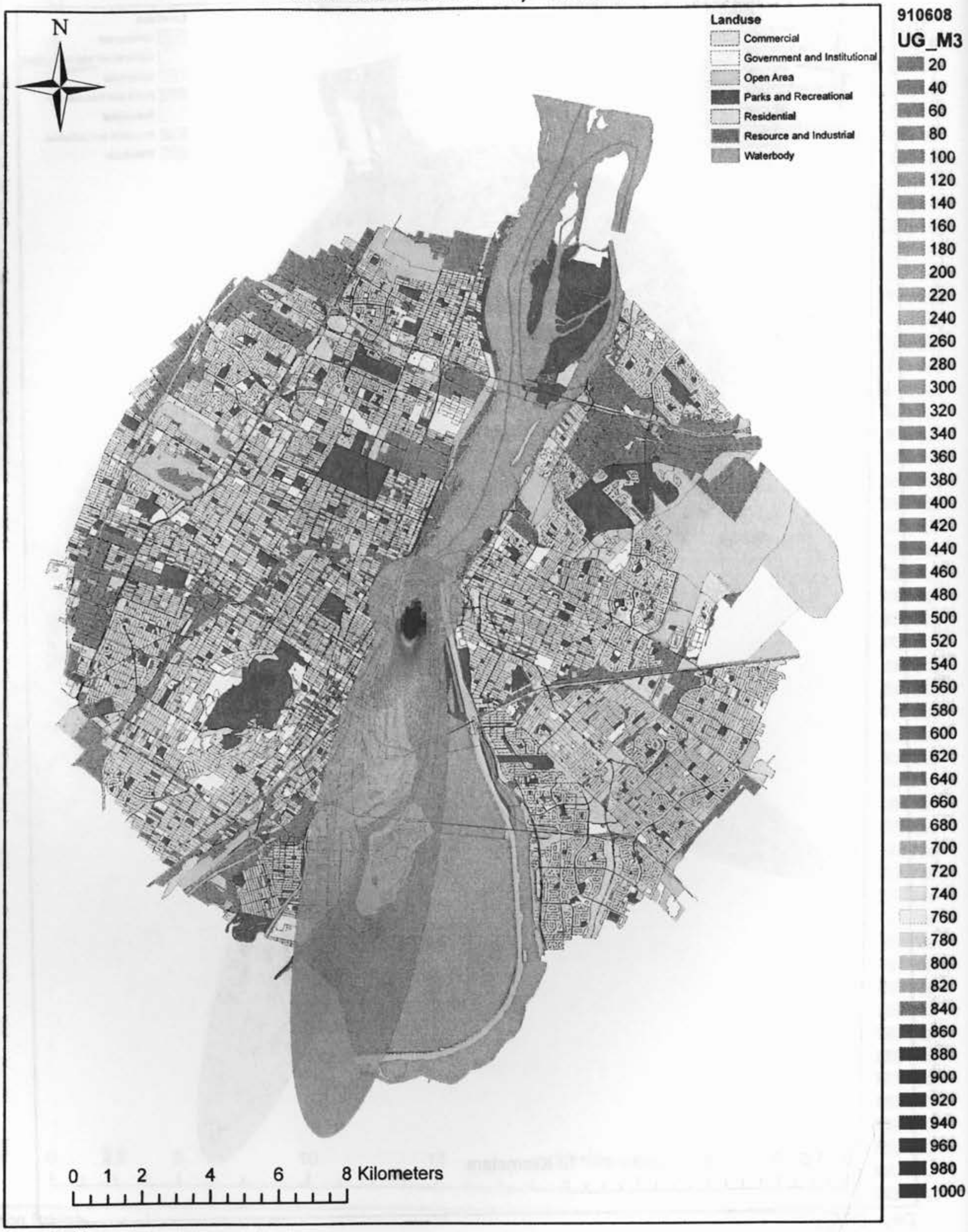
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 5, 1991



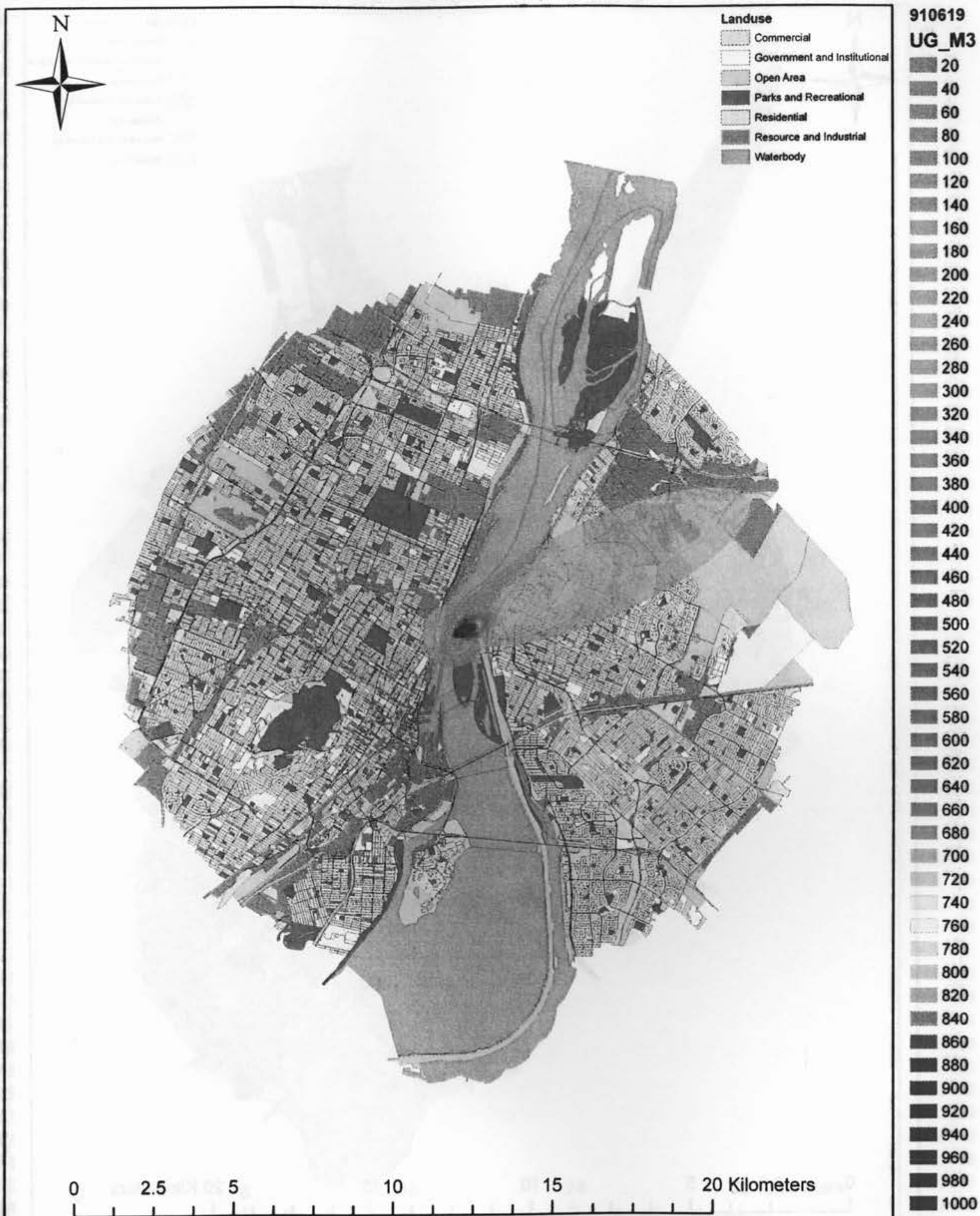
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 8, 1991



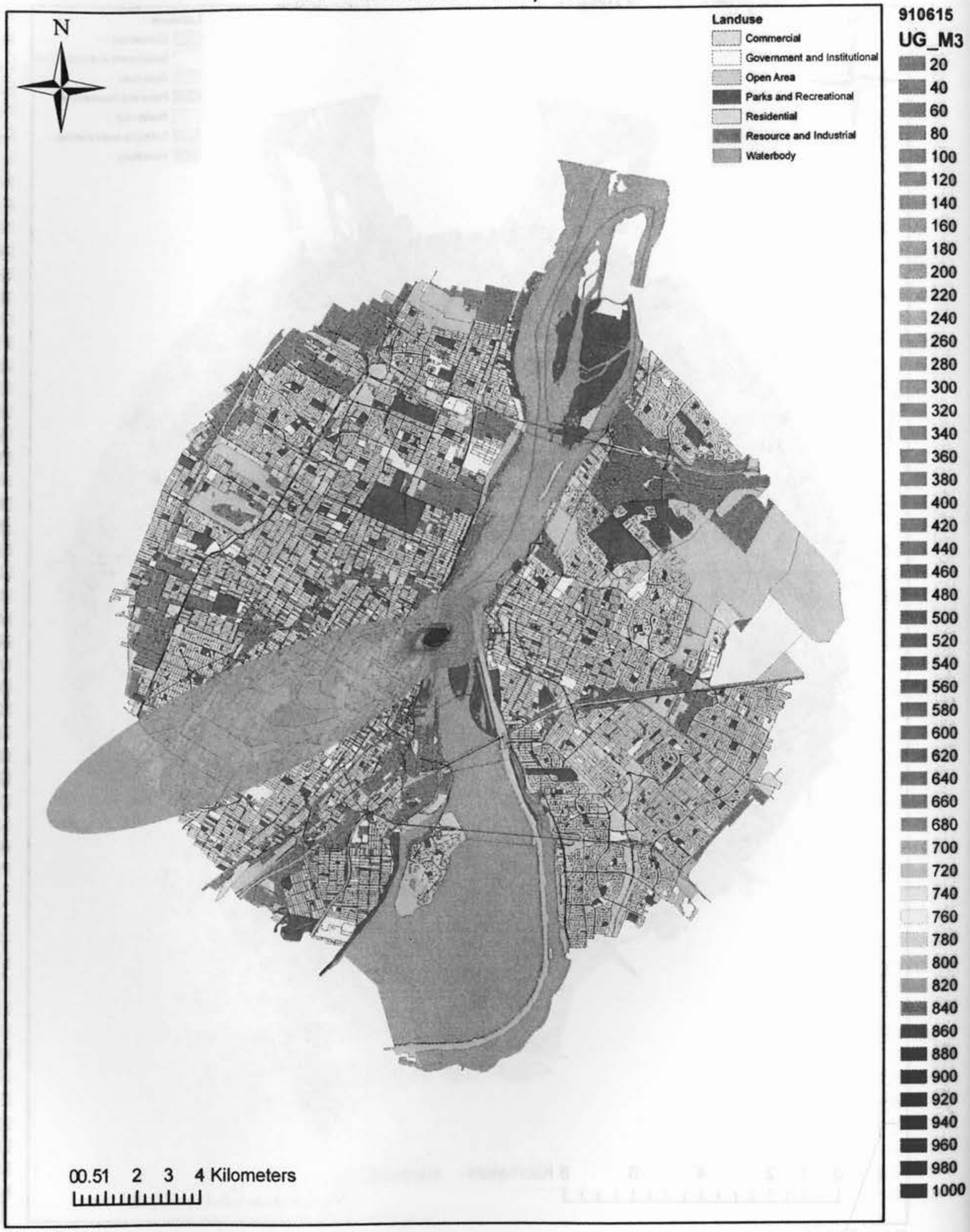
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 19, 1991



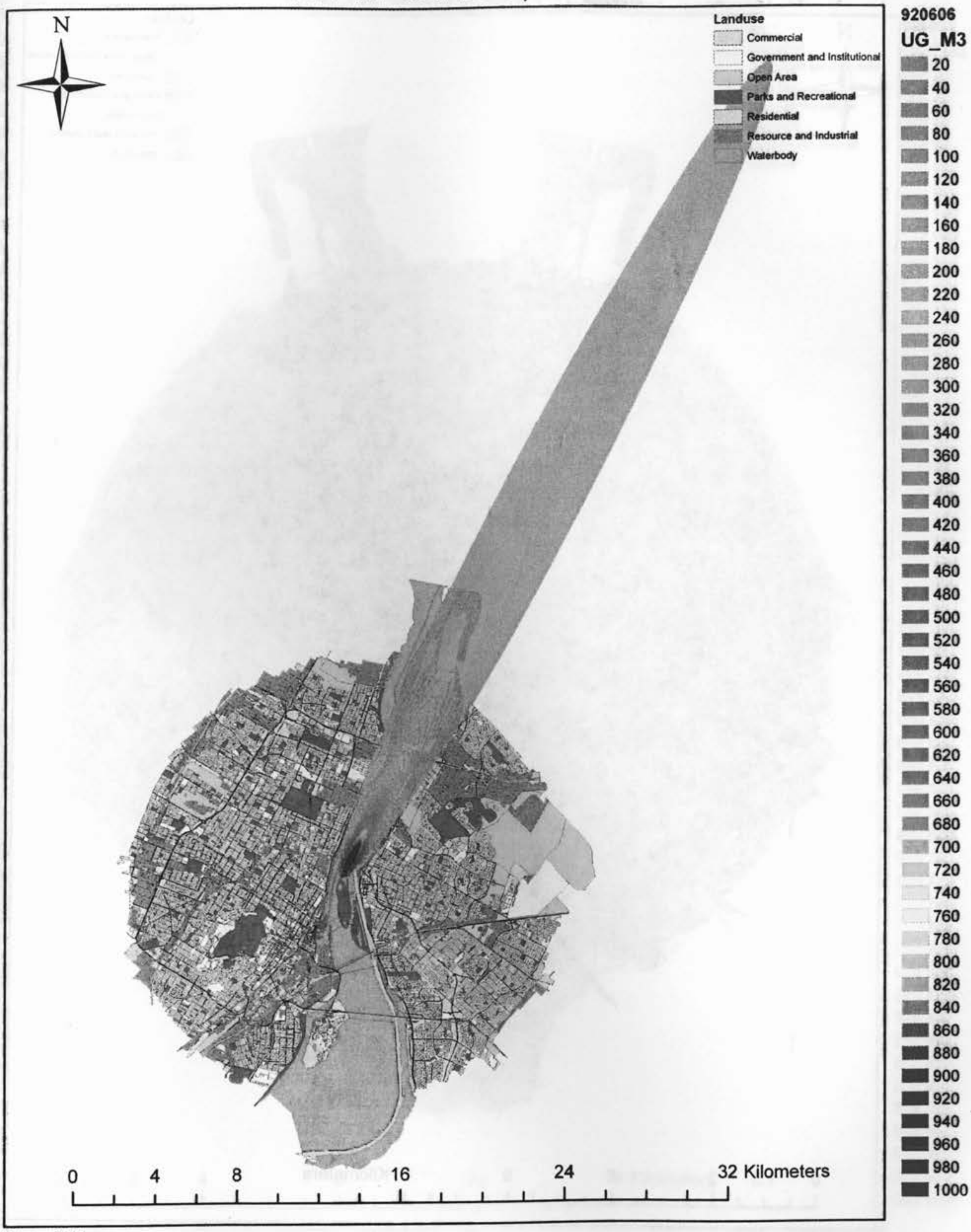
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 15, 1991



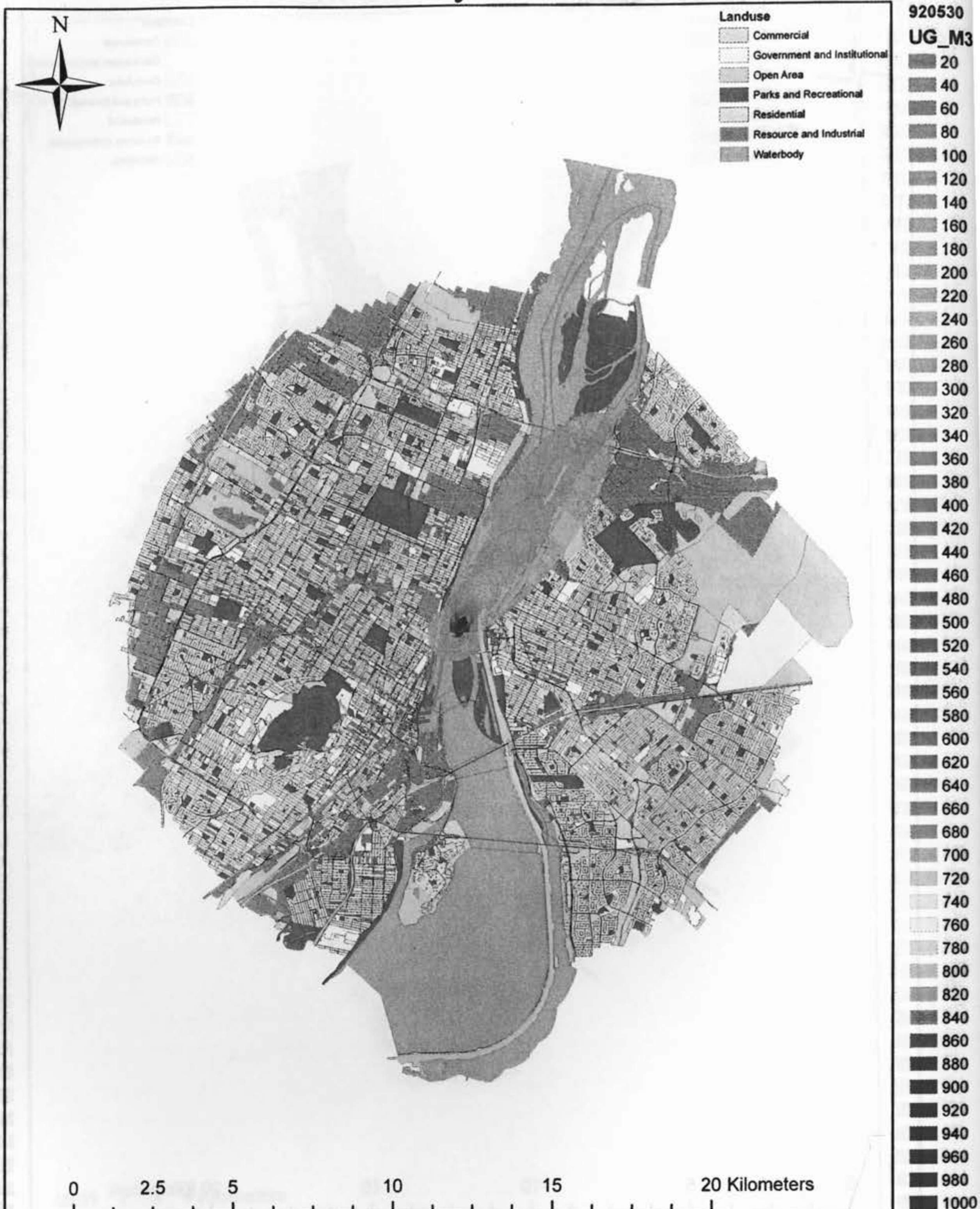
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 6, 1992



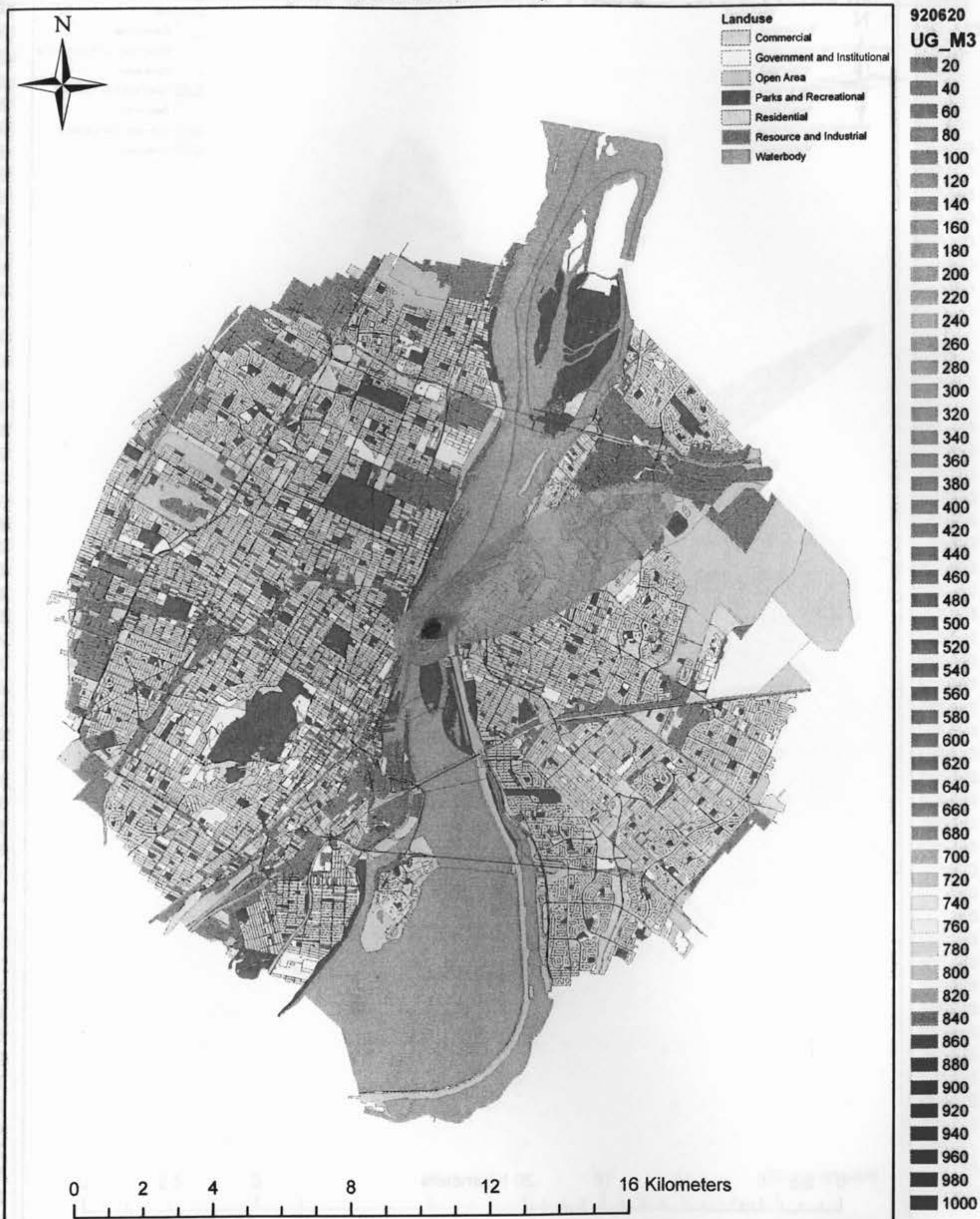
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM May 30, 1992



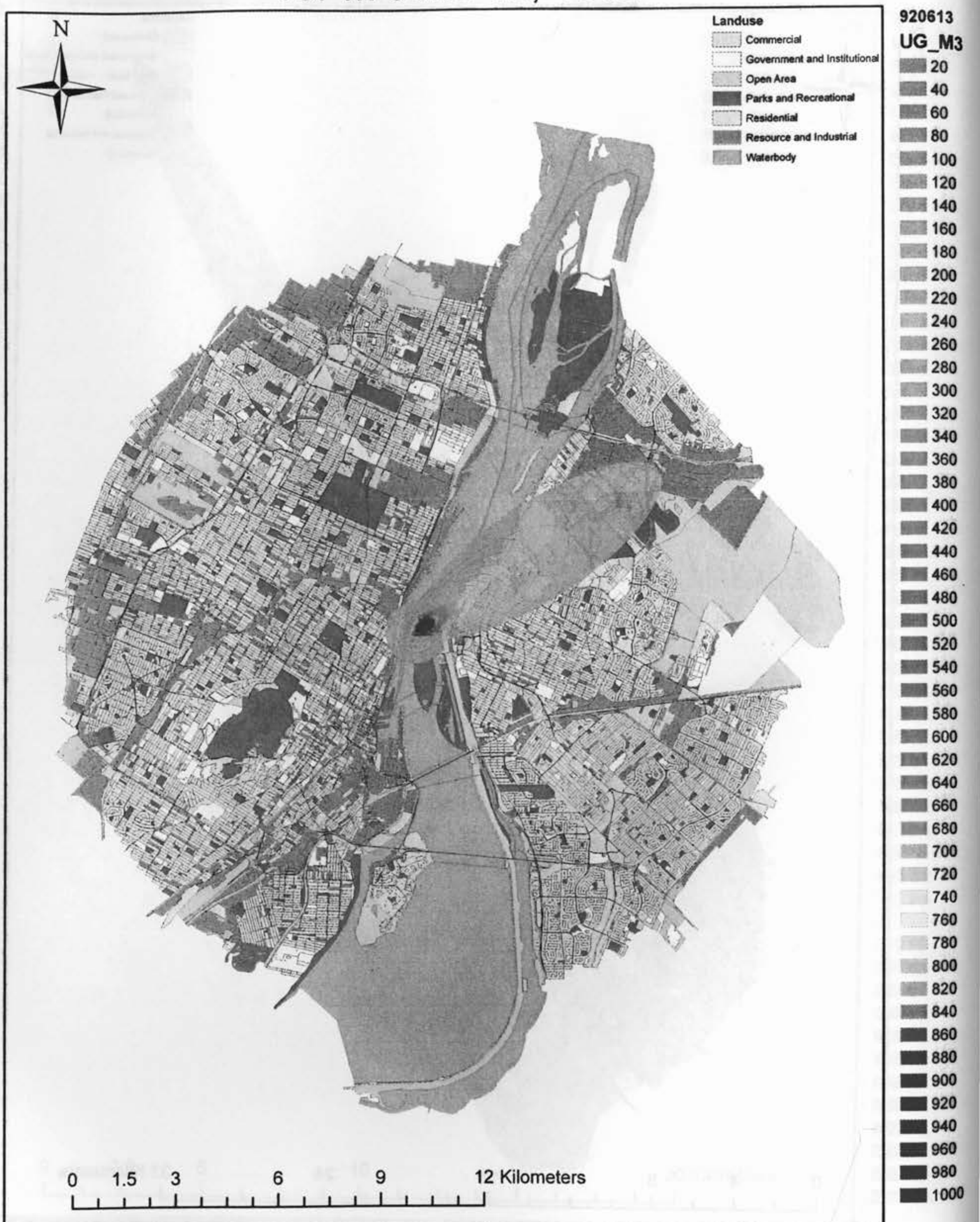
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 20, 1992



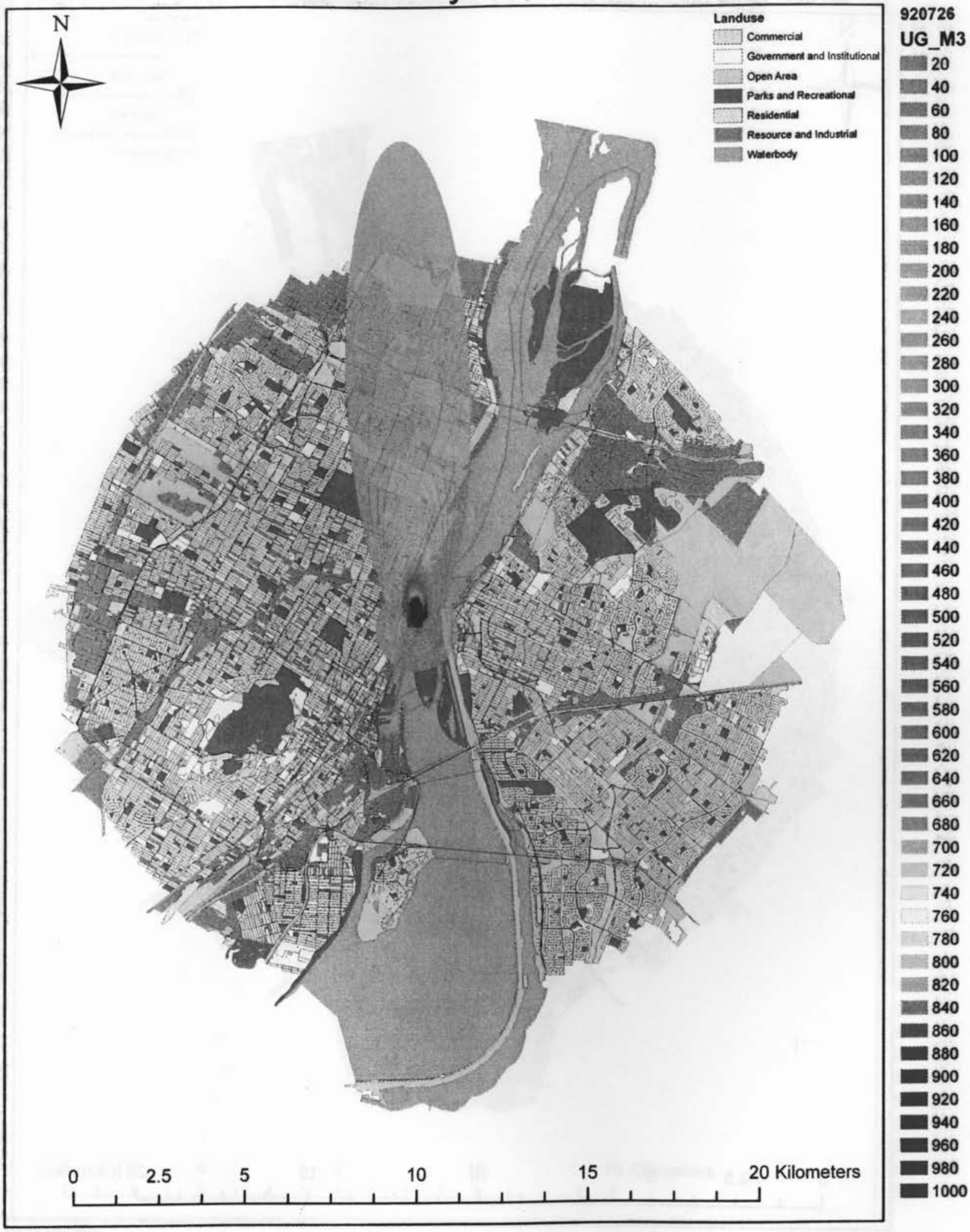
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 13, 1992



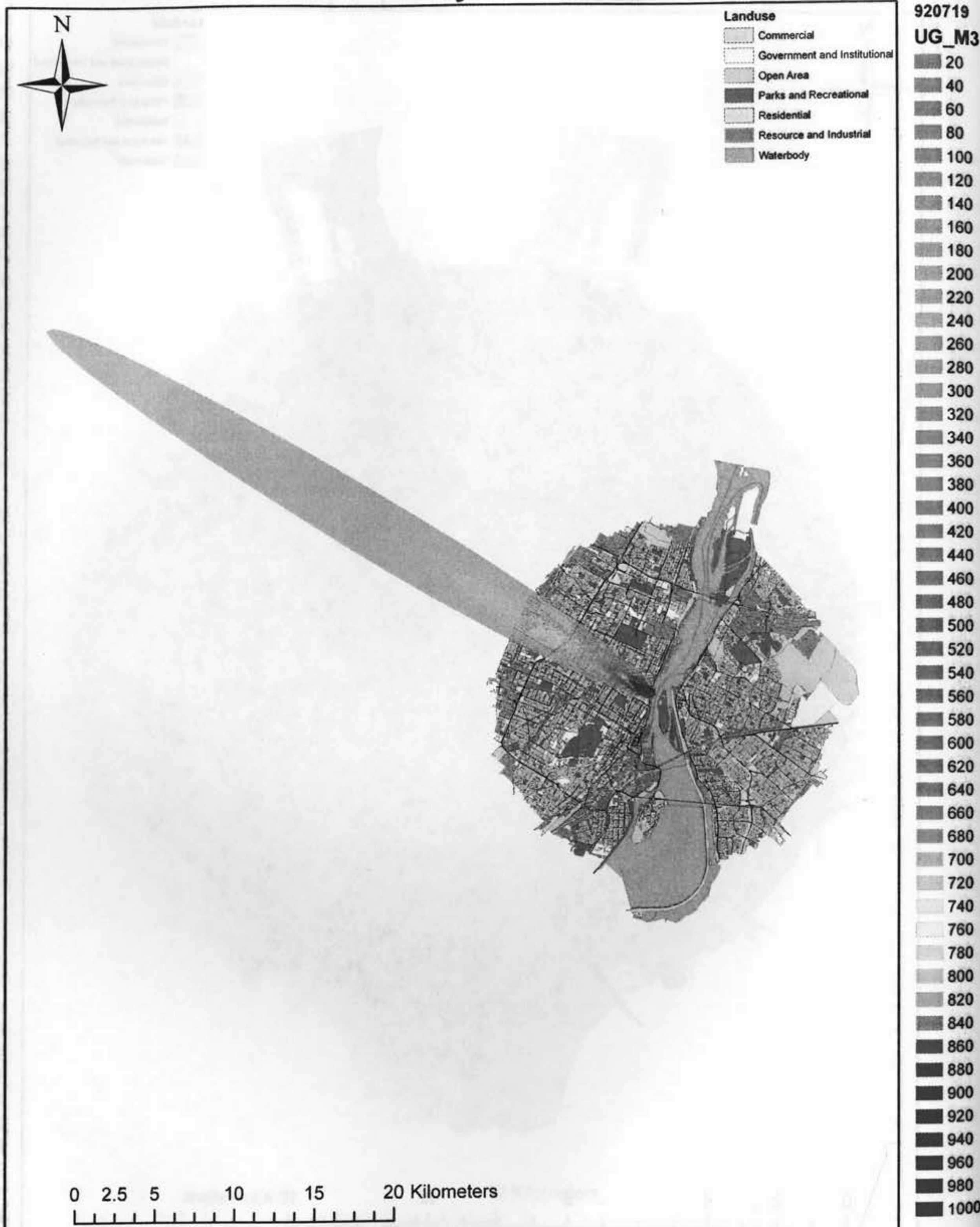
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 26, 1992



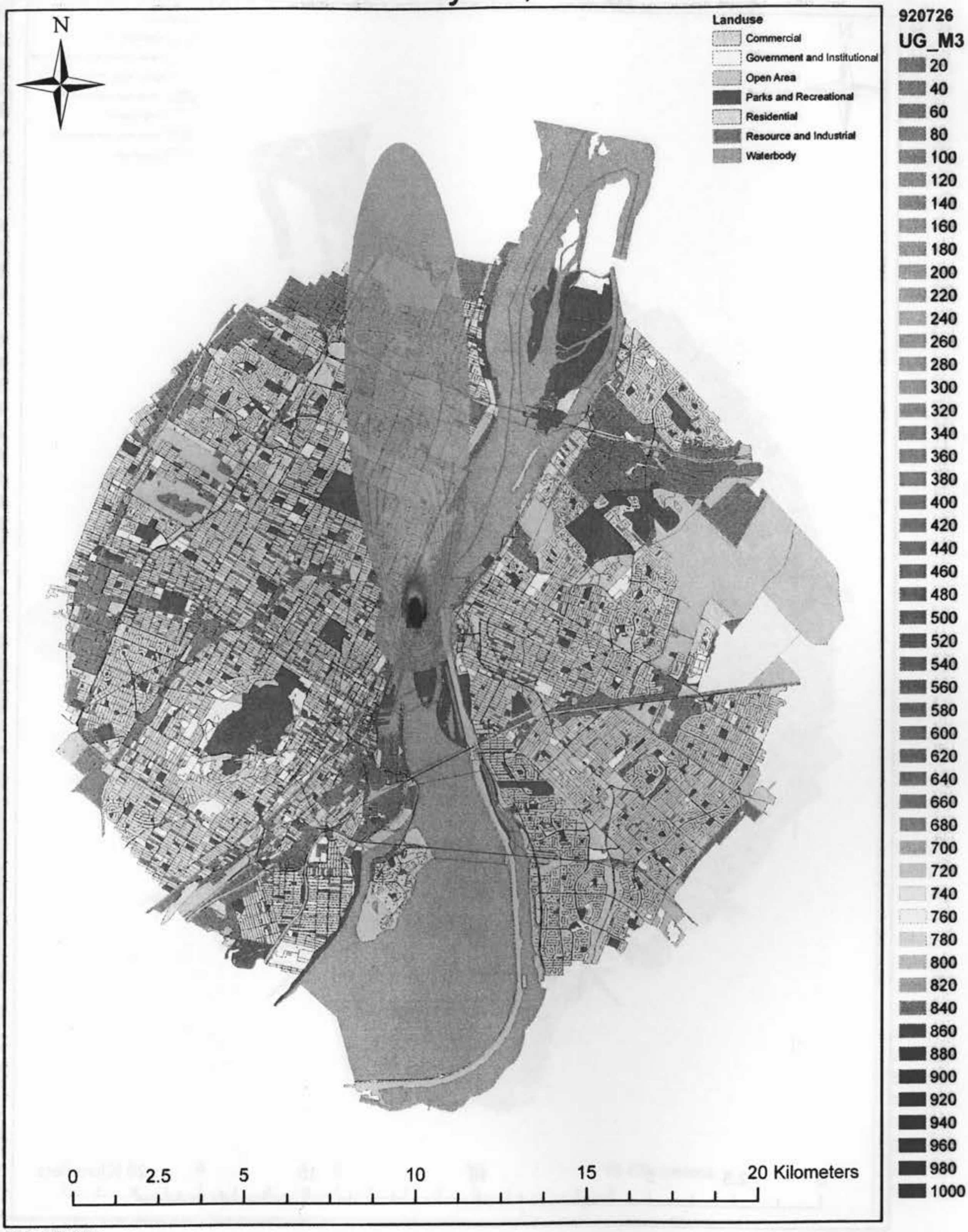
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 19, 1992



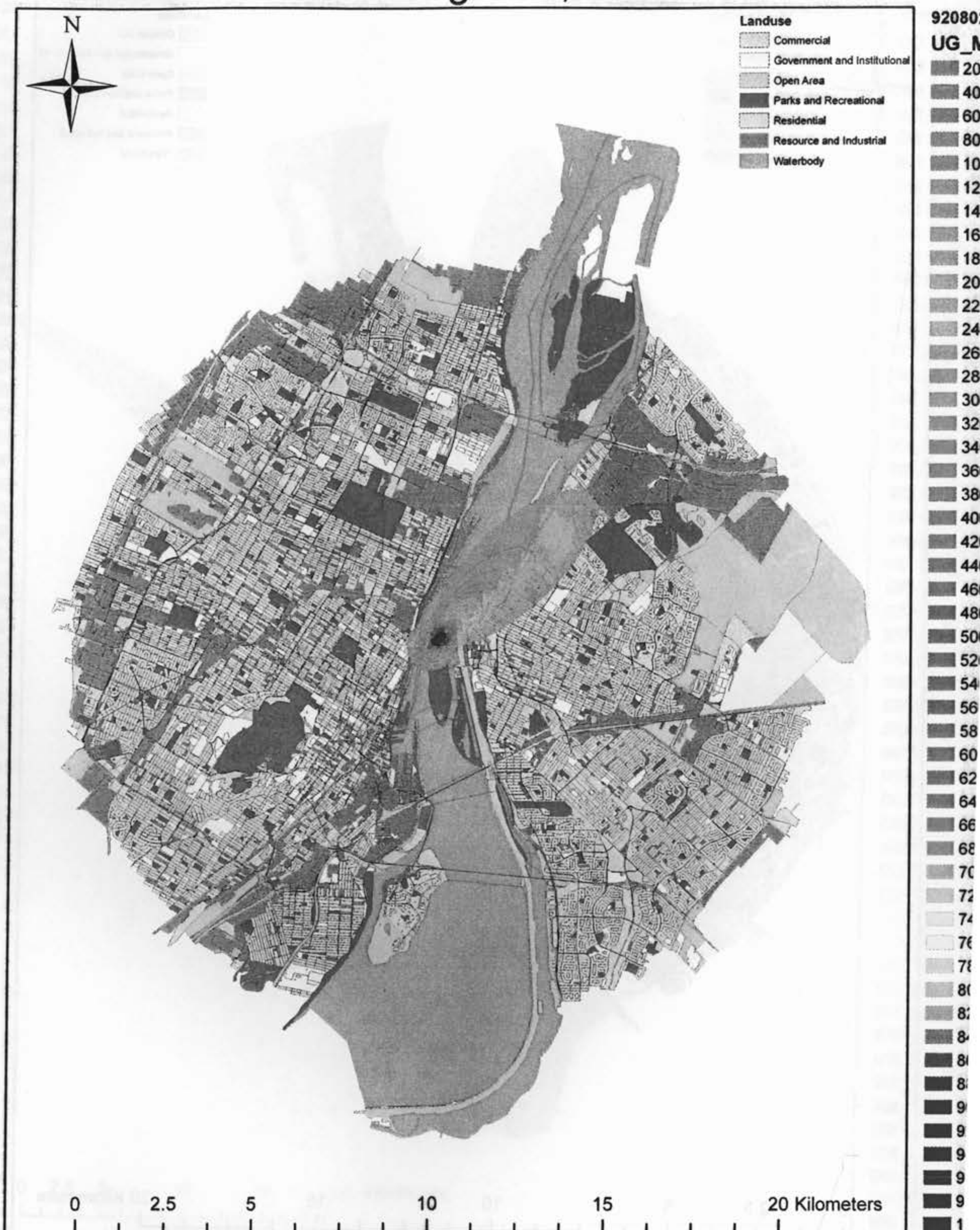
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 26, 1992



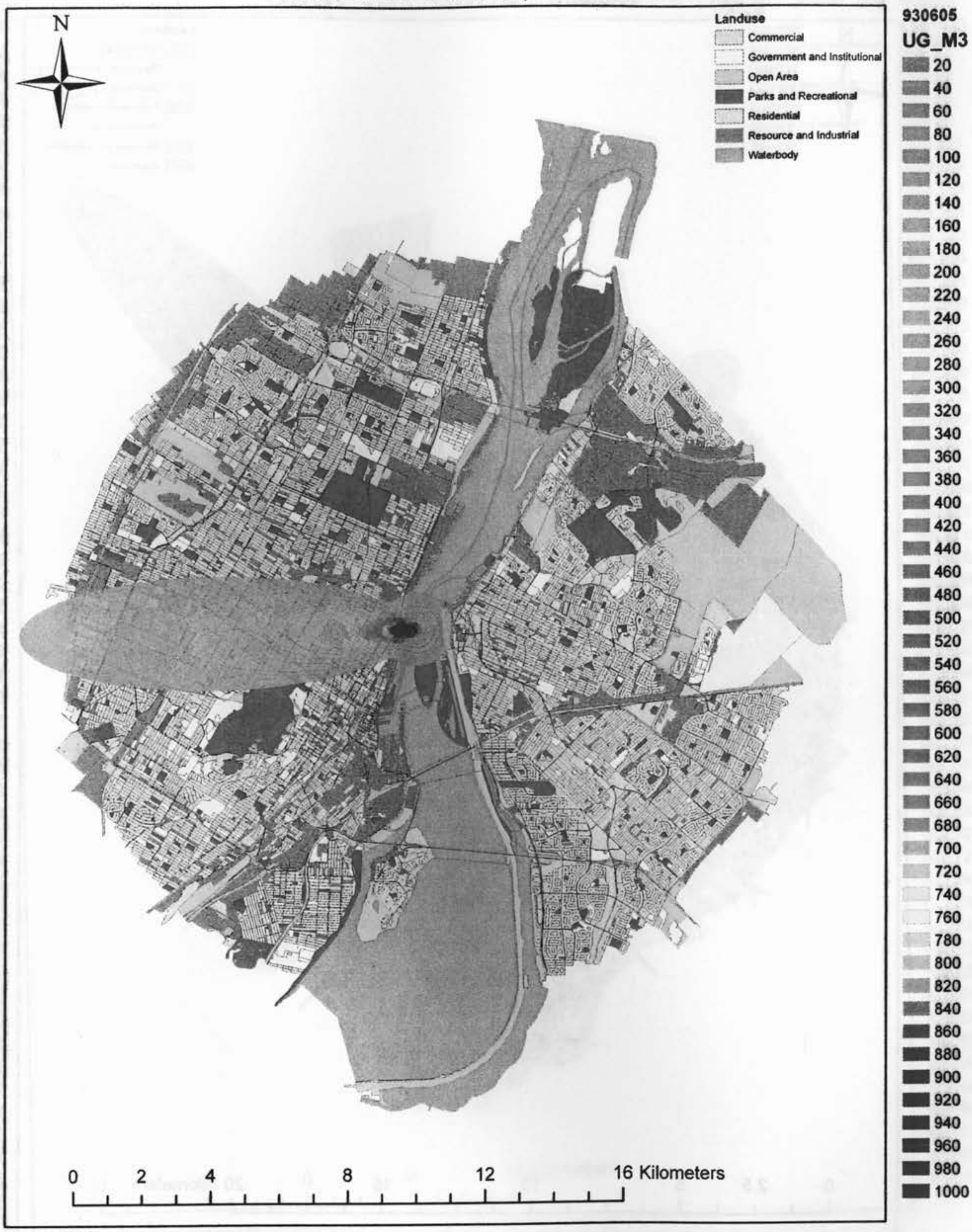
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal
10PM August 2, 1992

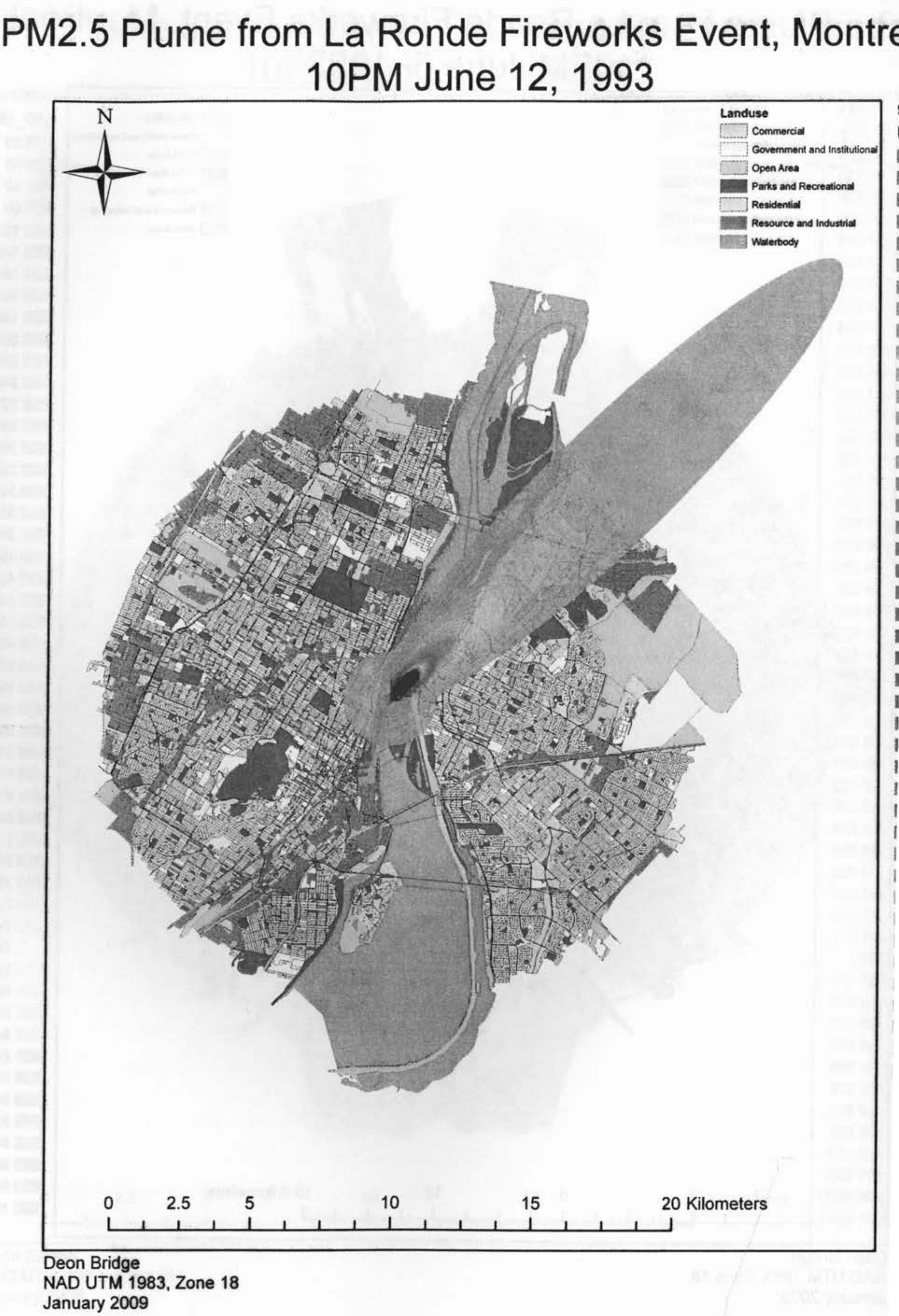


Deon Bridge
NAD UTM 1983, Zone 18
January 2009

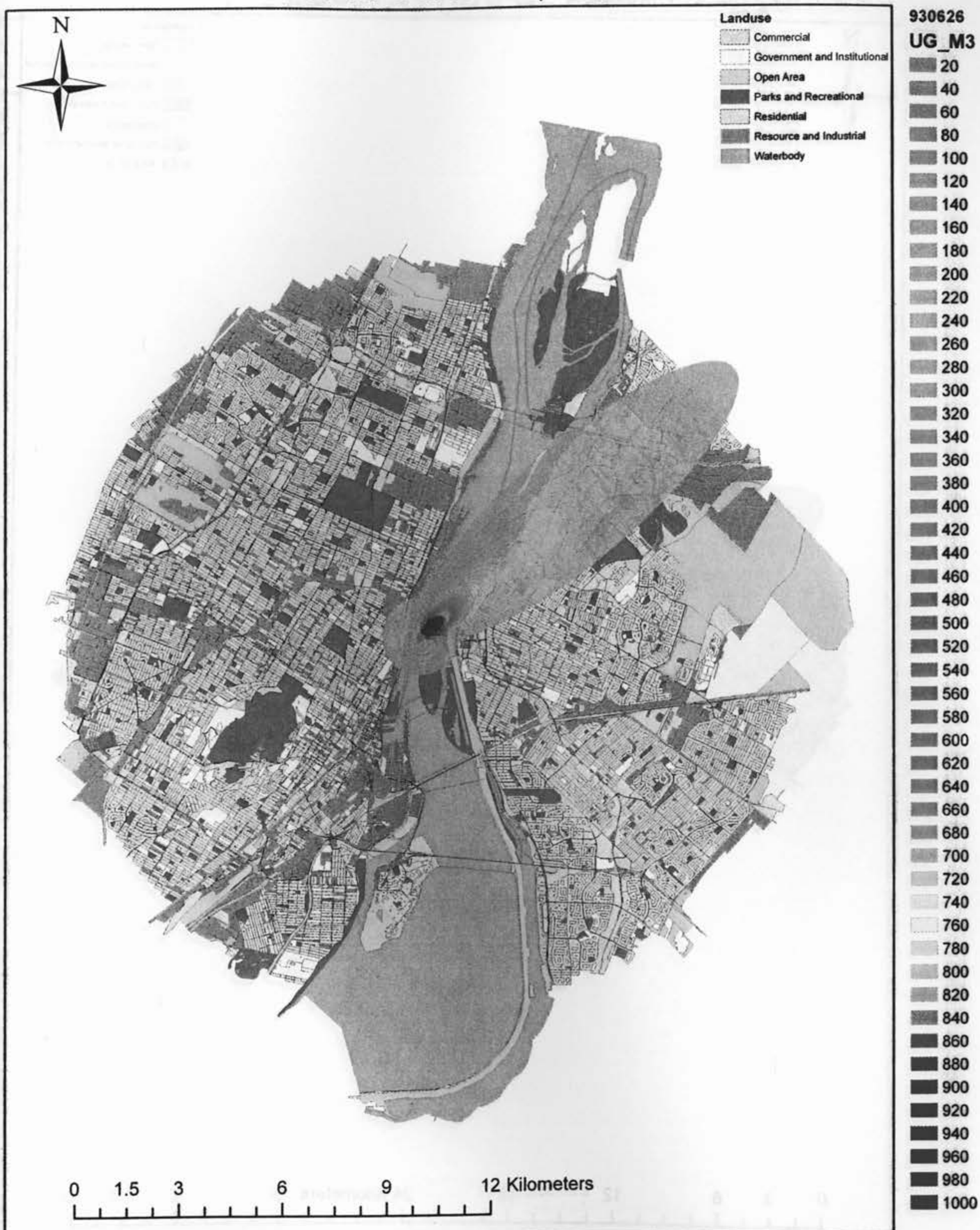
PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 5, 1993



Deon Bridge
NAD UTM 1983, Zone 18
January 2009

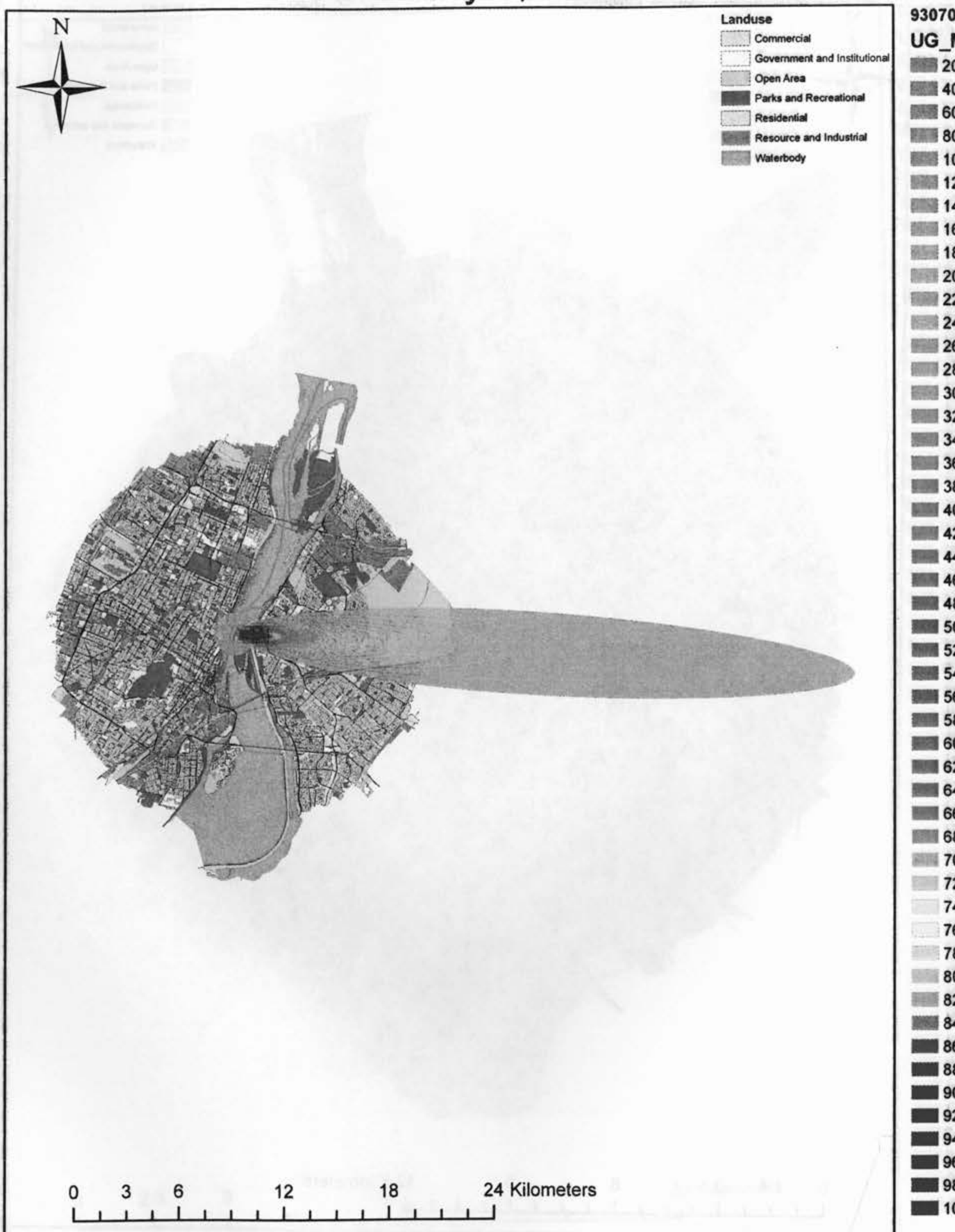

PM2.5 Plume from La Ronde Fireworks Event, Montre
10PM June 12, 1993
N
Landuse
Commercial
Government and Institutional
Open Area
Parks and Recreational
Residential
Resource and Industrial
Waterbody
0 2.5 5 10 15 20 Kilometers
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 26, 1993



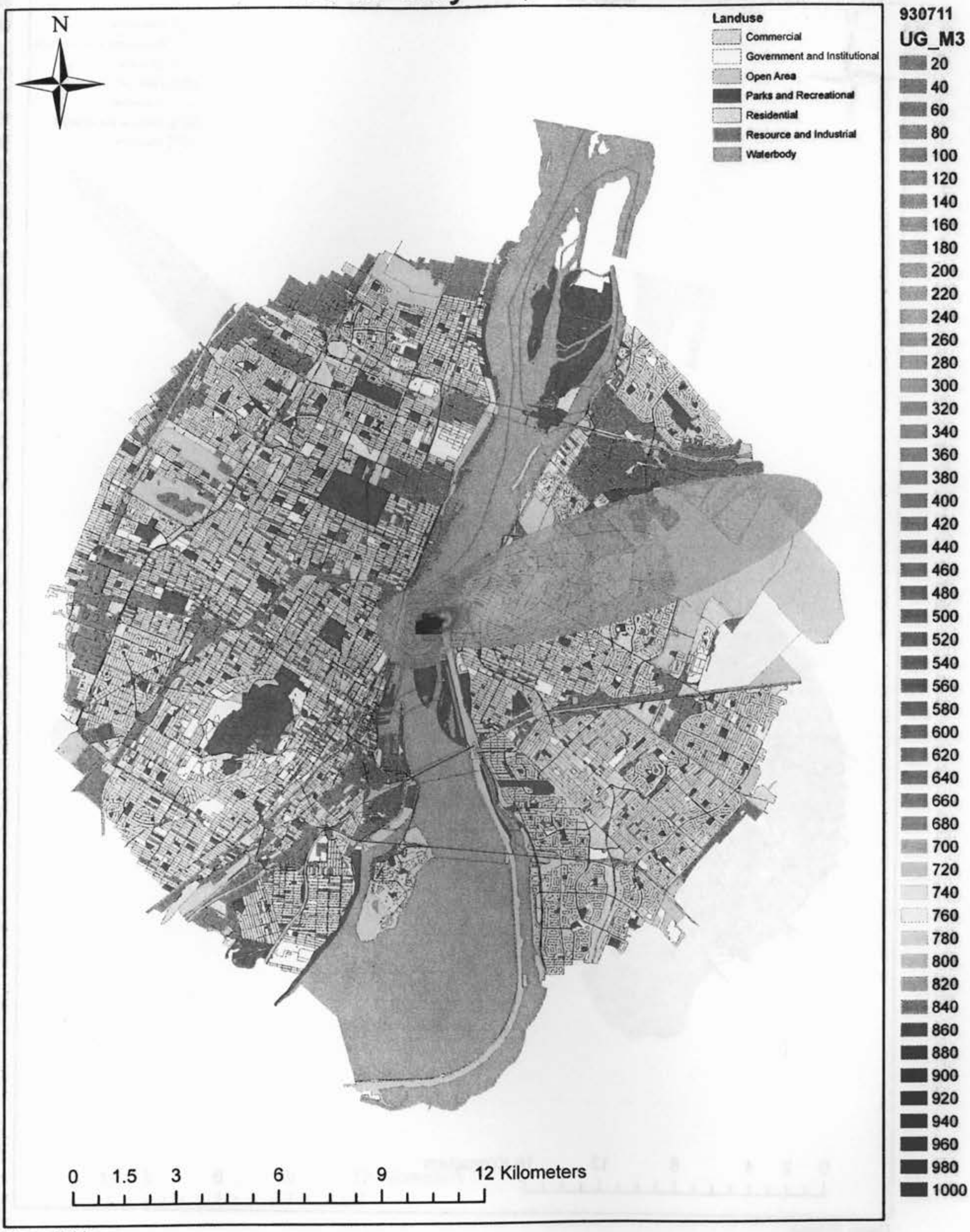
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 4, 1993



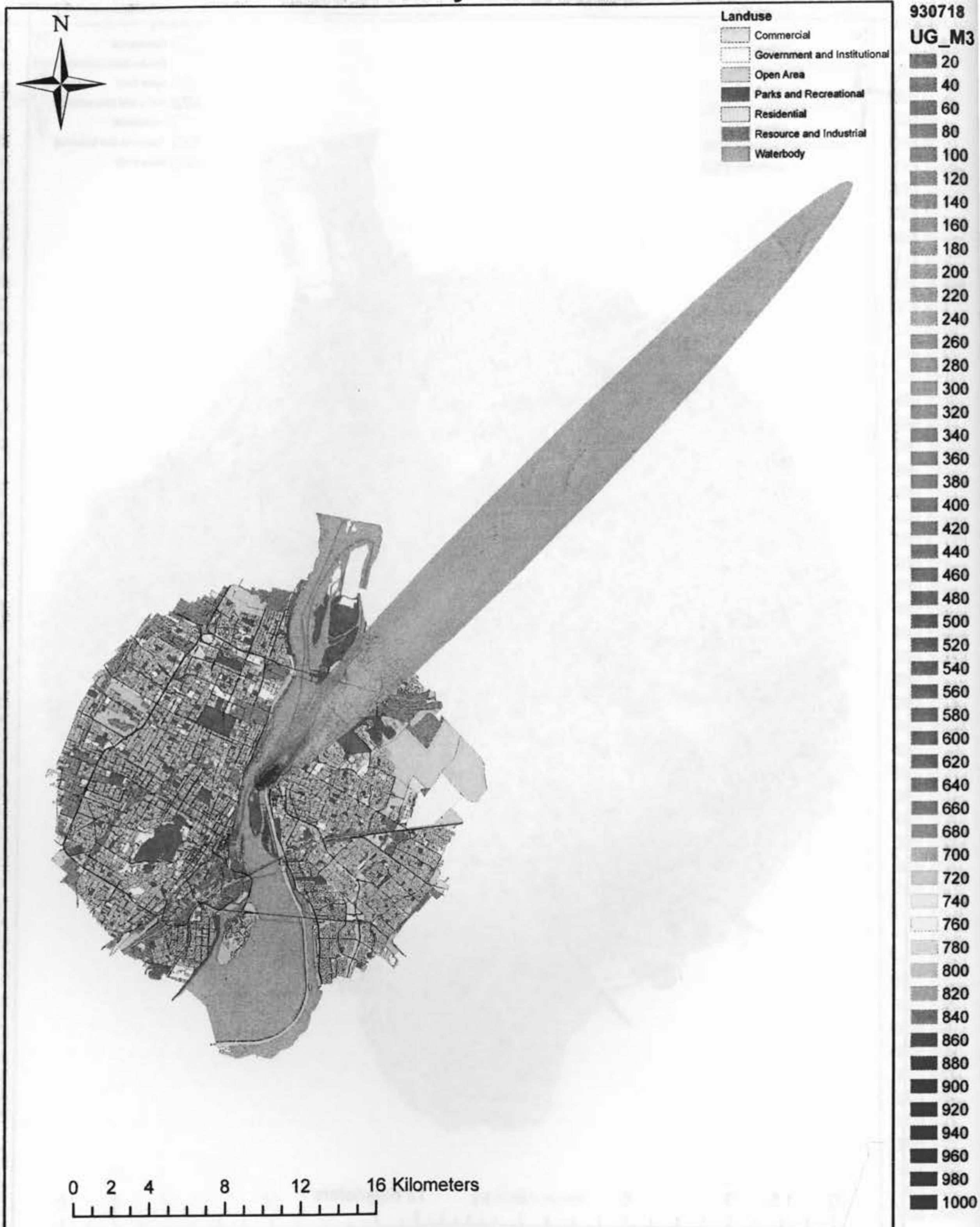
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 11, 1993



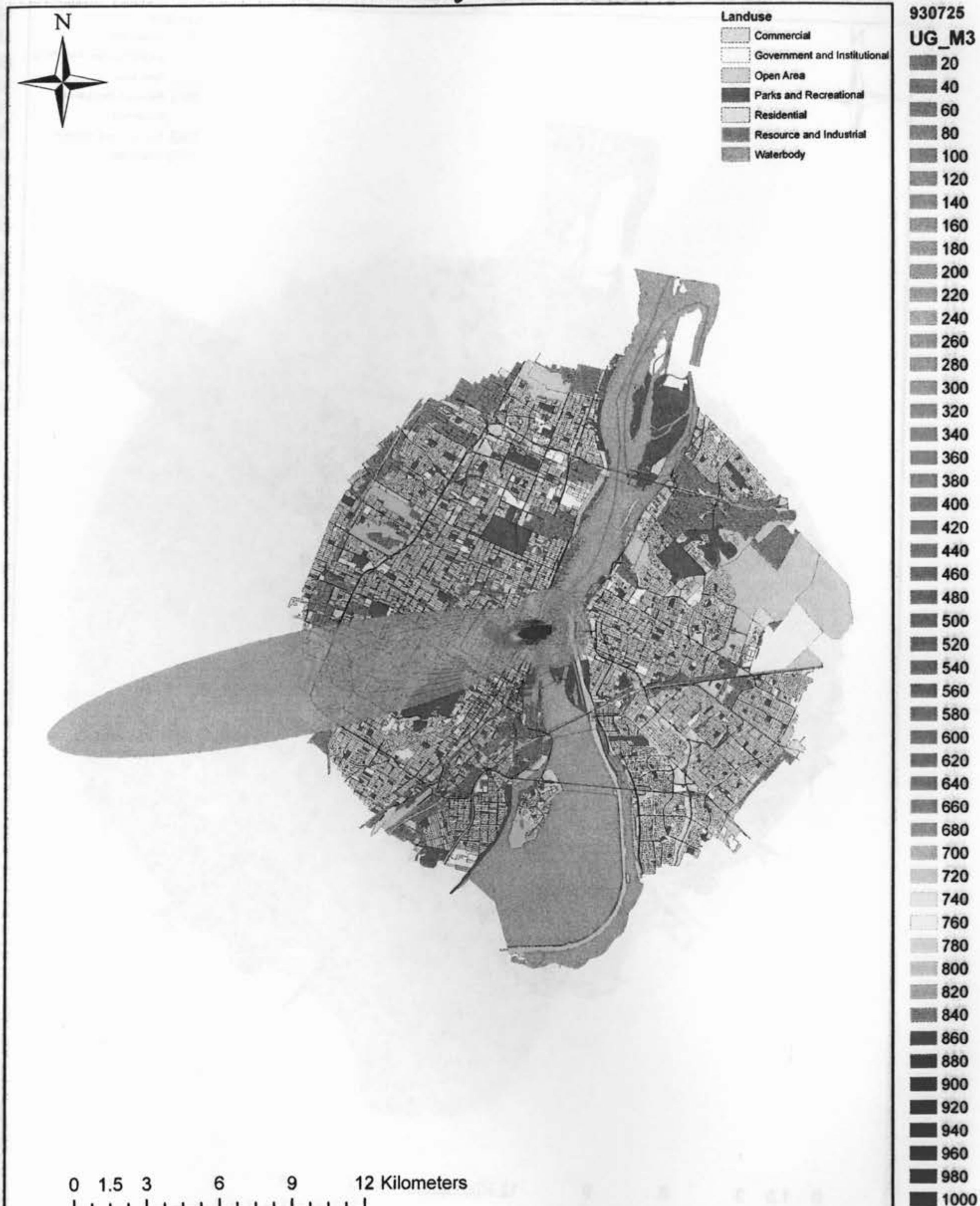
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 18, 1993



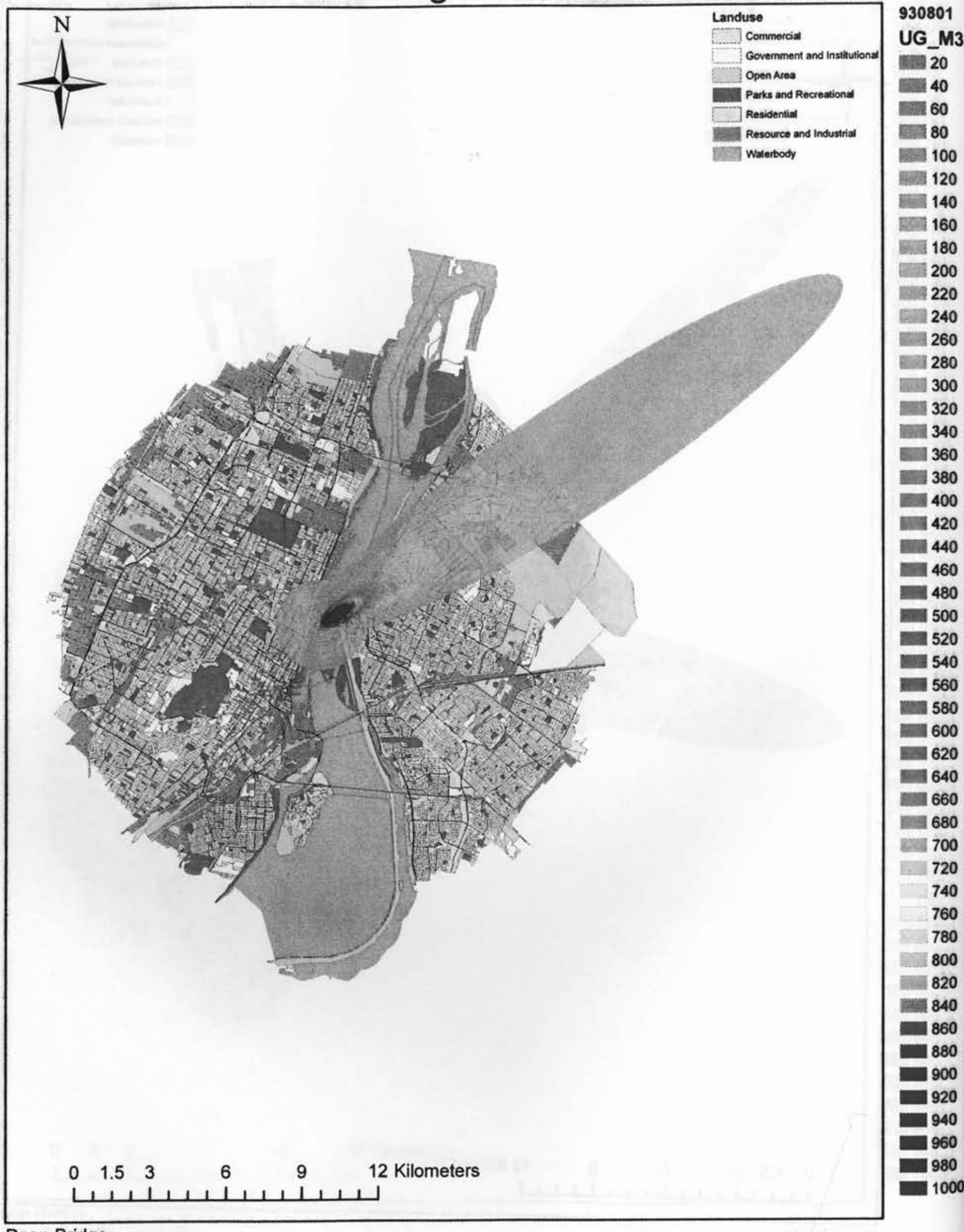
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 25, 1993



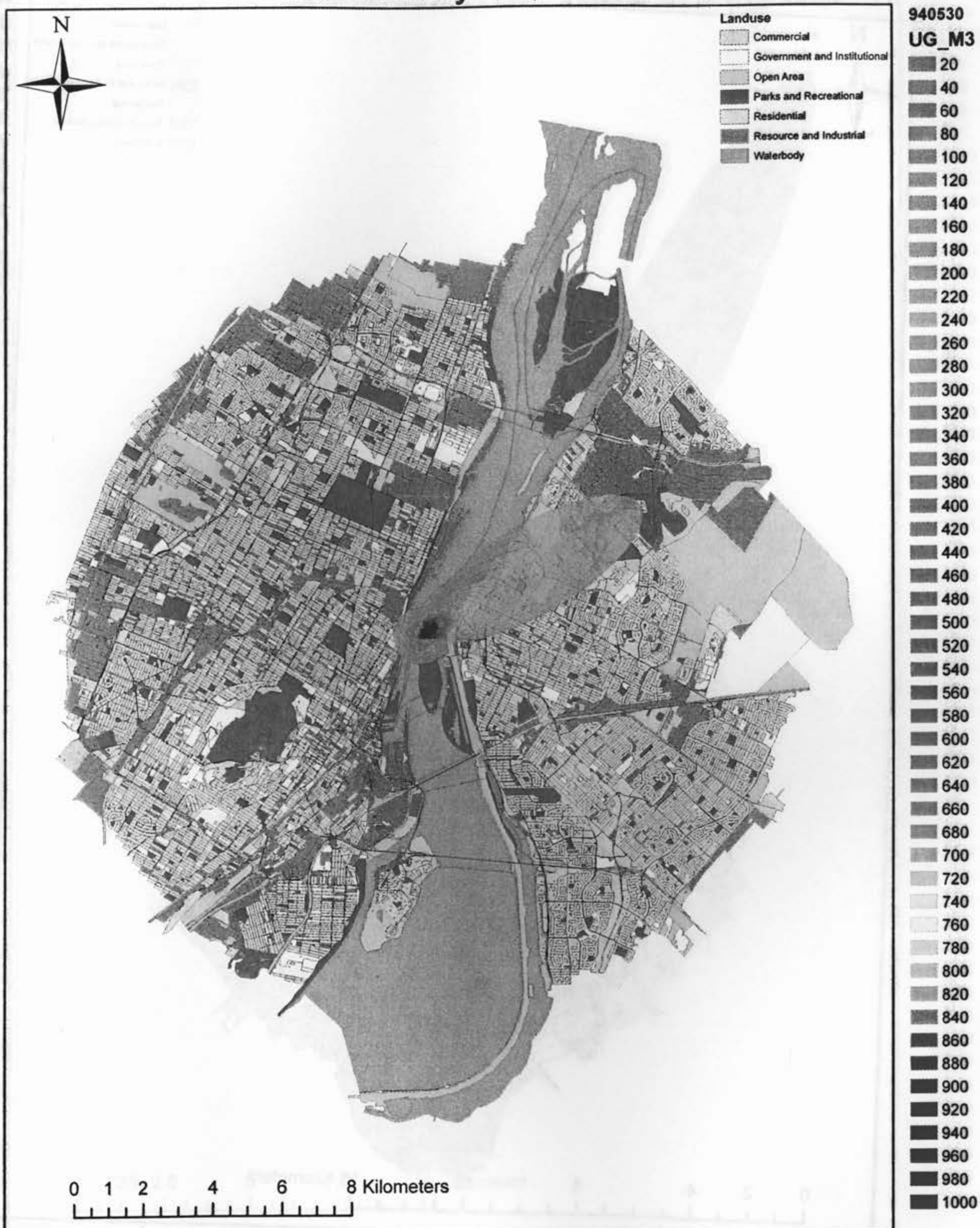
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM August 1, 1993



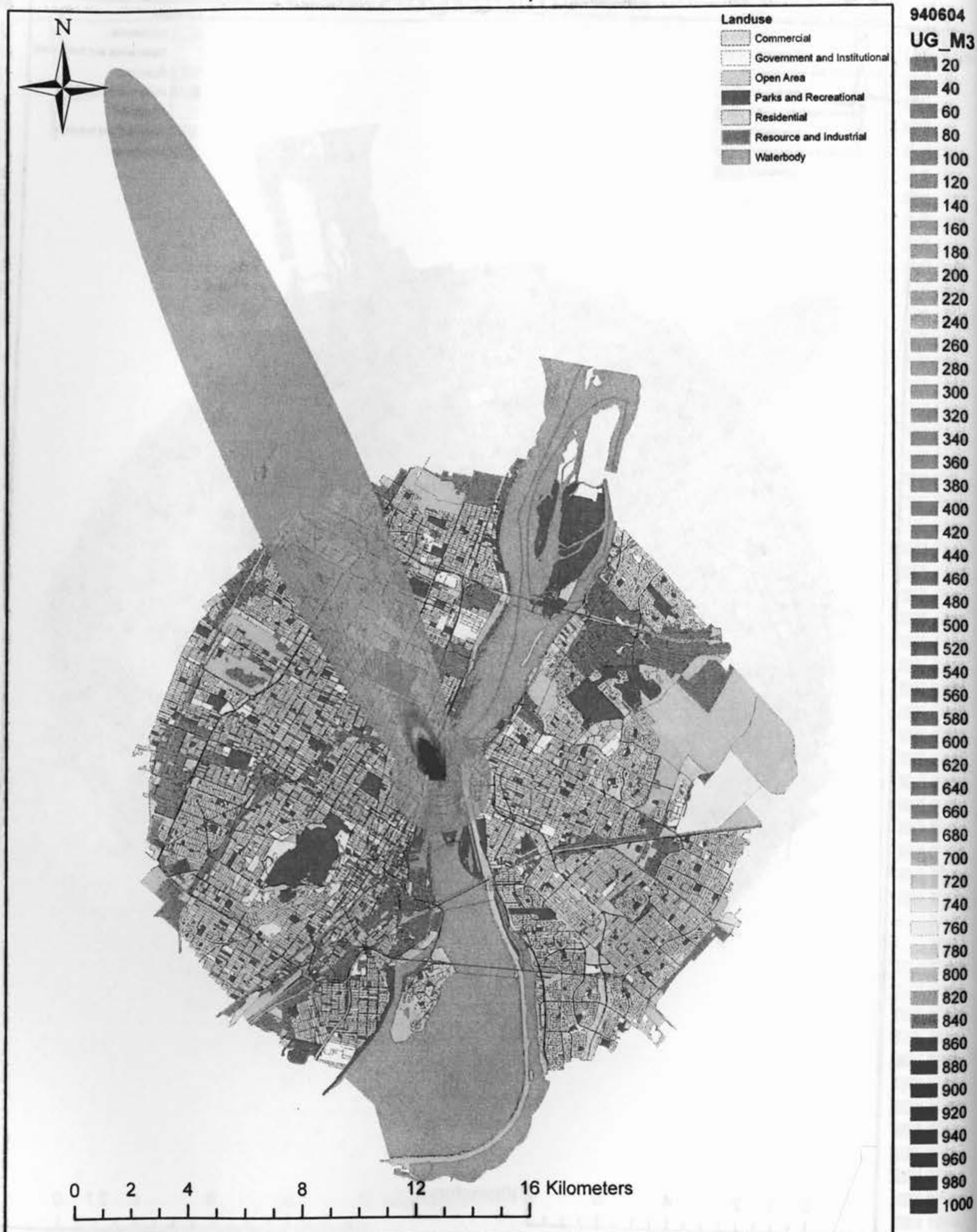
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM May 30, 1994



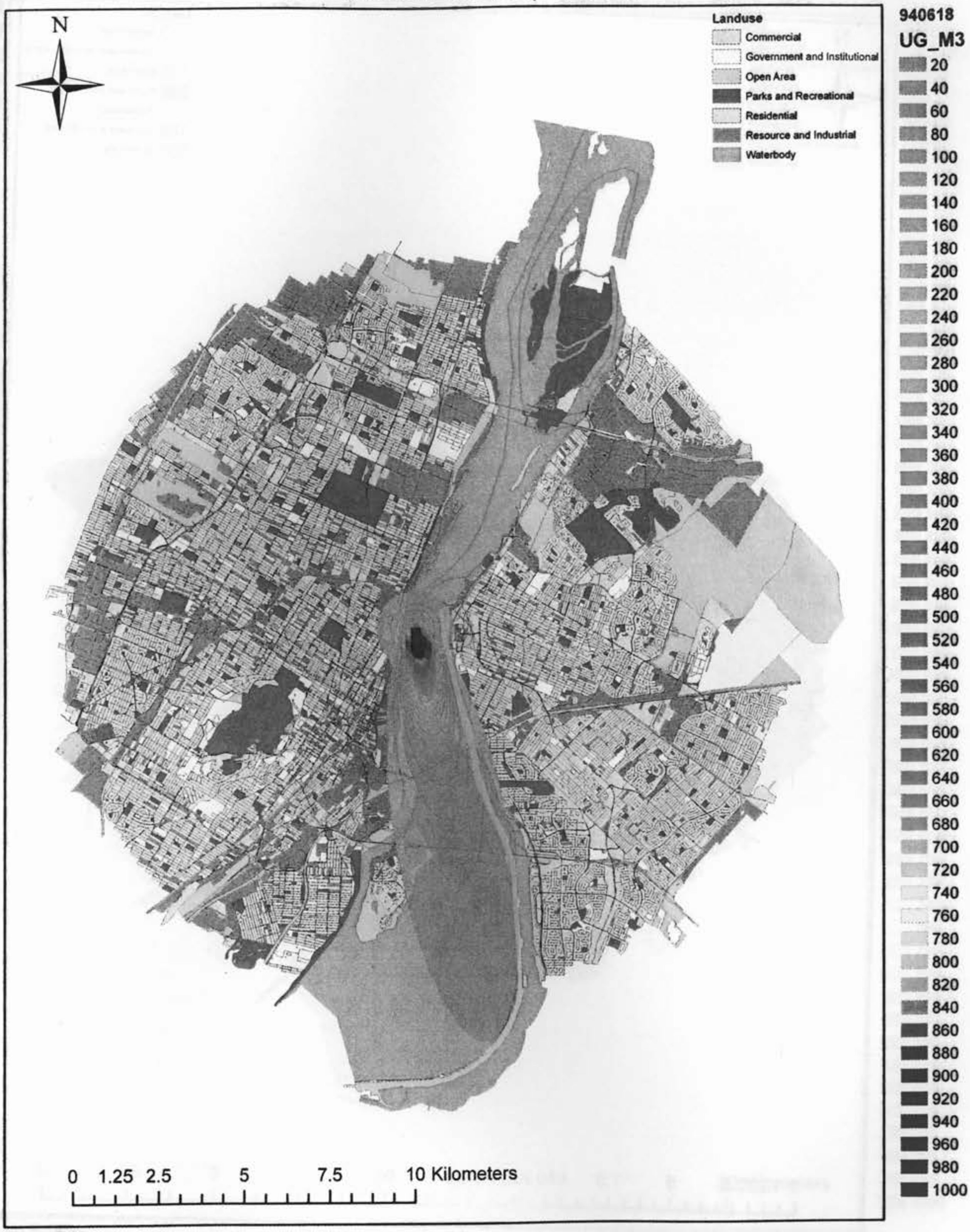
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 4, 1994



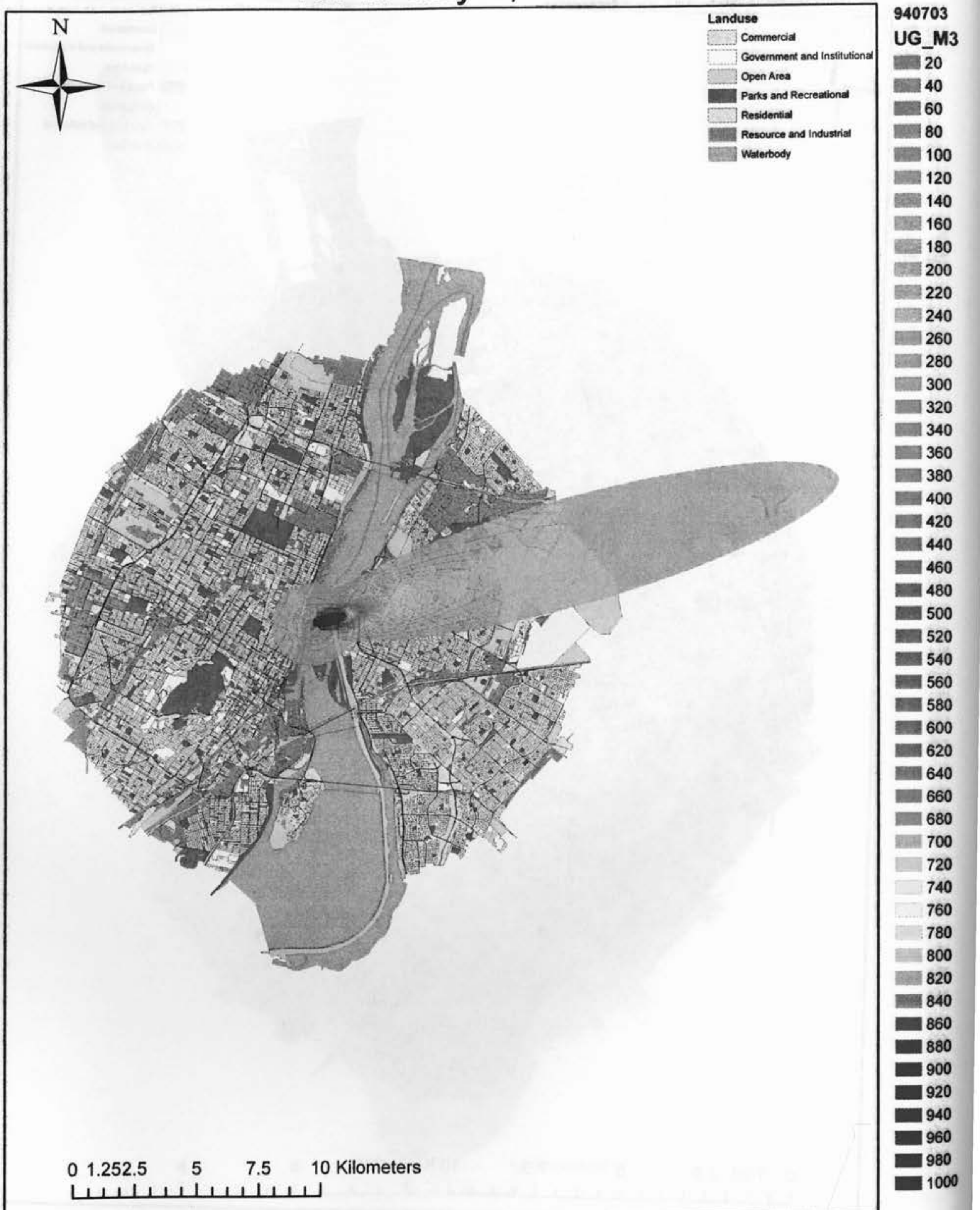
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 18, 1994



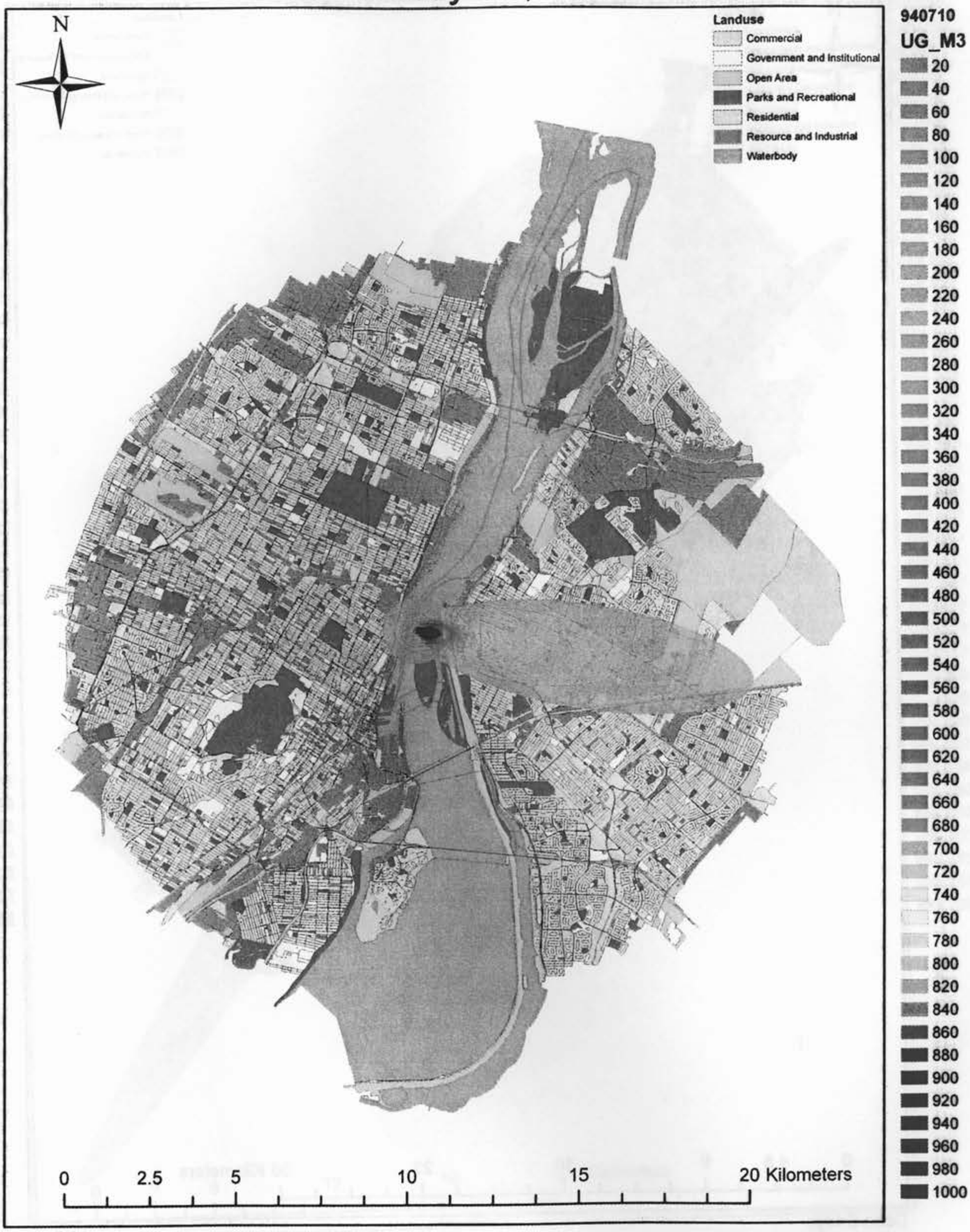
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 3, 1994



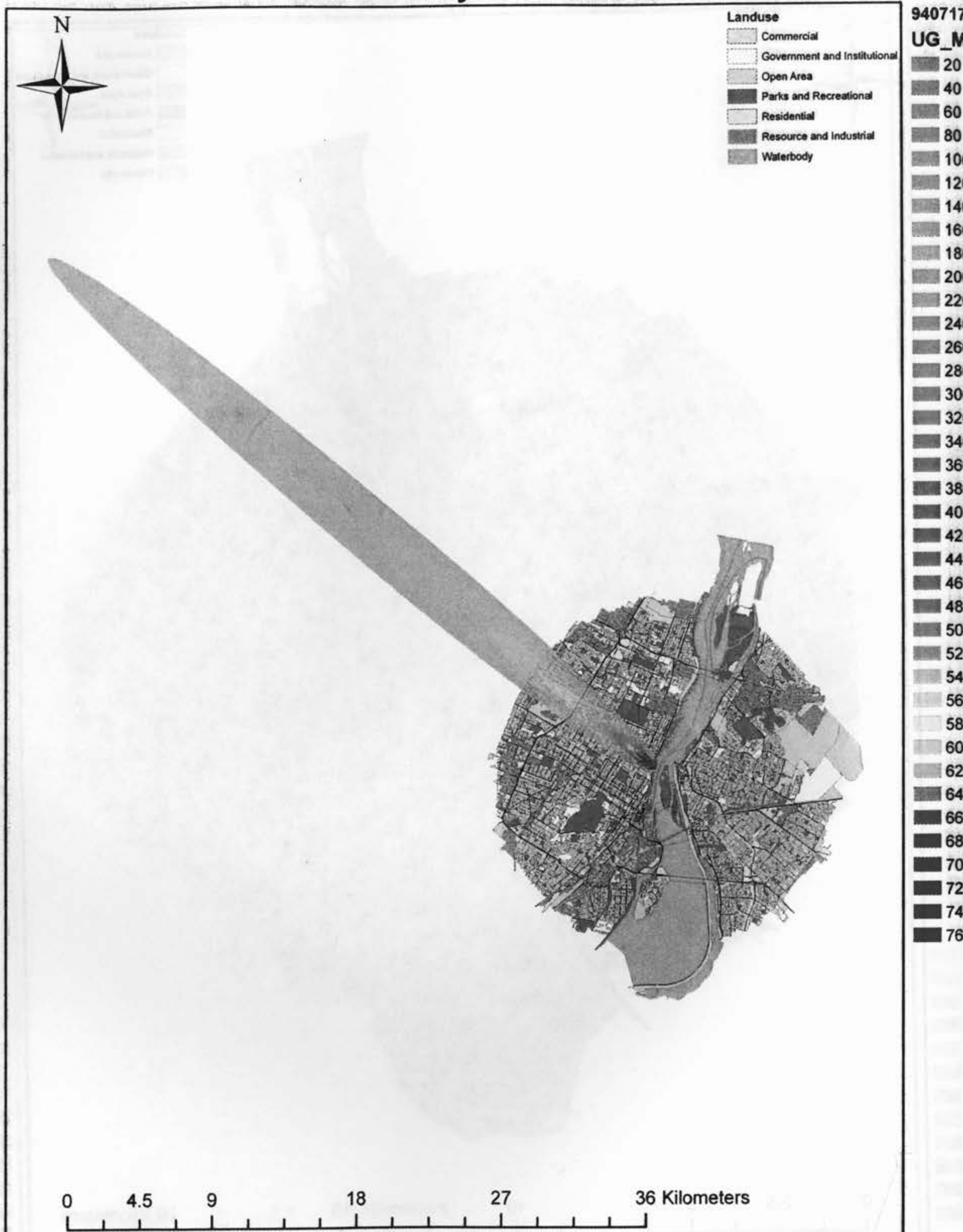
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 10, 1994



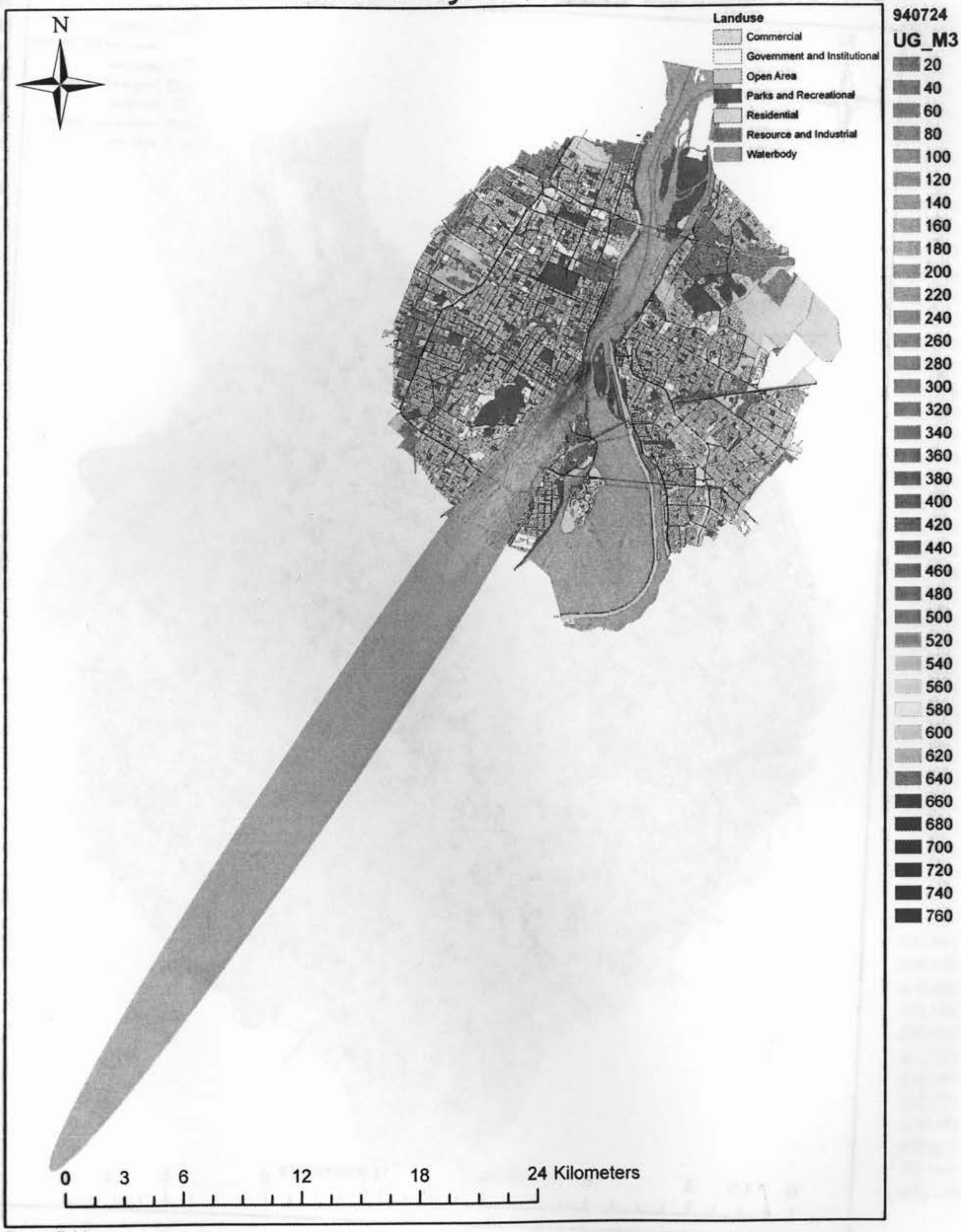
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 17, 1994



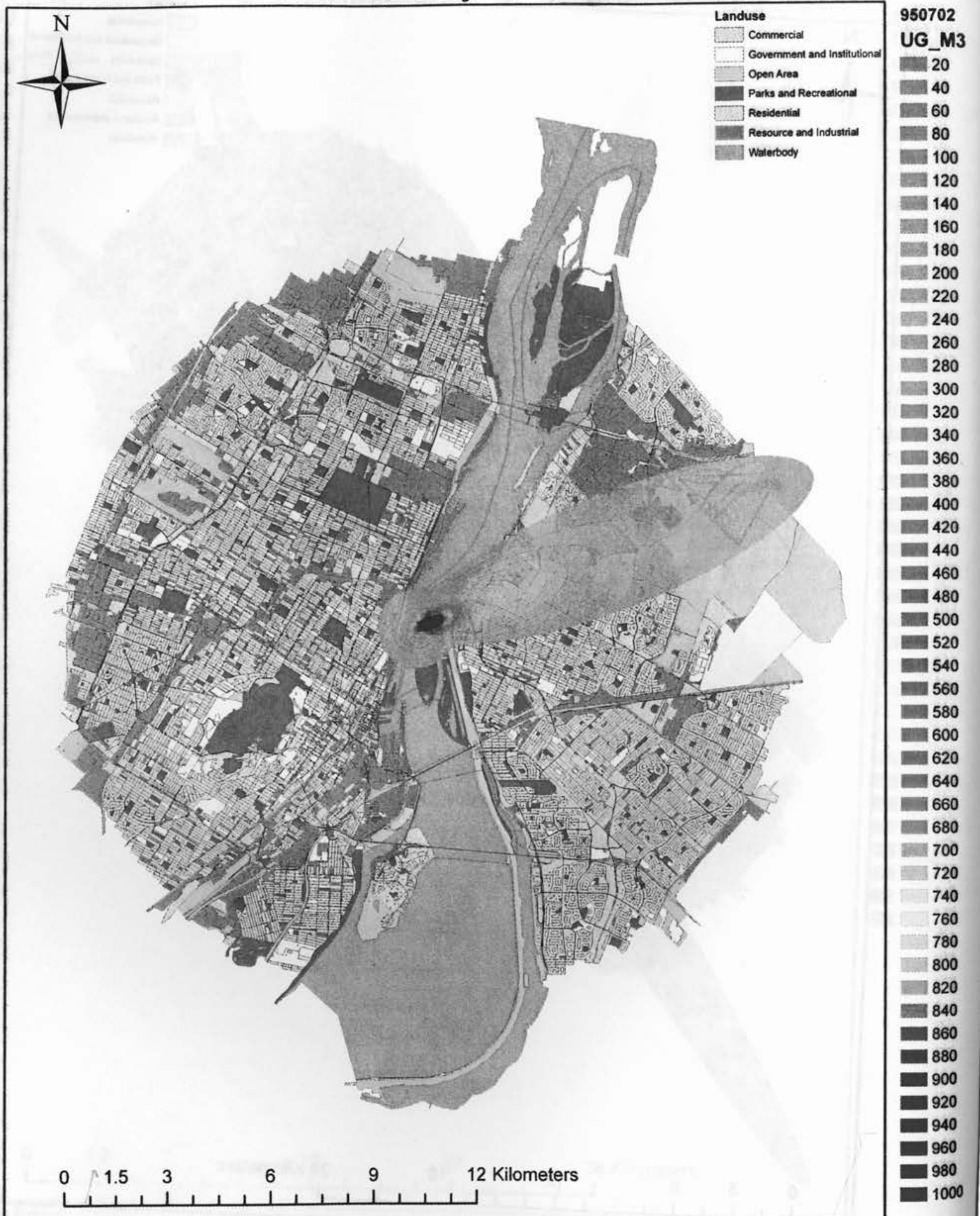
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 24, 1994



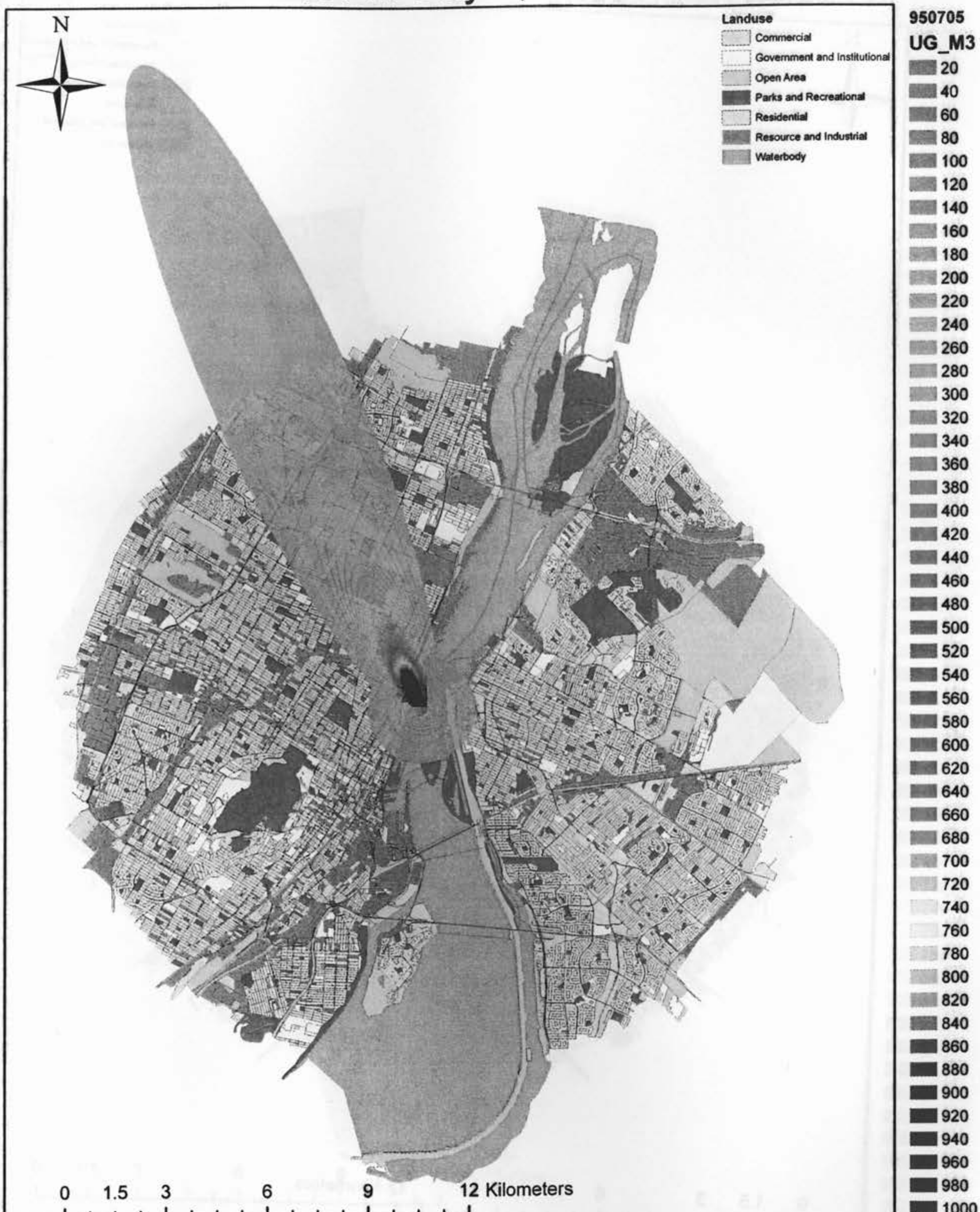
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 2, 1995



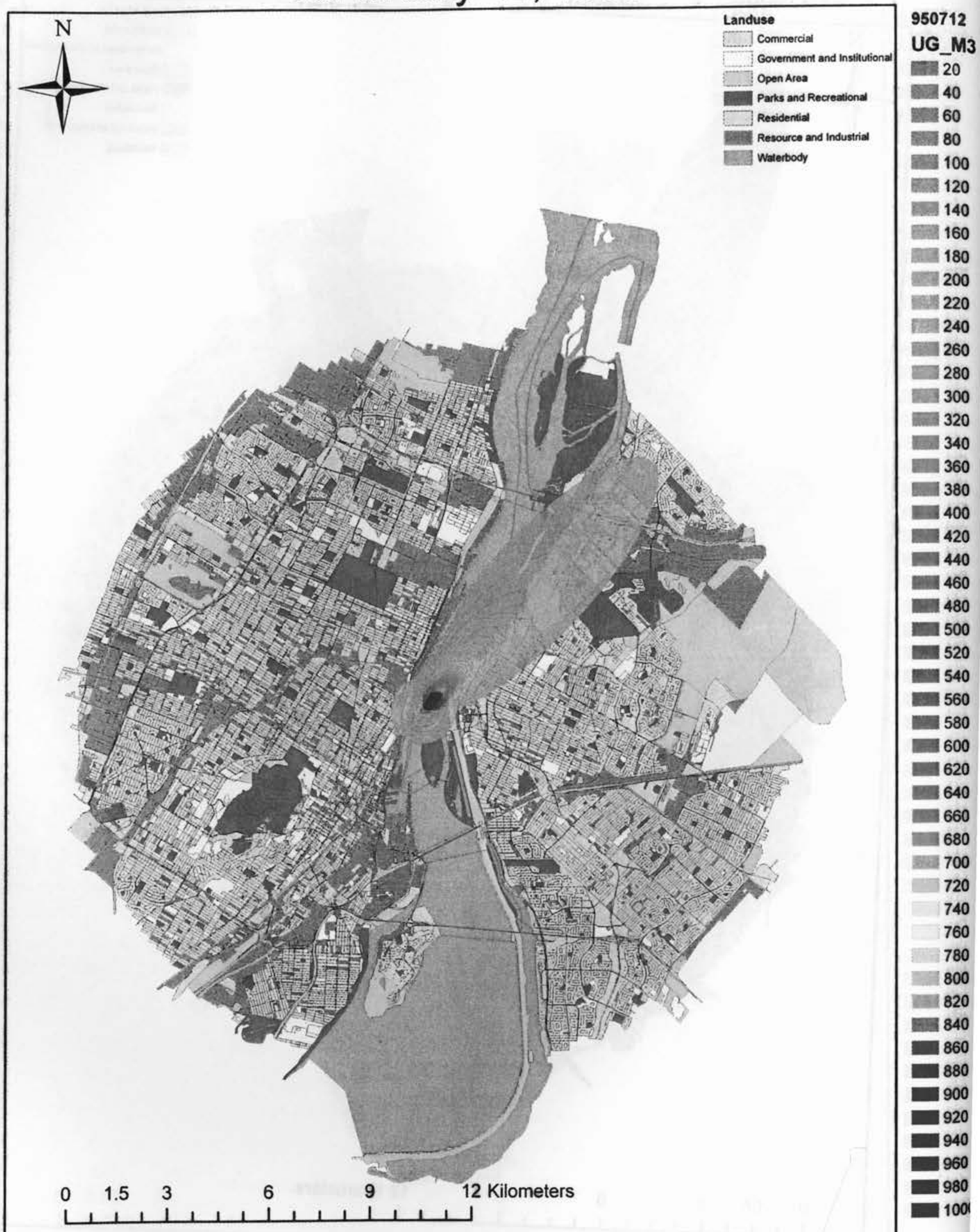
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 5, 1995



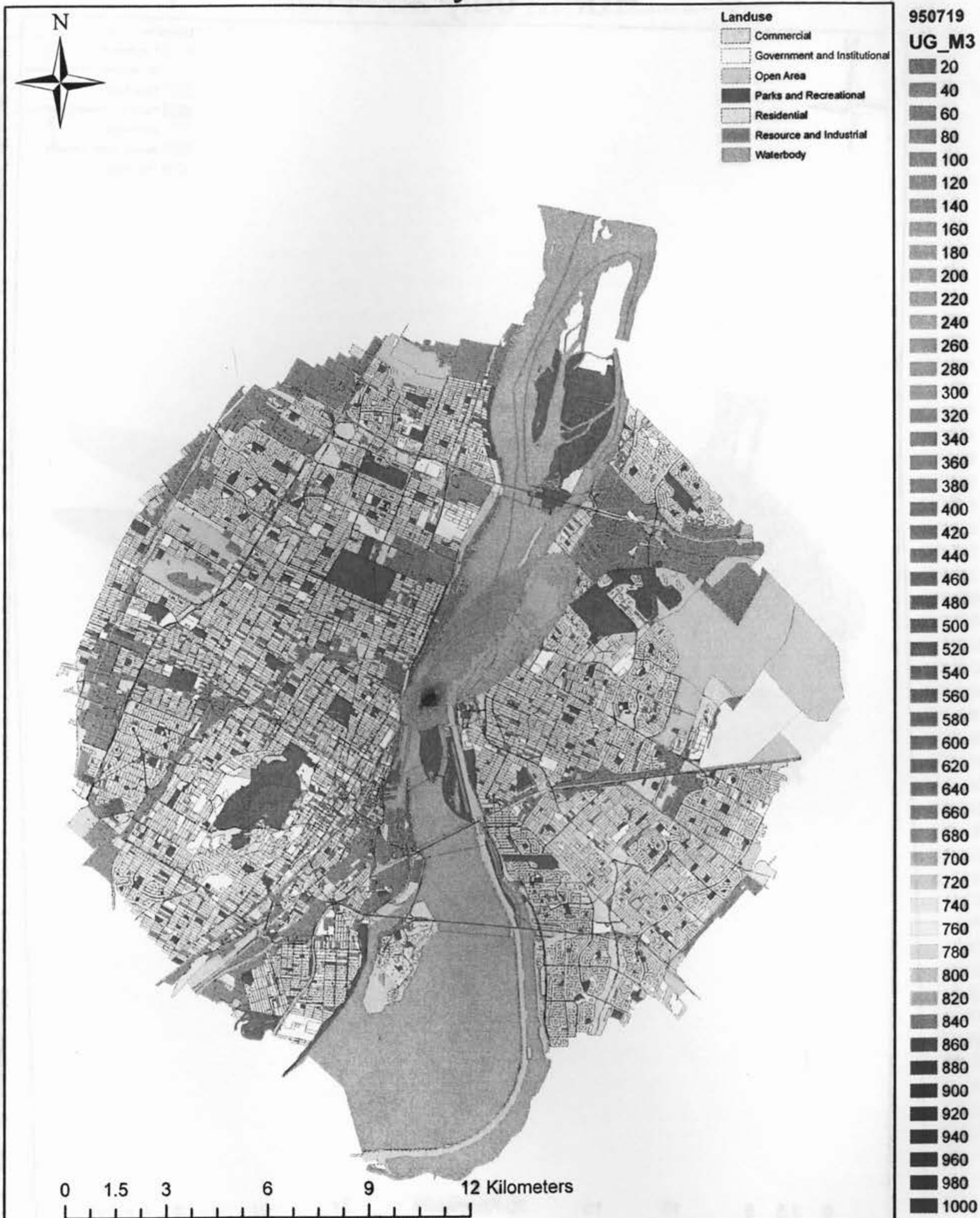
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 12, 1995



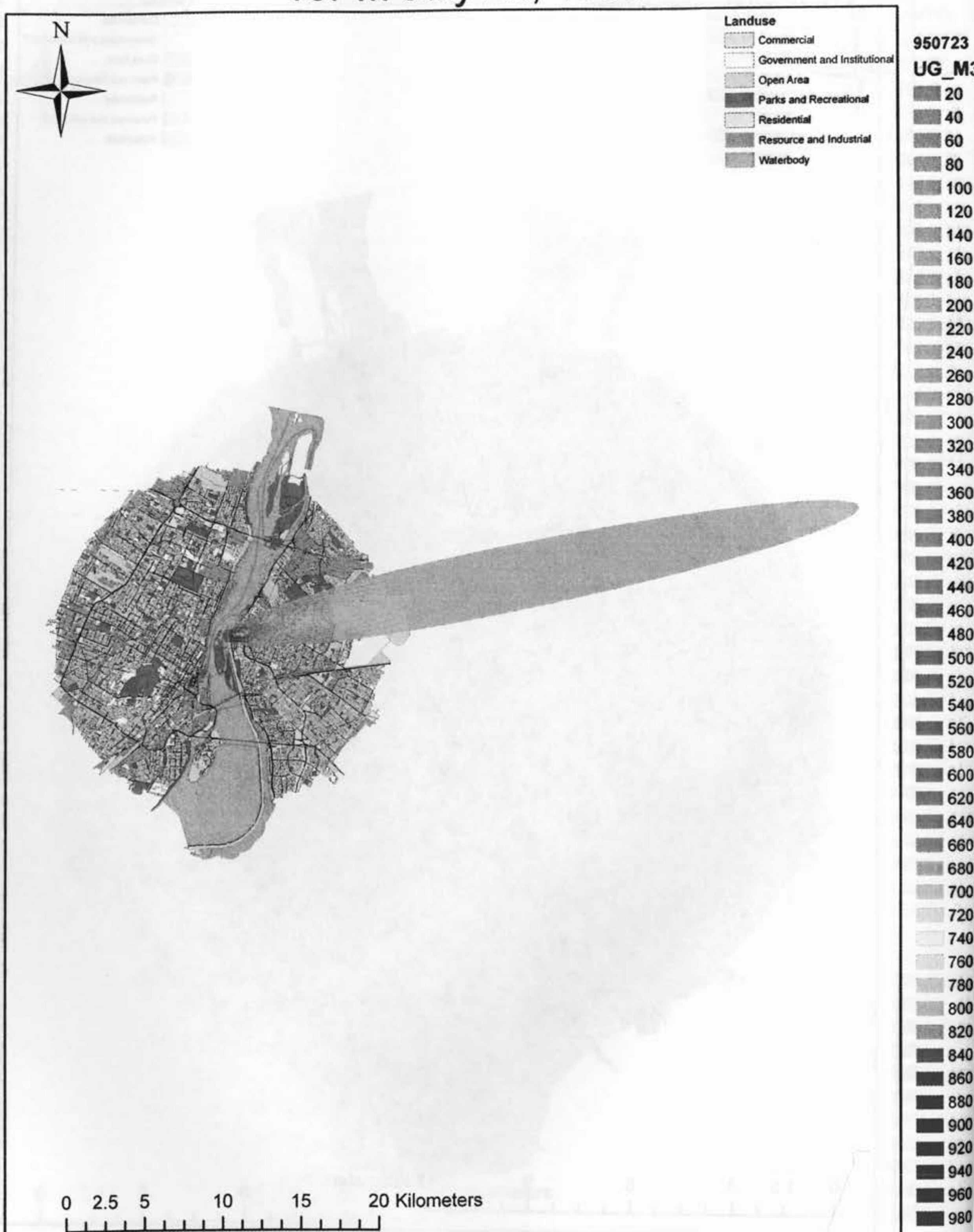
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 19, 1995



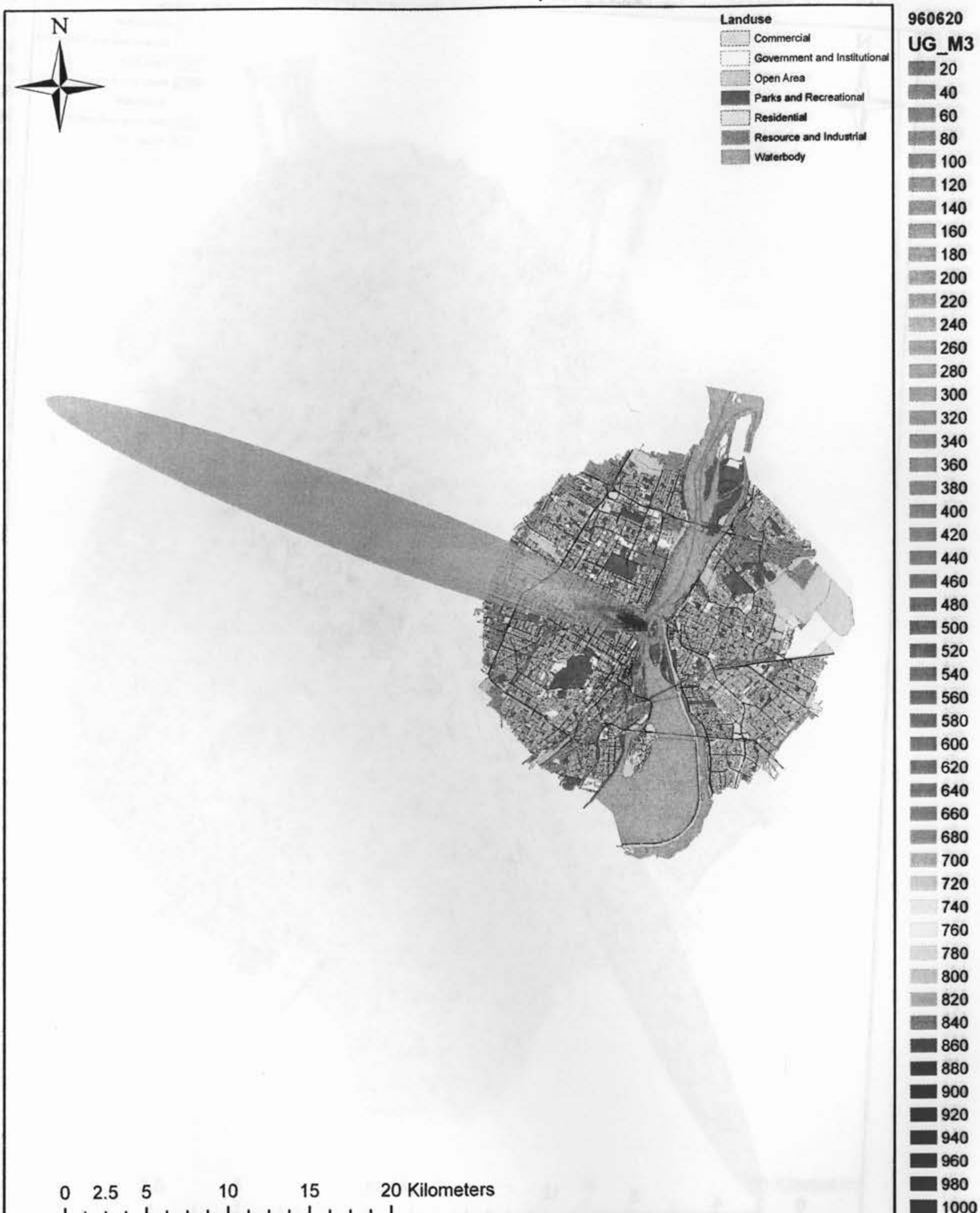
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 23, 1995



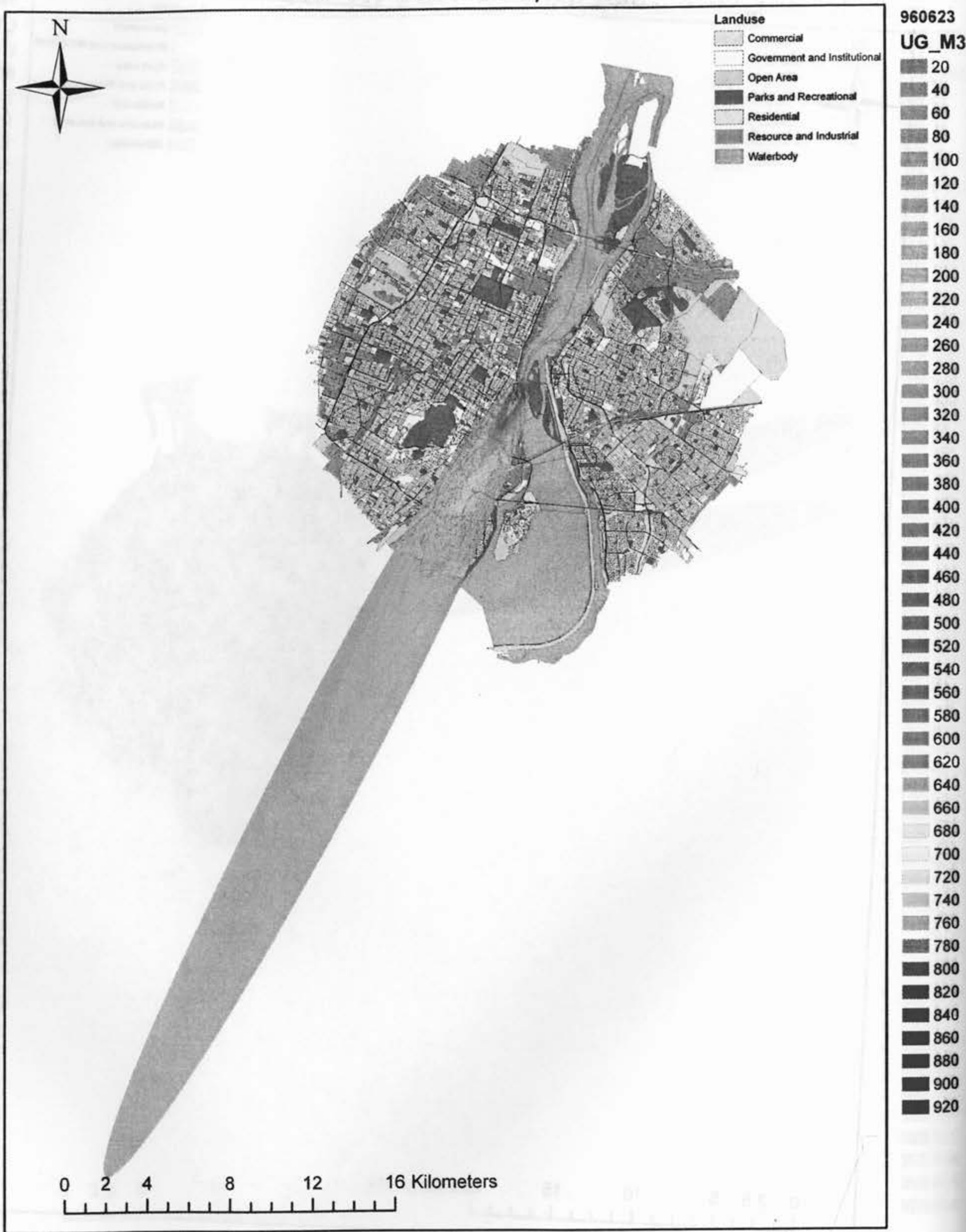
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 20, 1996



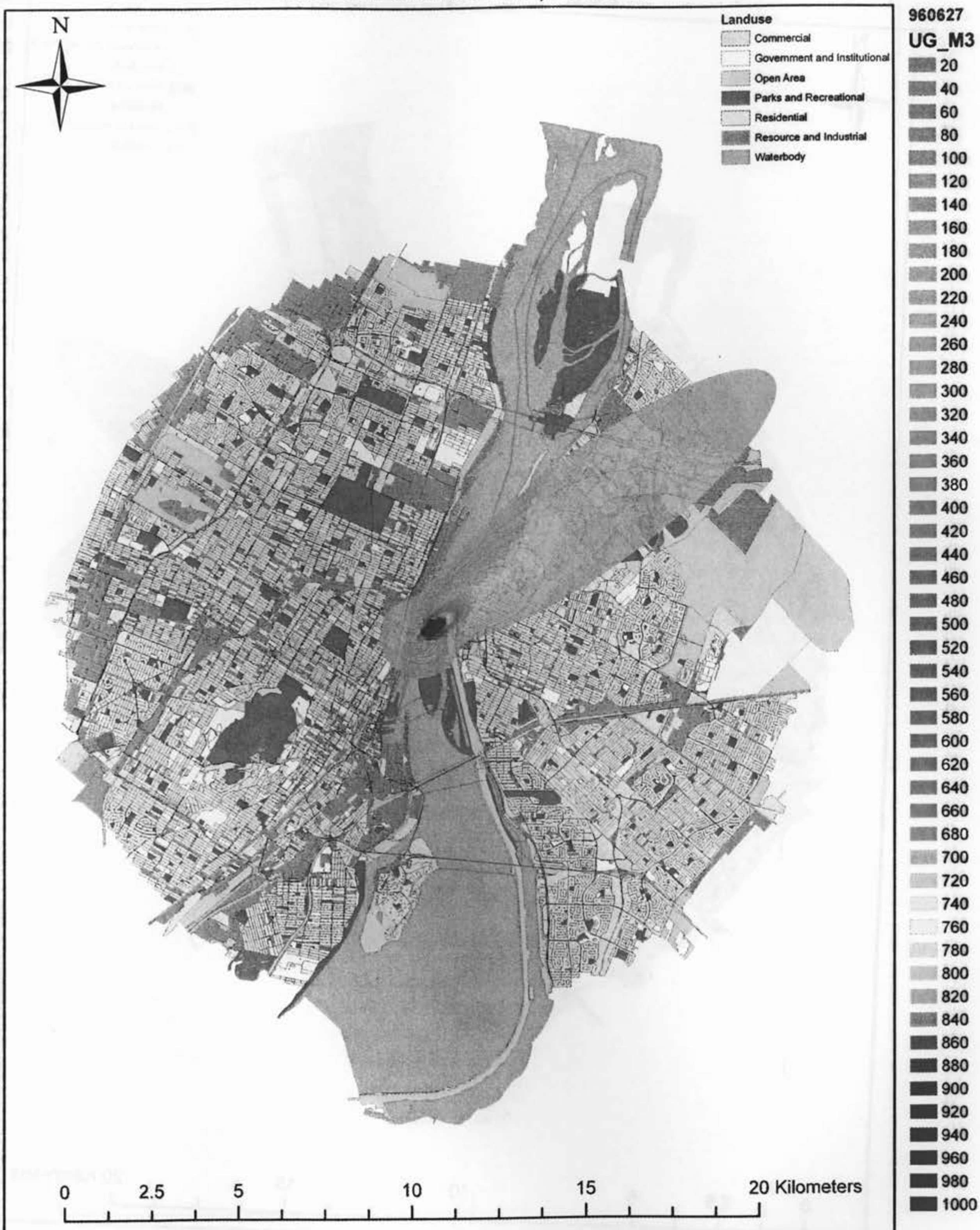
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 23, 1996



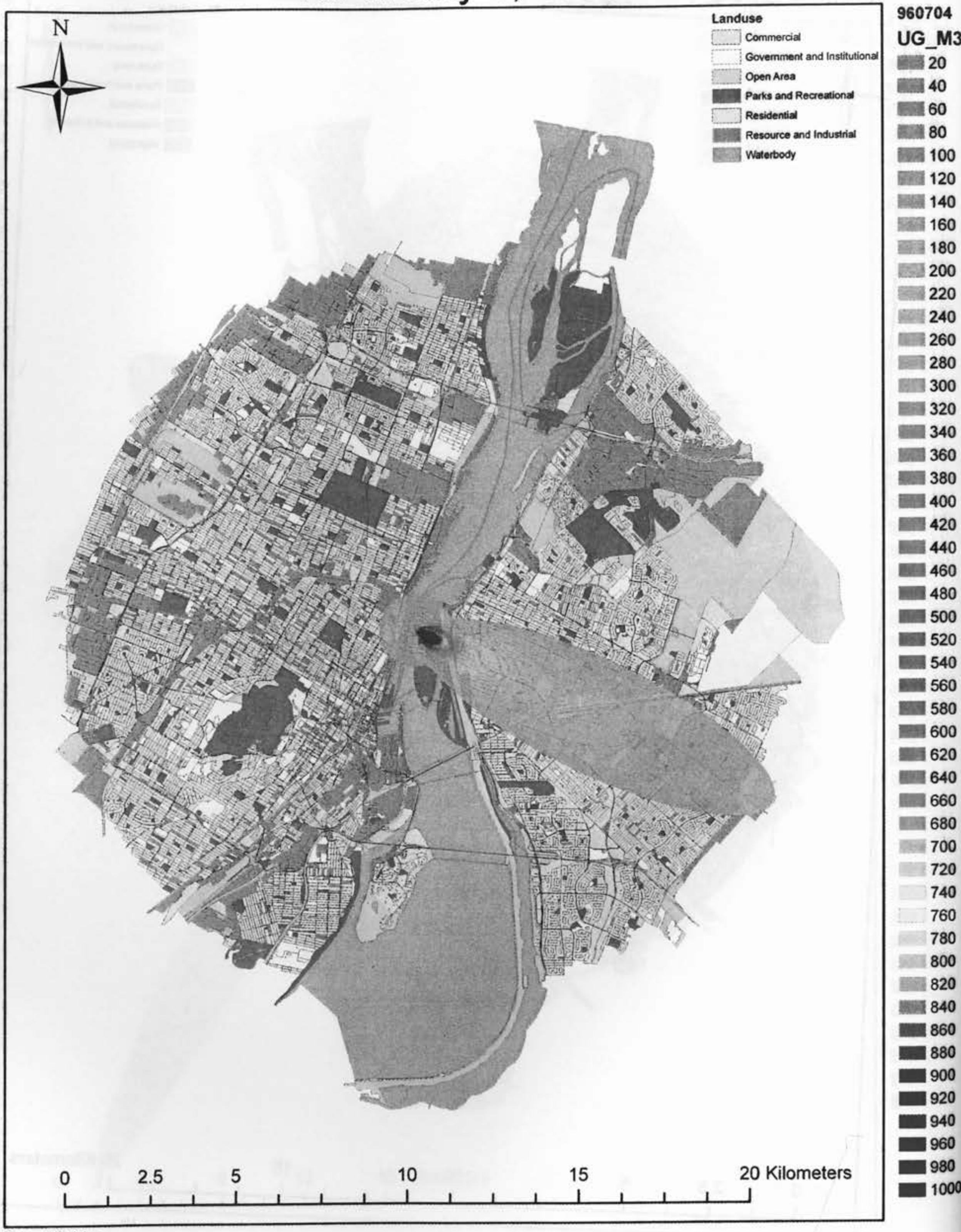
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 27, 1996



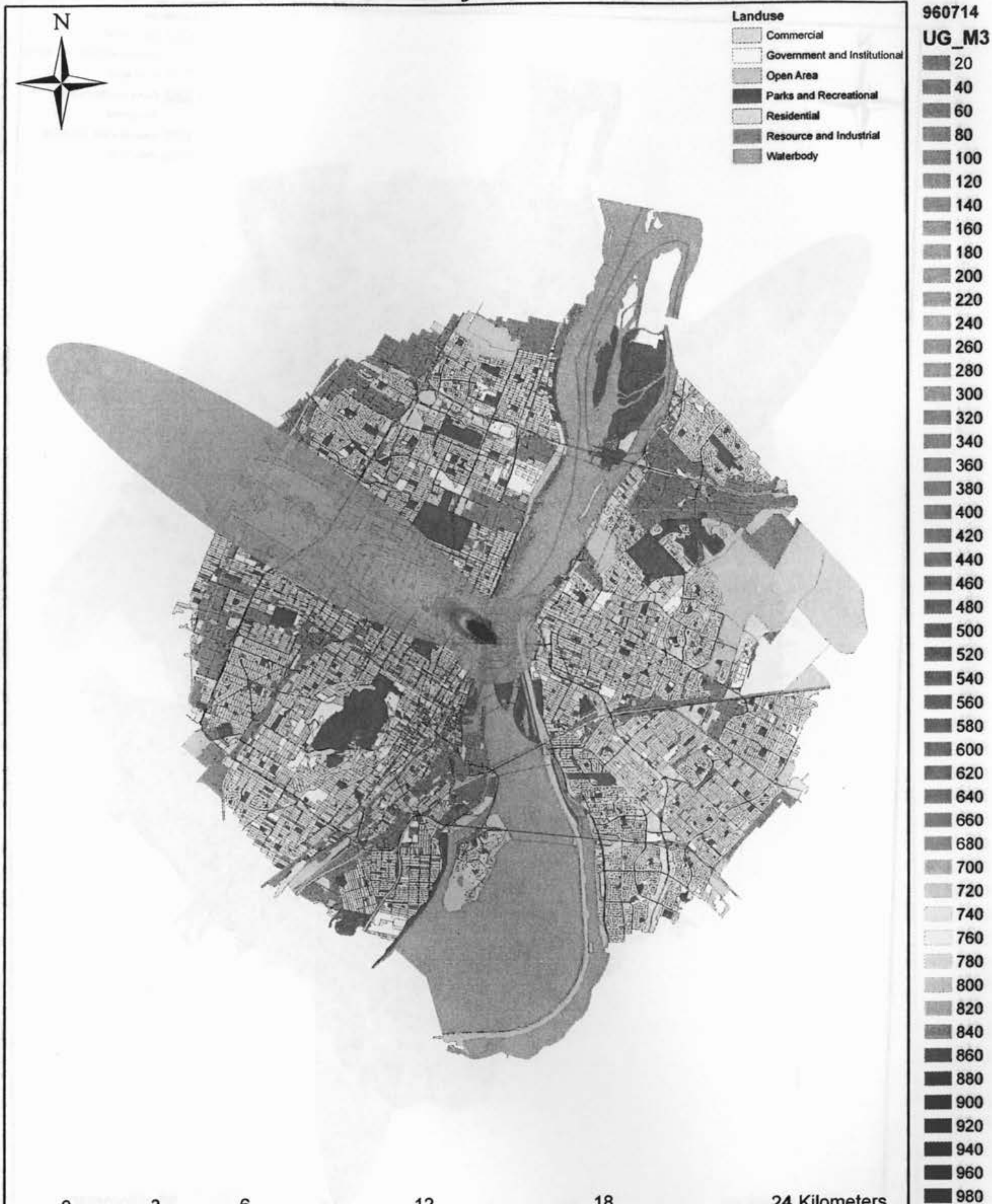
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 4, 1996



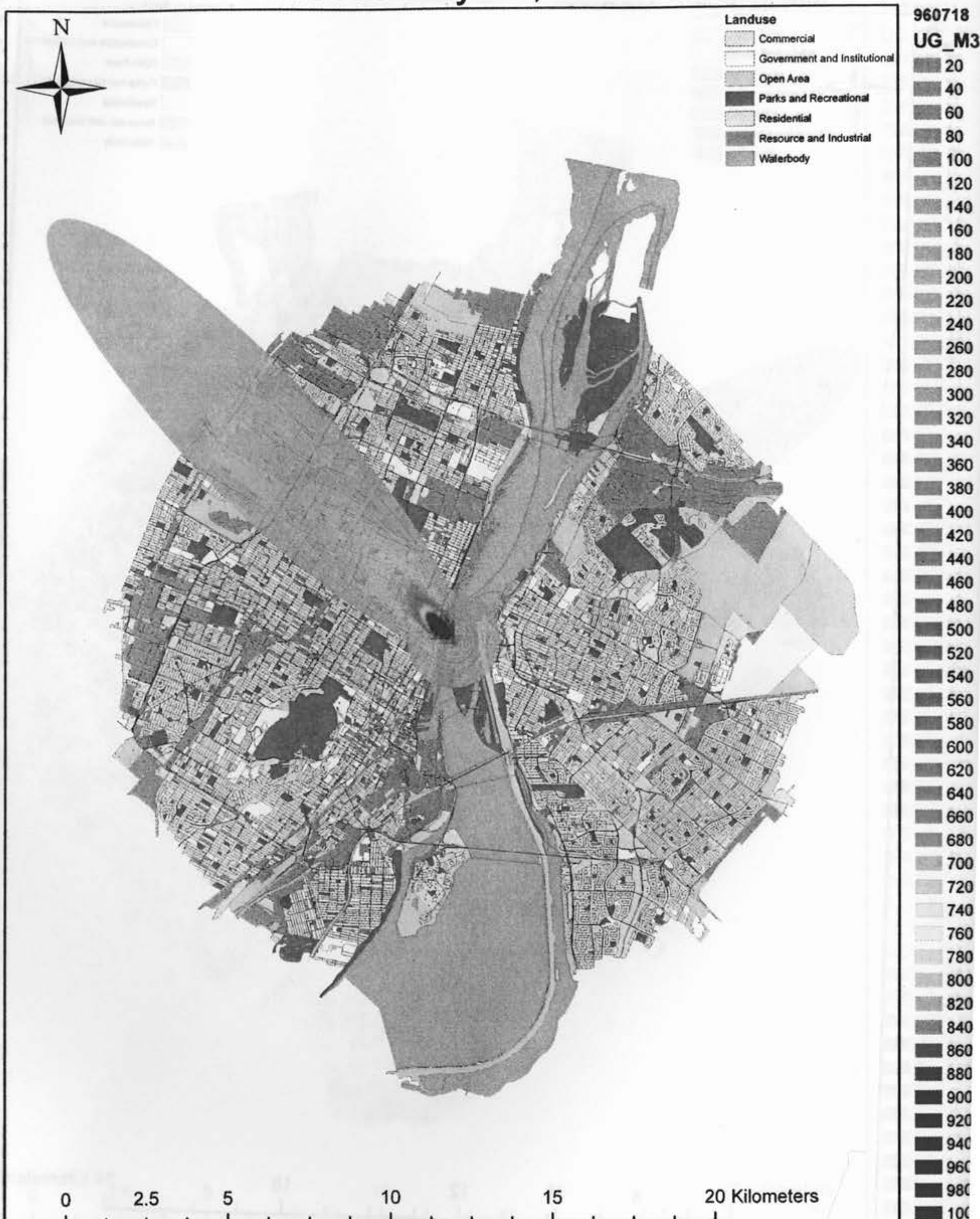
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 14, 1996



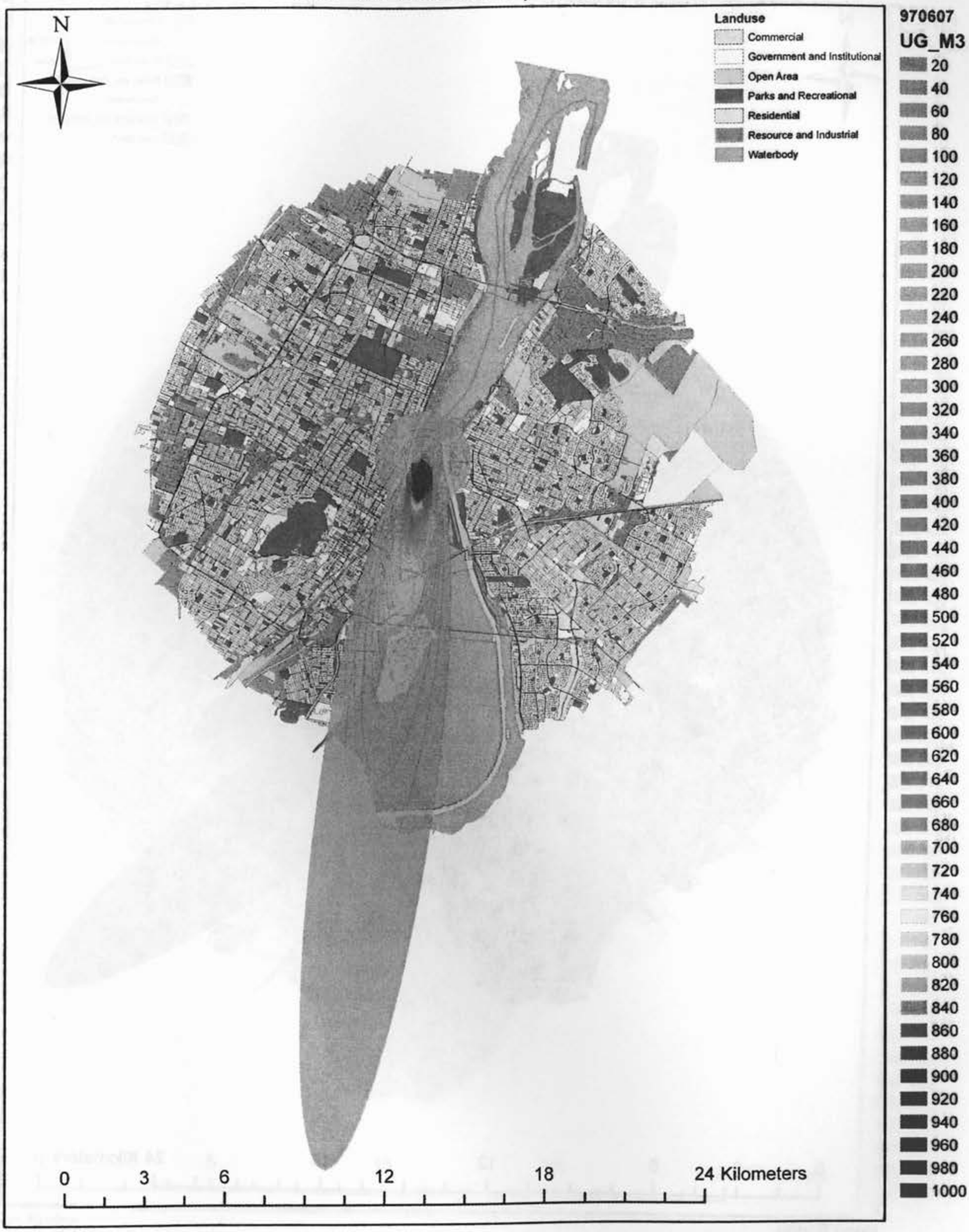
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 18, 1996



Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 7, 1997

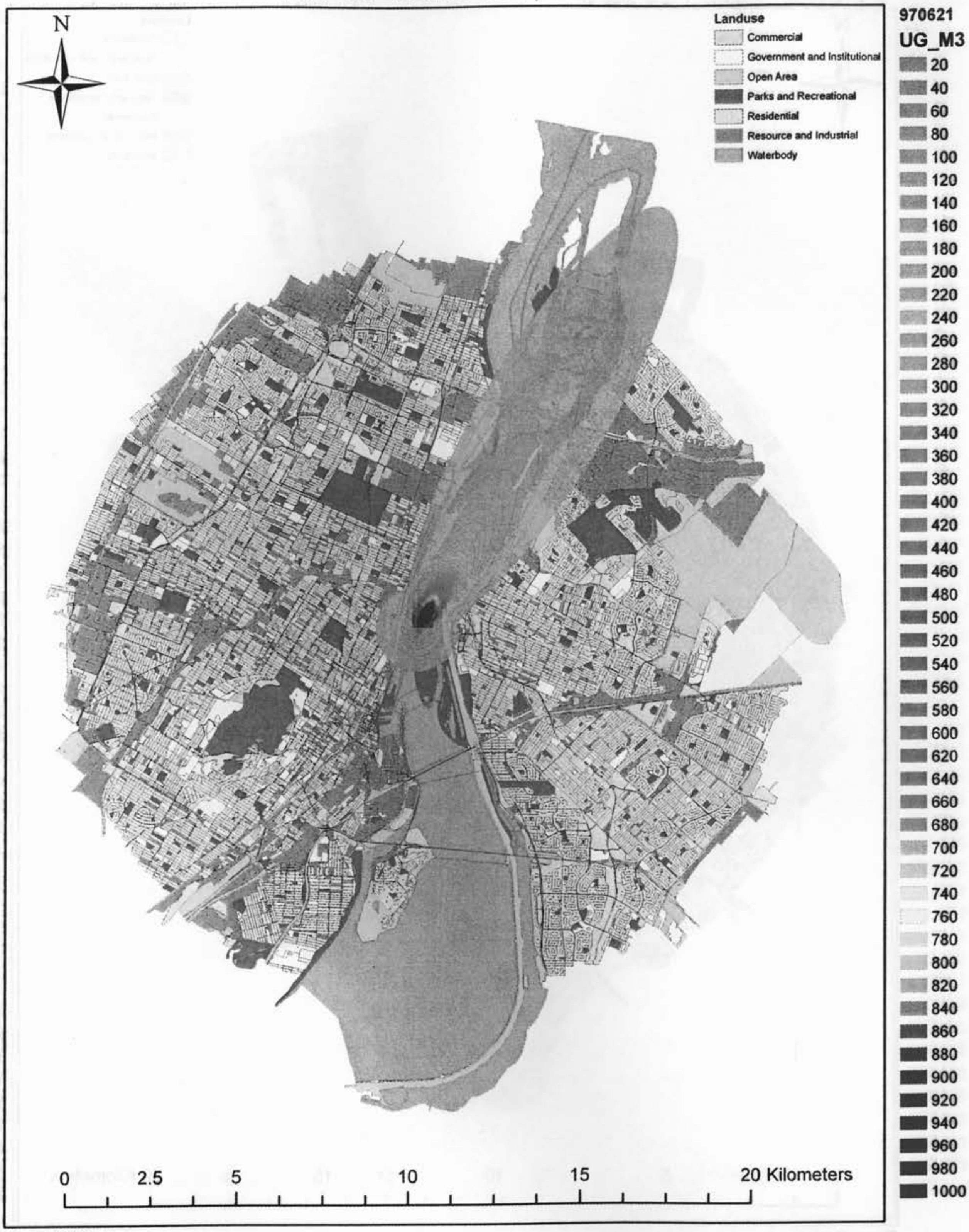


Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 14, 1997

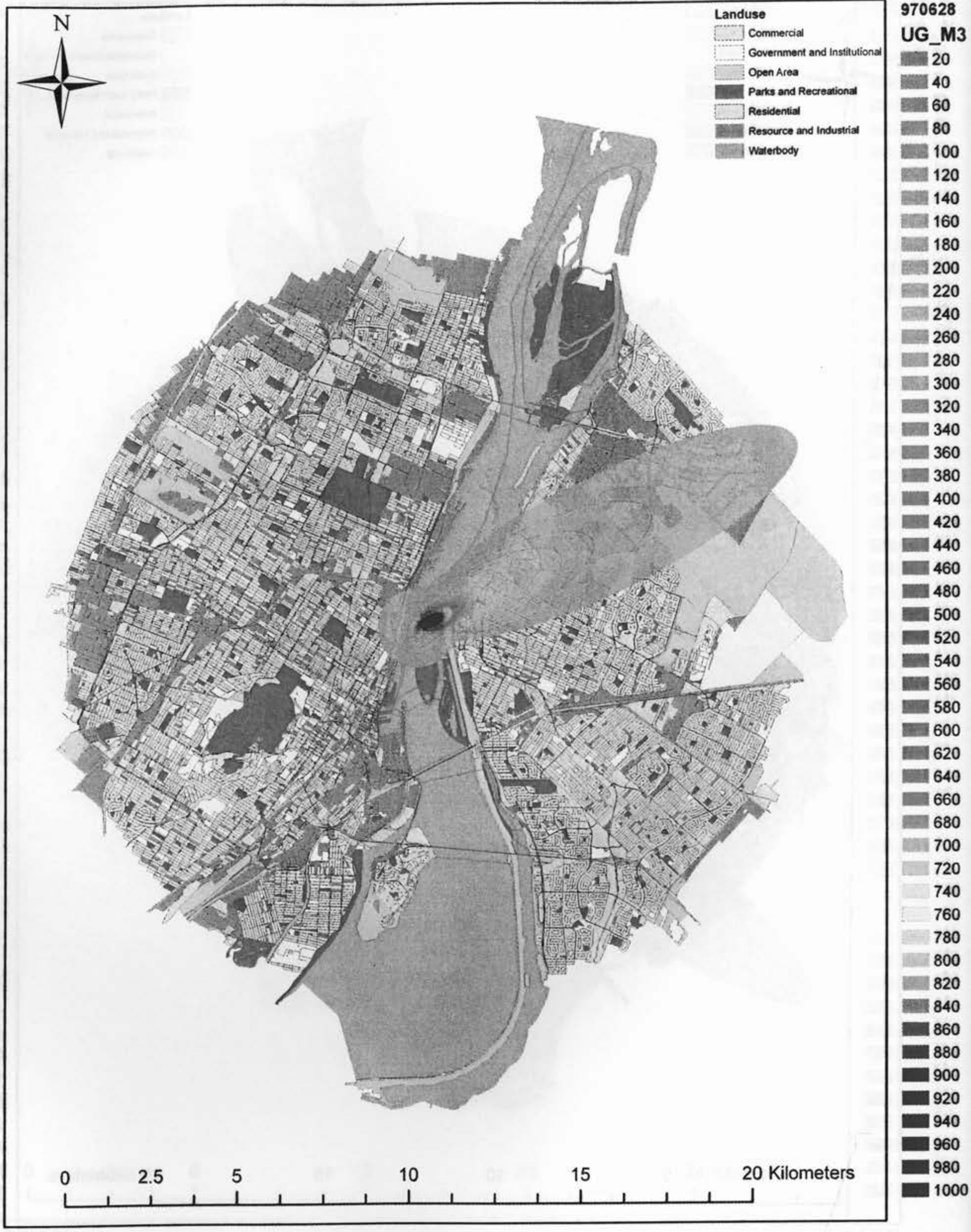
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 21, 1997



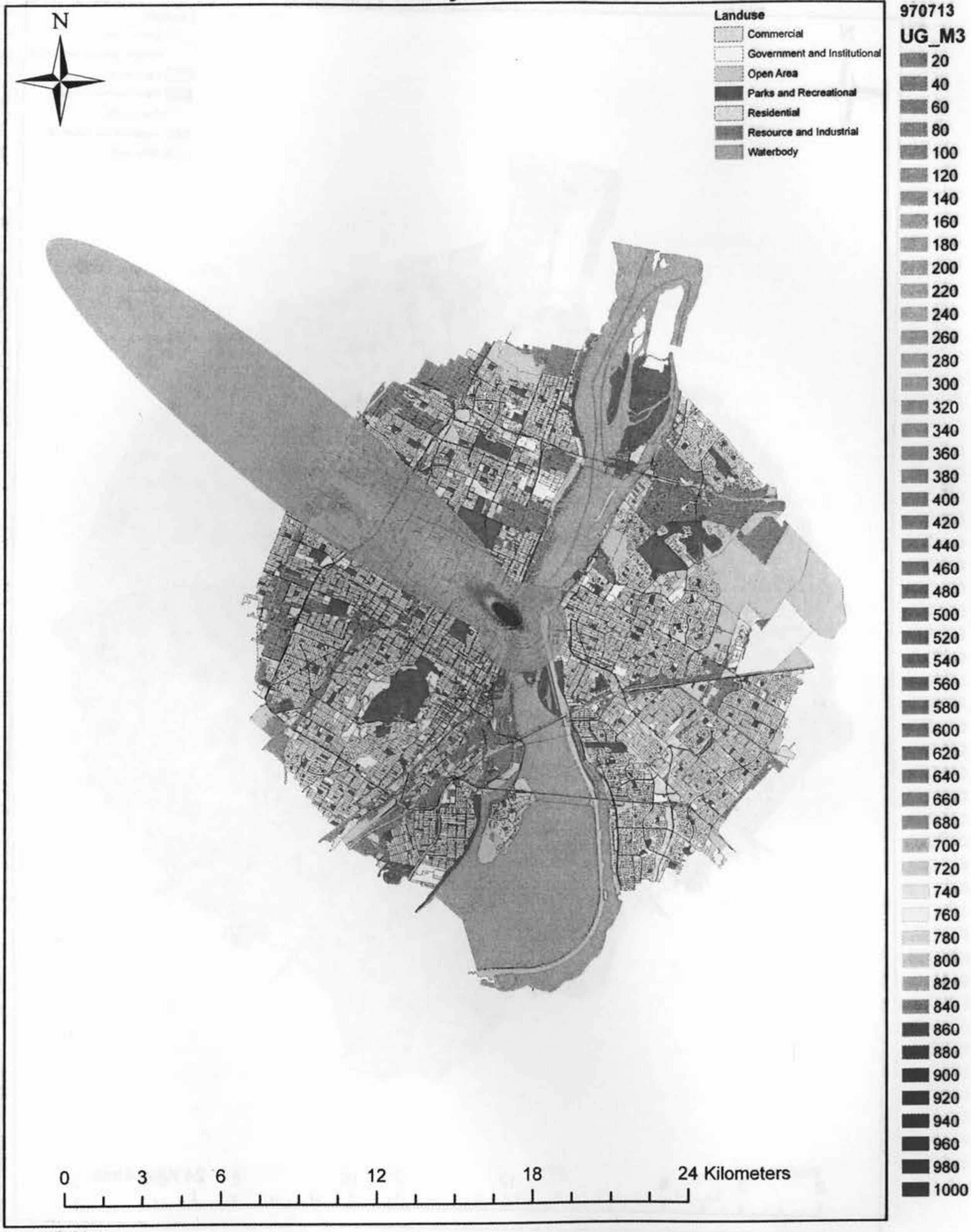
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 28, 1997



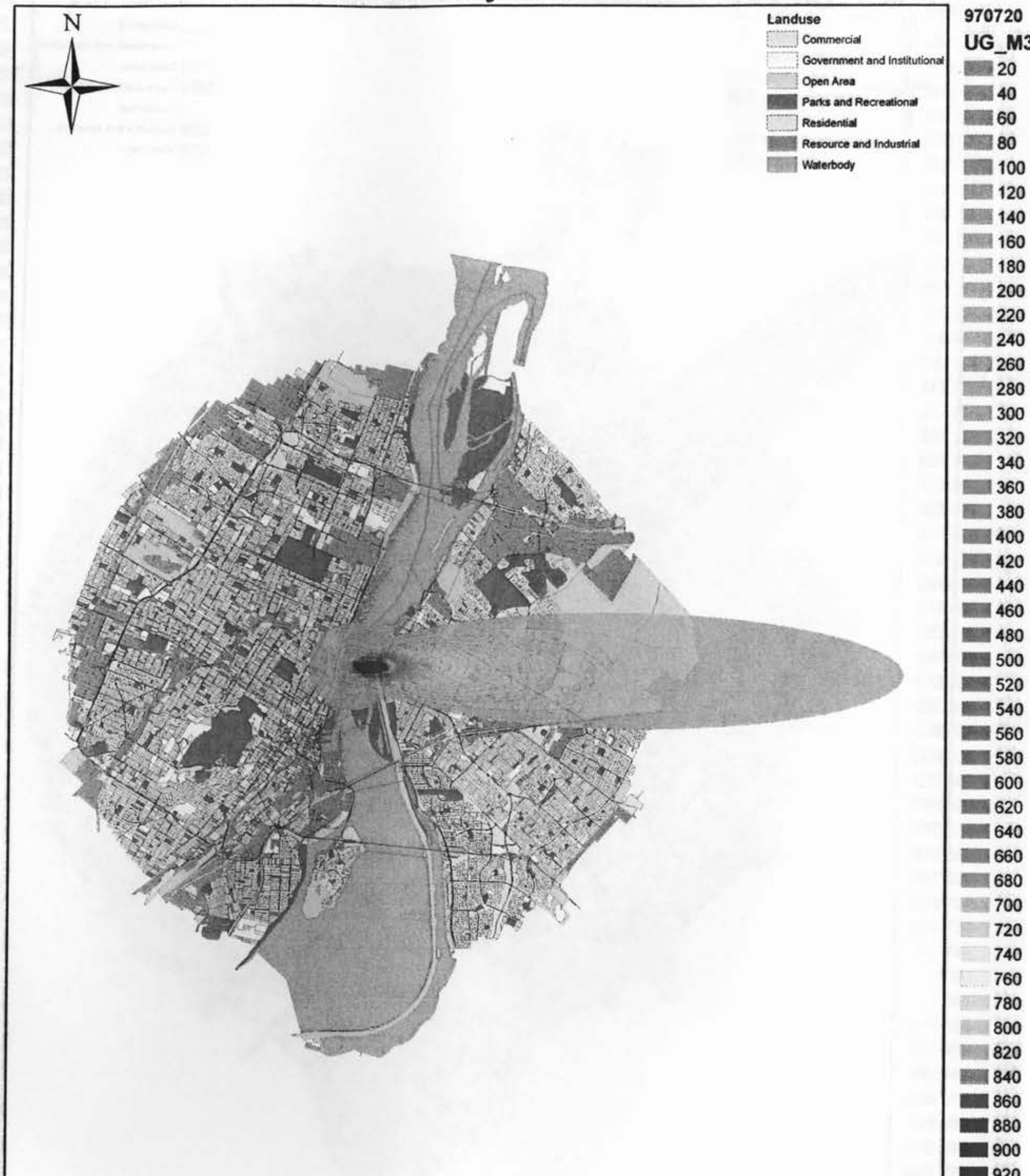
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 13, 1997



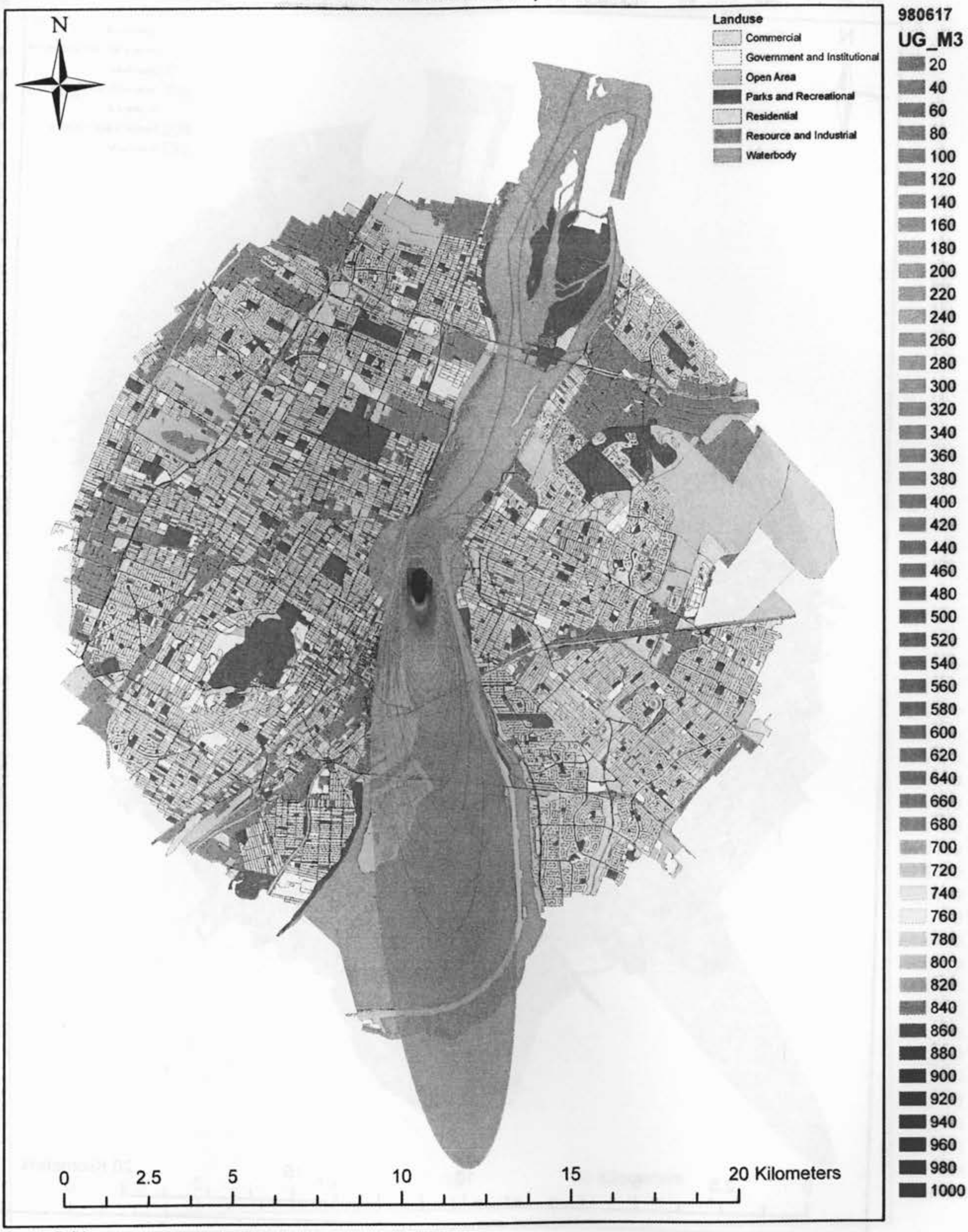
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 20, 1997



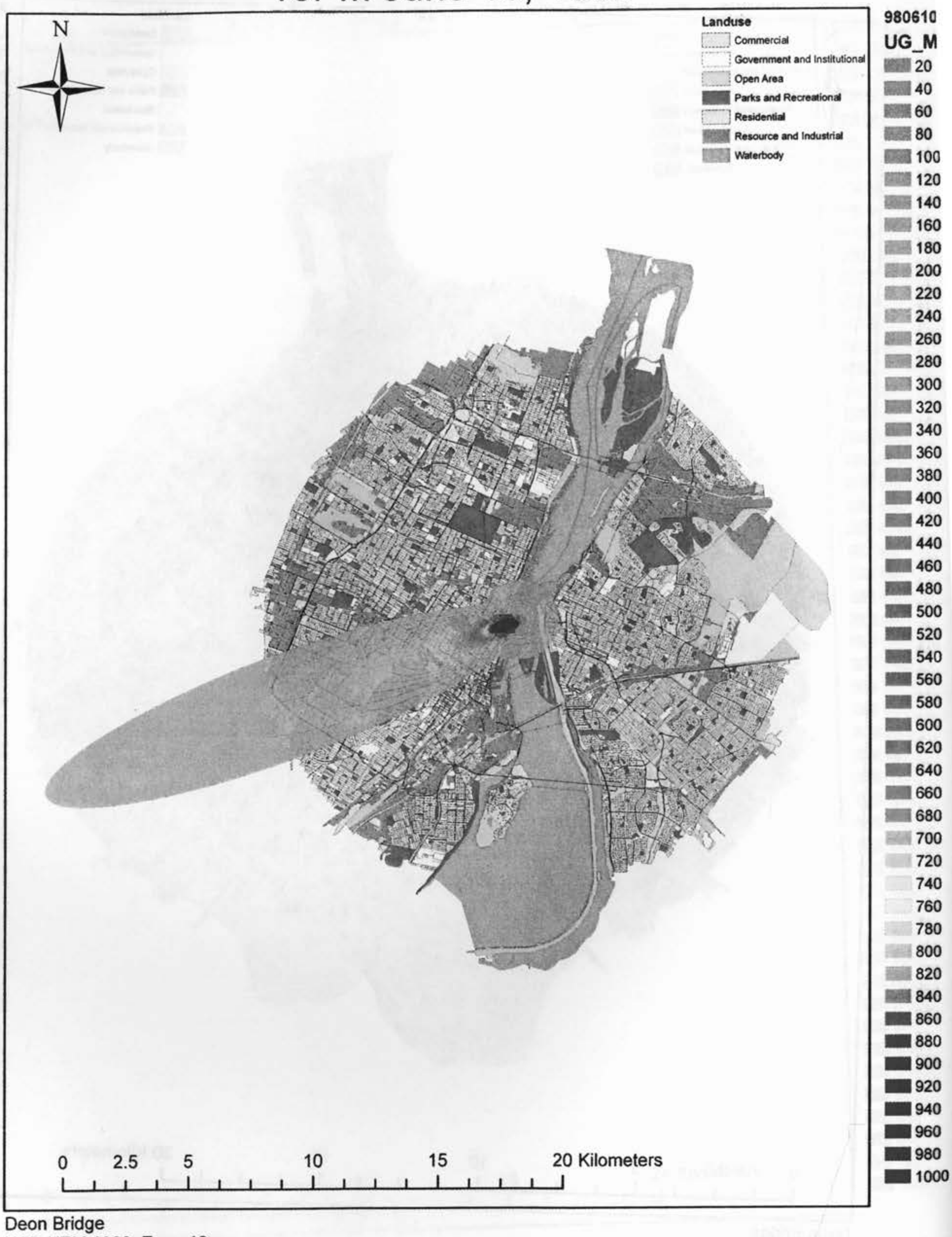
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 17, 1998



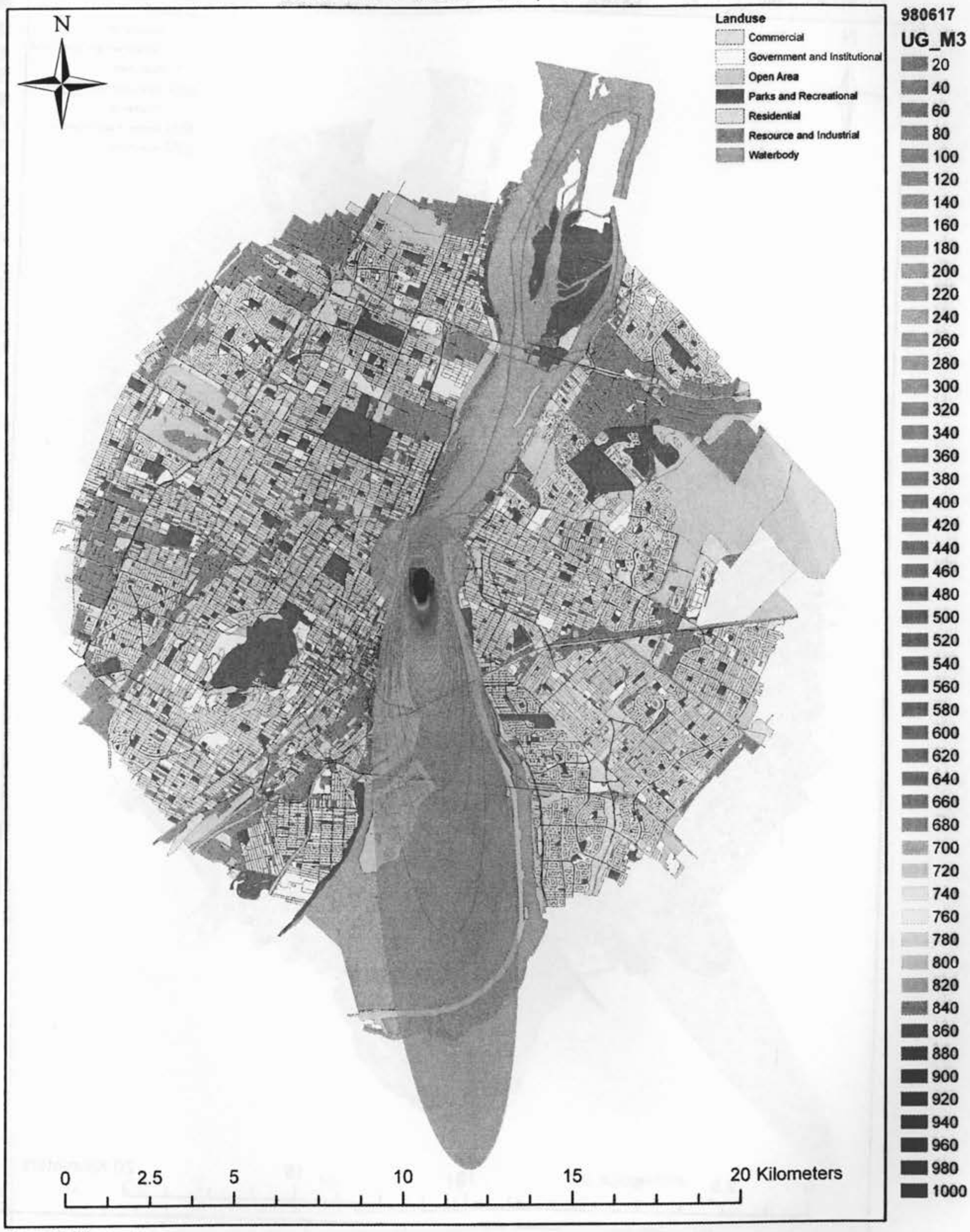
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 10, 1998



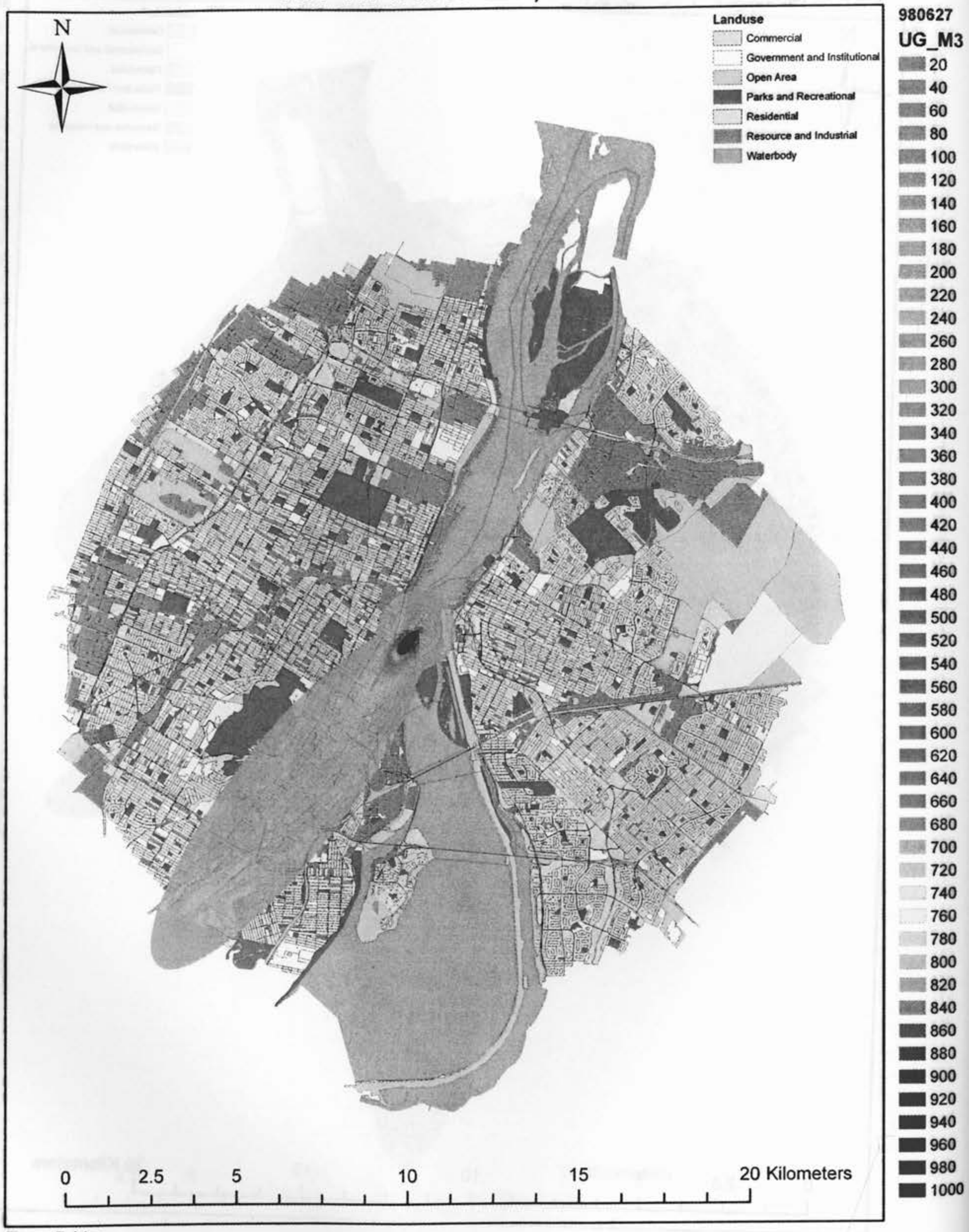
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 17, 1998

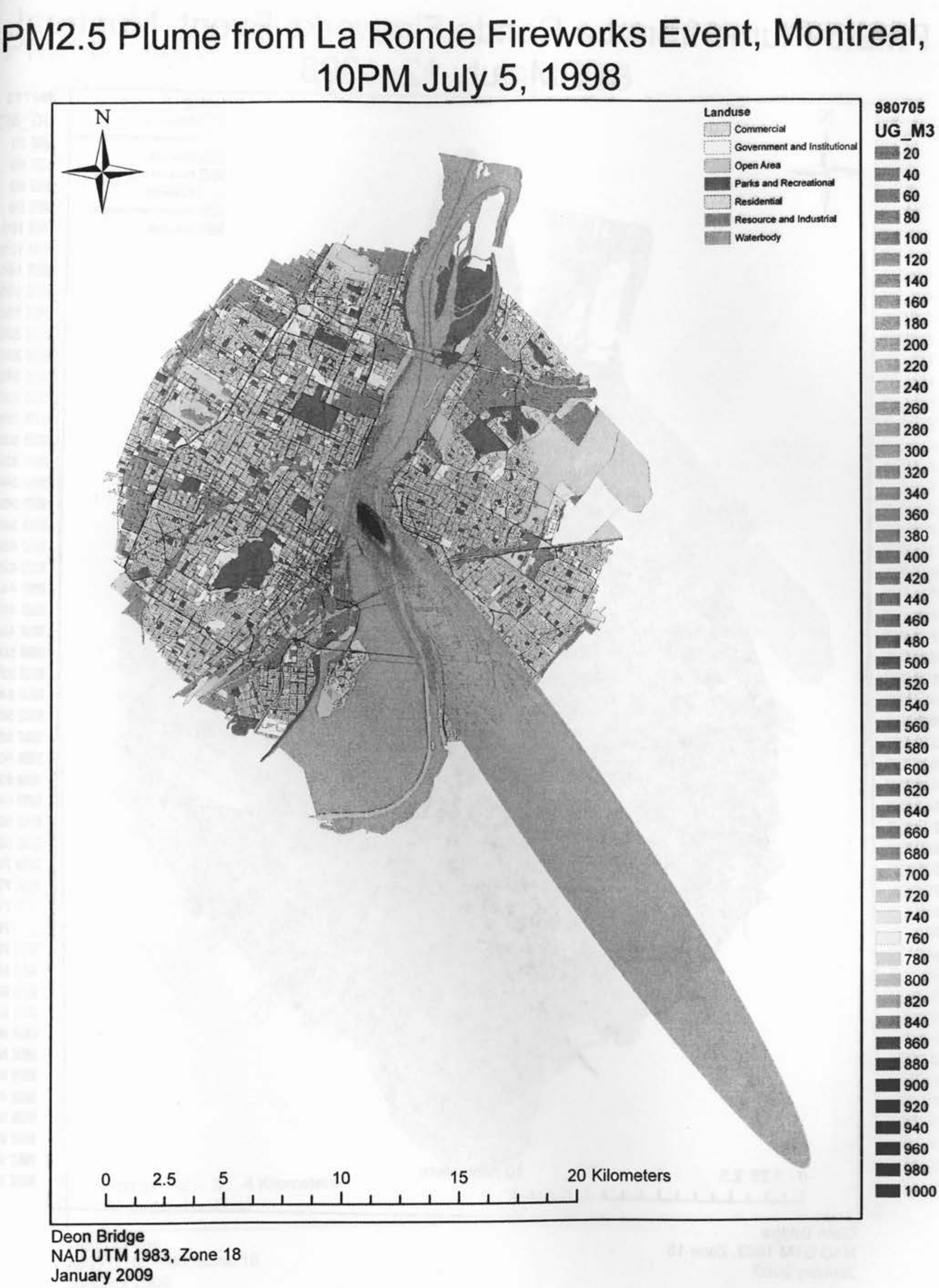


Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 27, 1998



Deon Bridge
NAD UTM 1983, Zone 18
January 2009


PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 5, 1998
N
Landuse
Commercial
Government and Institutional
Open Area
Parks and Recreational
Residential
Resource and Industrial
Waterbody
980705
UG_M3
20
40
60
80
100
120
140
160
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200
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540
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580
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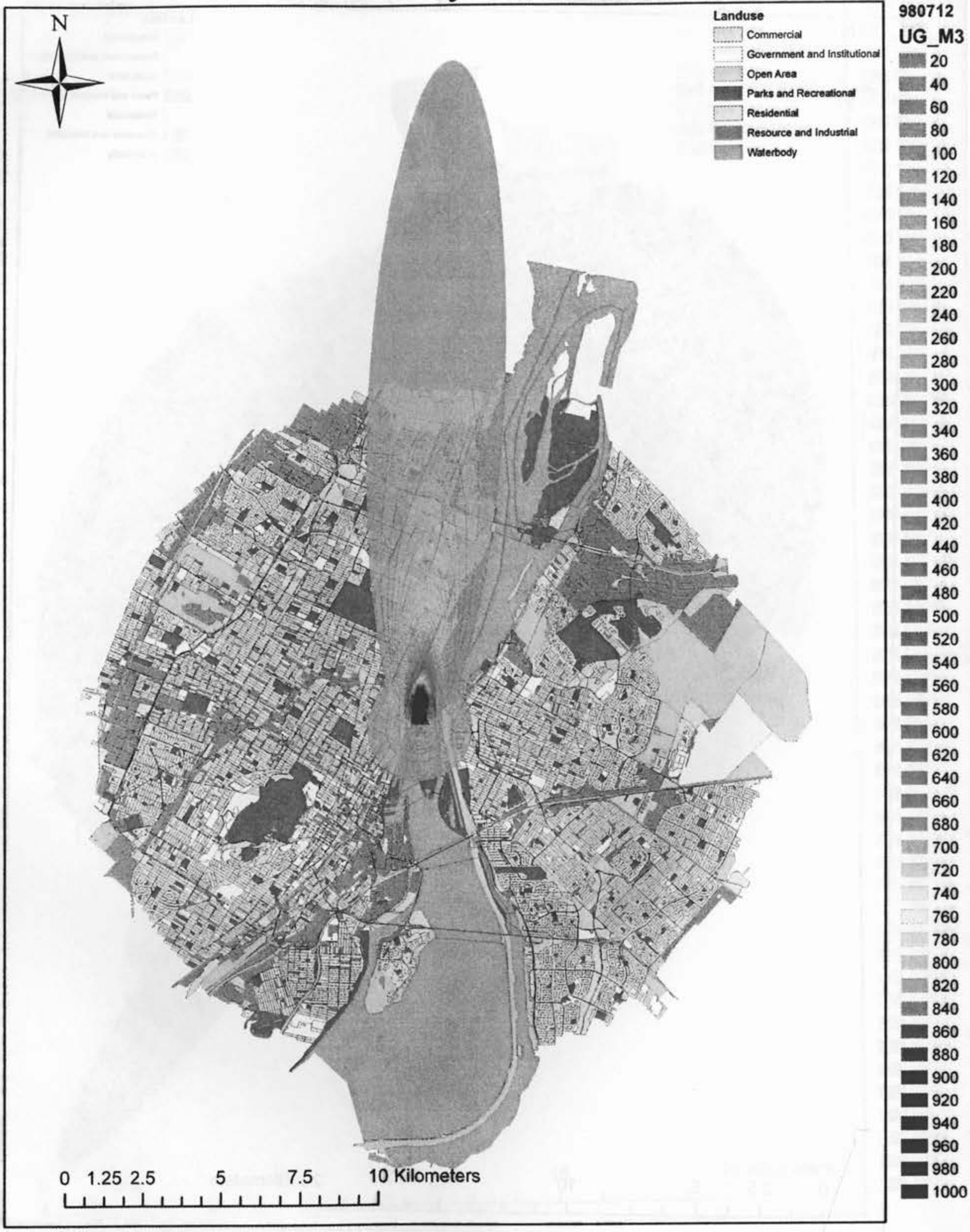
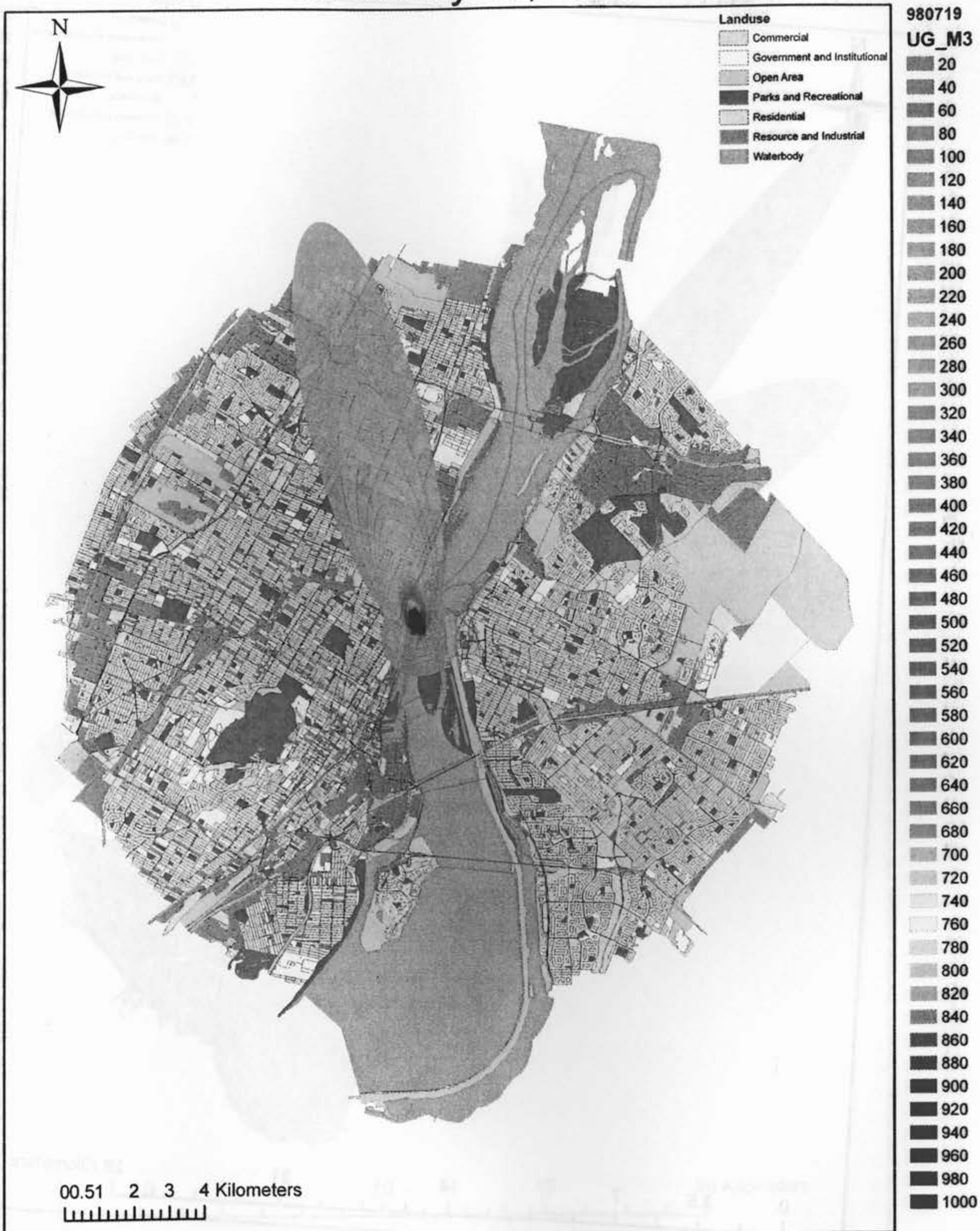
700
720
740
760
780
800
820
840
860
880
900
920
940
960
980
1000
0 2.5 5 10 15 20 Kilometers
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 12, 1998



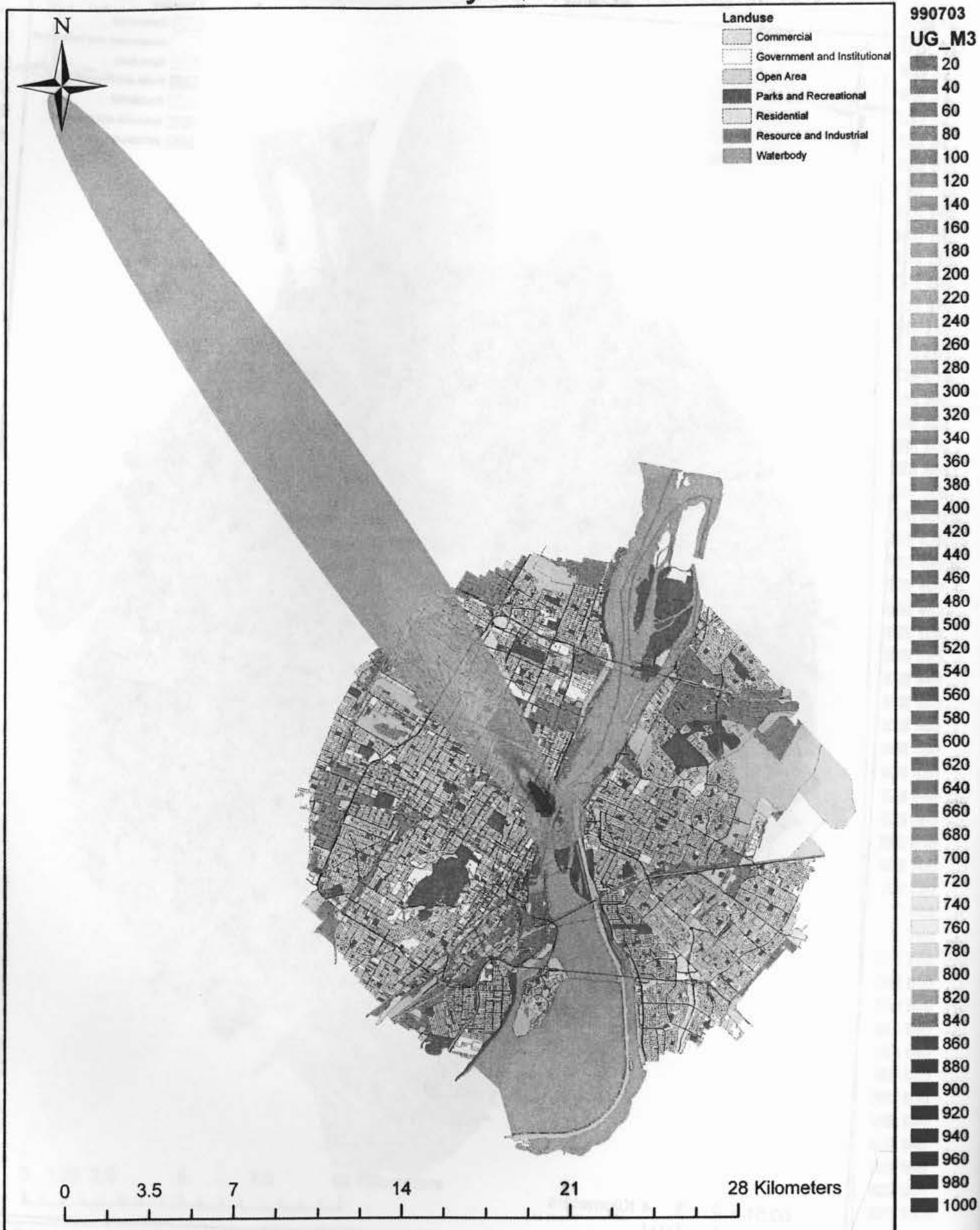
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 19, 1998



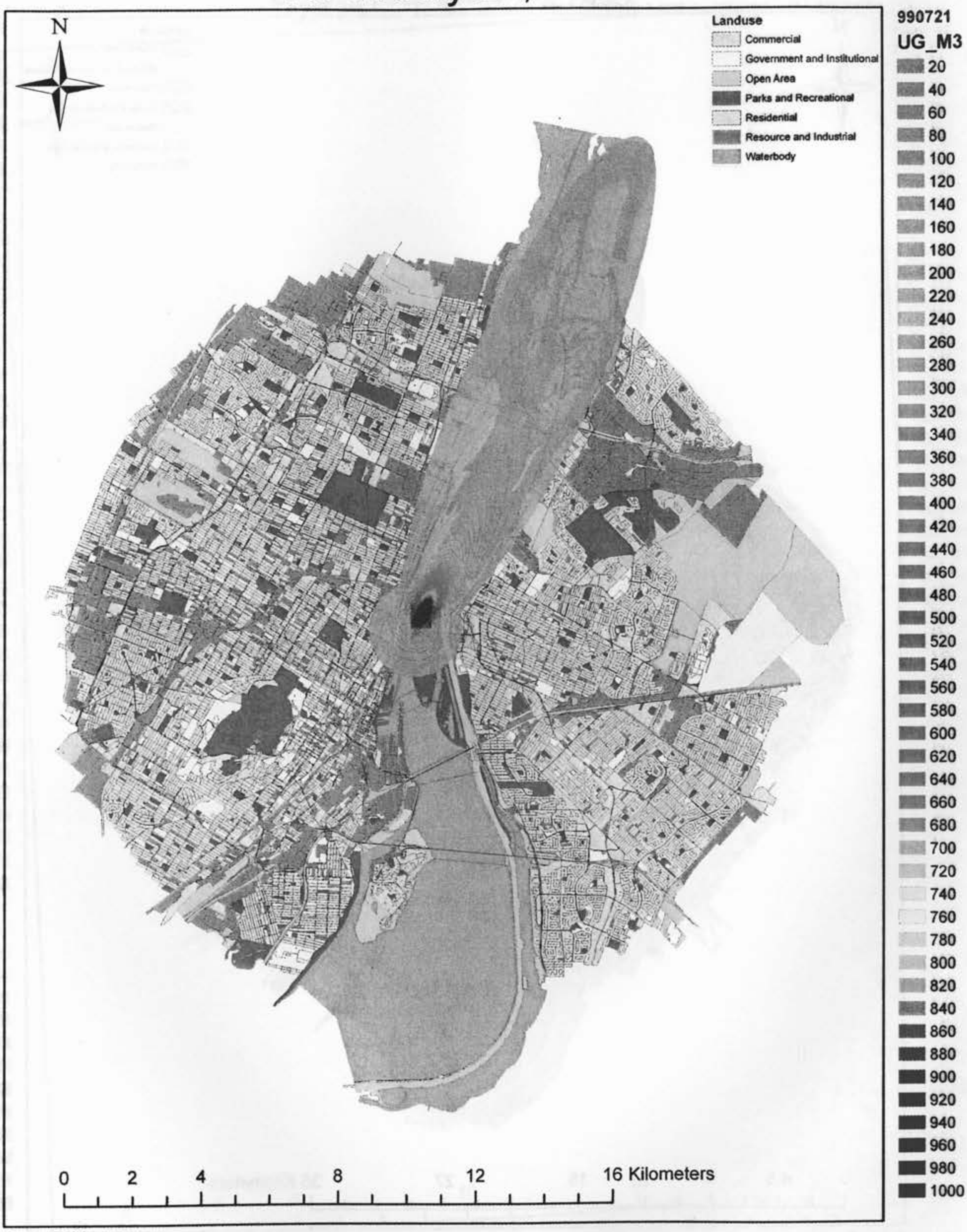
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 3, 1999



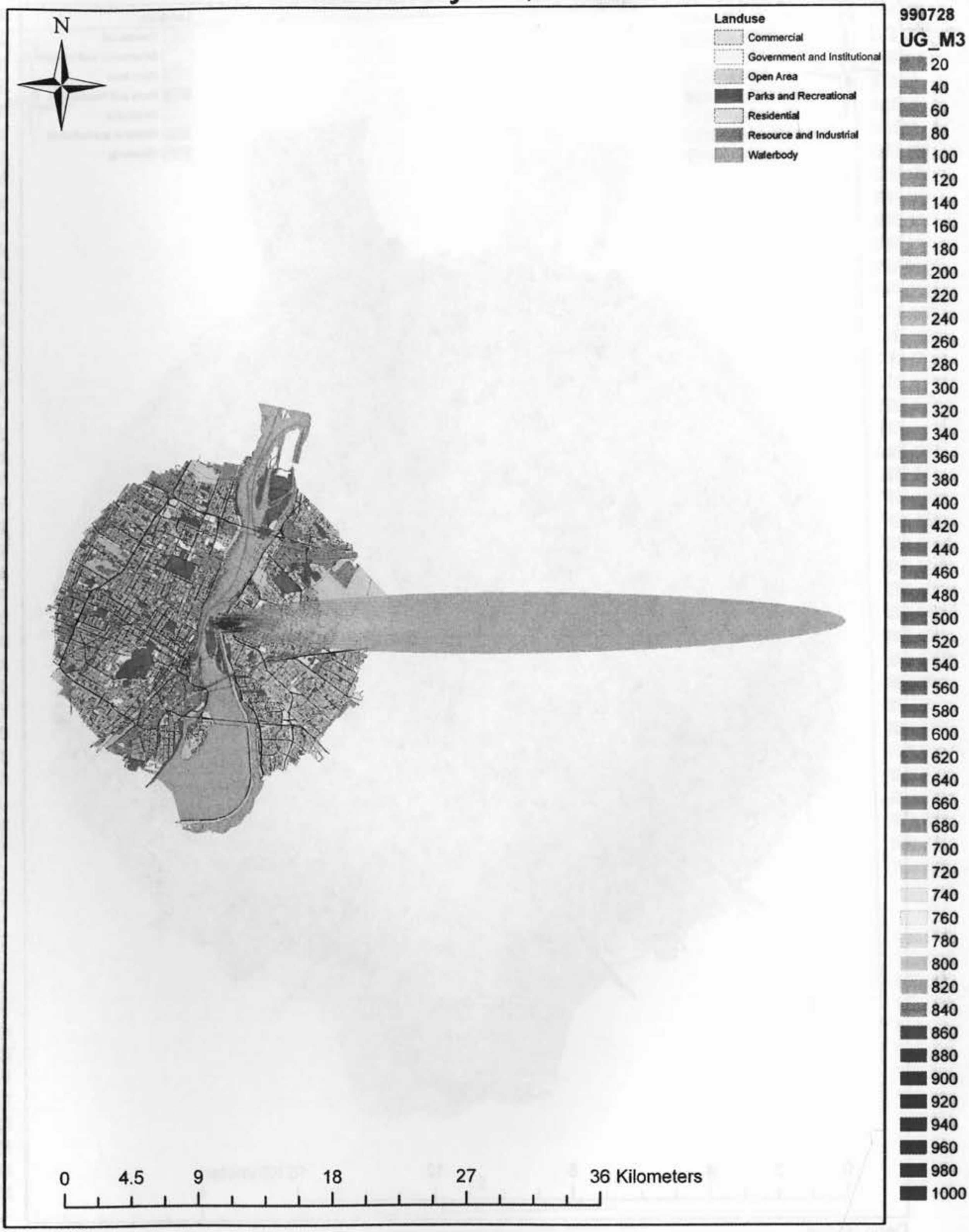
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 21, 1999



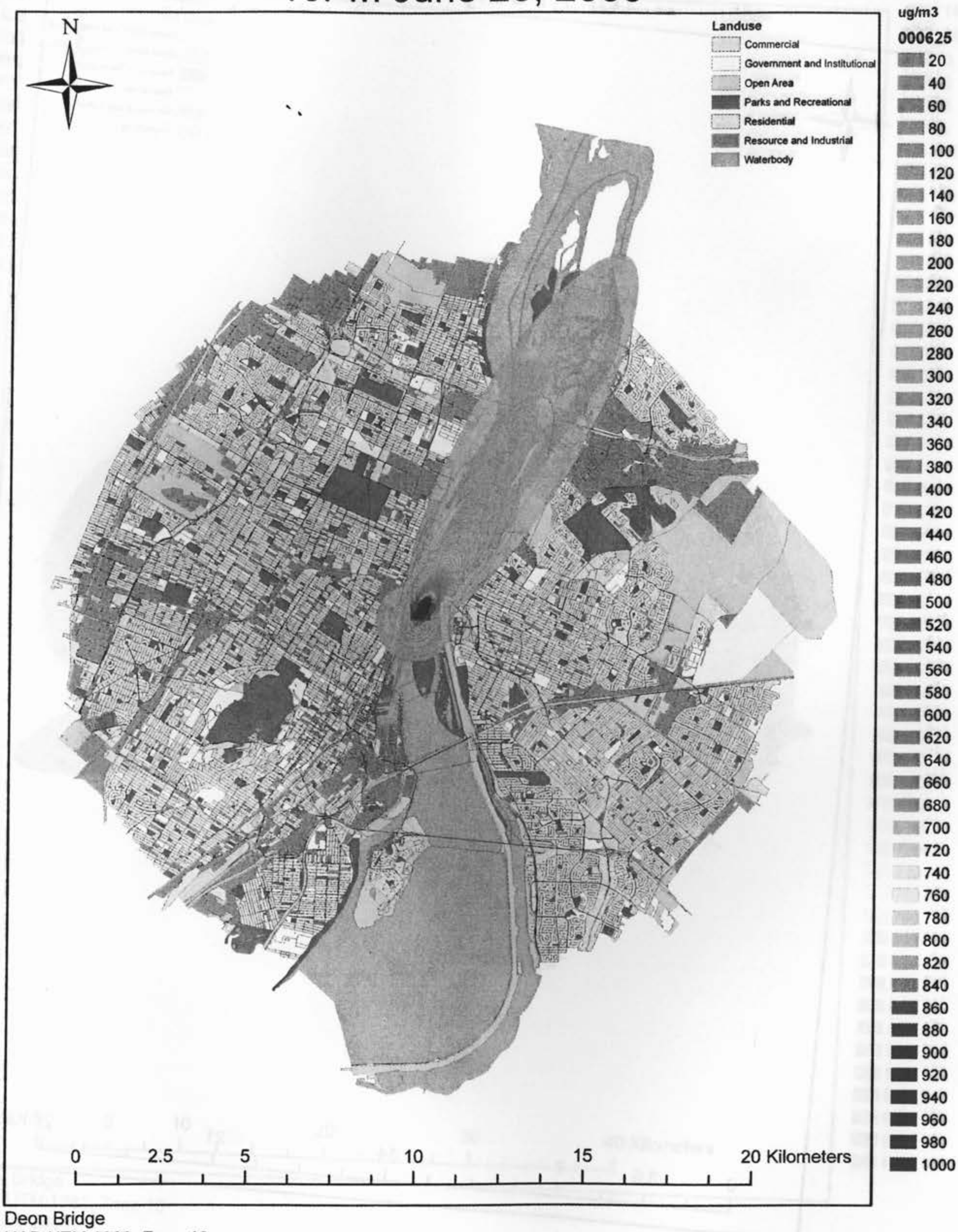
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 28, 1999



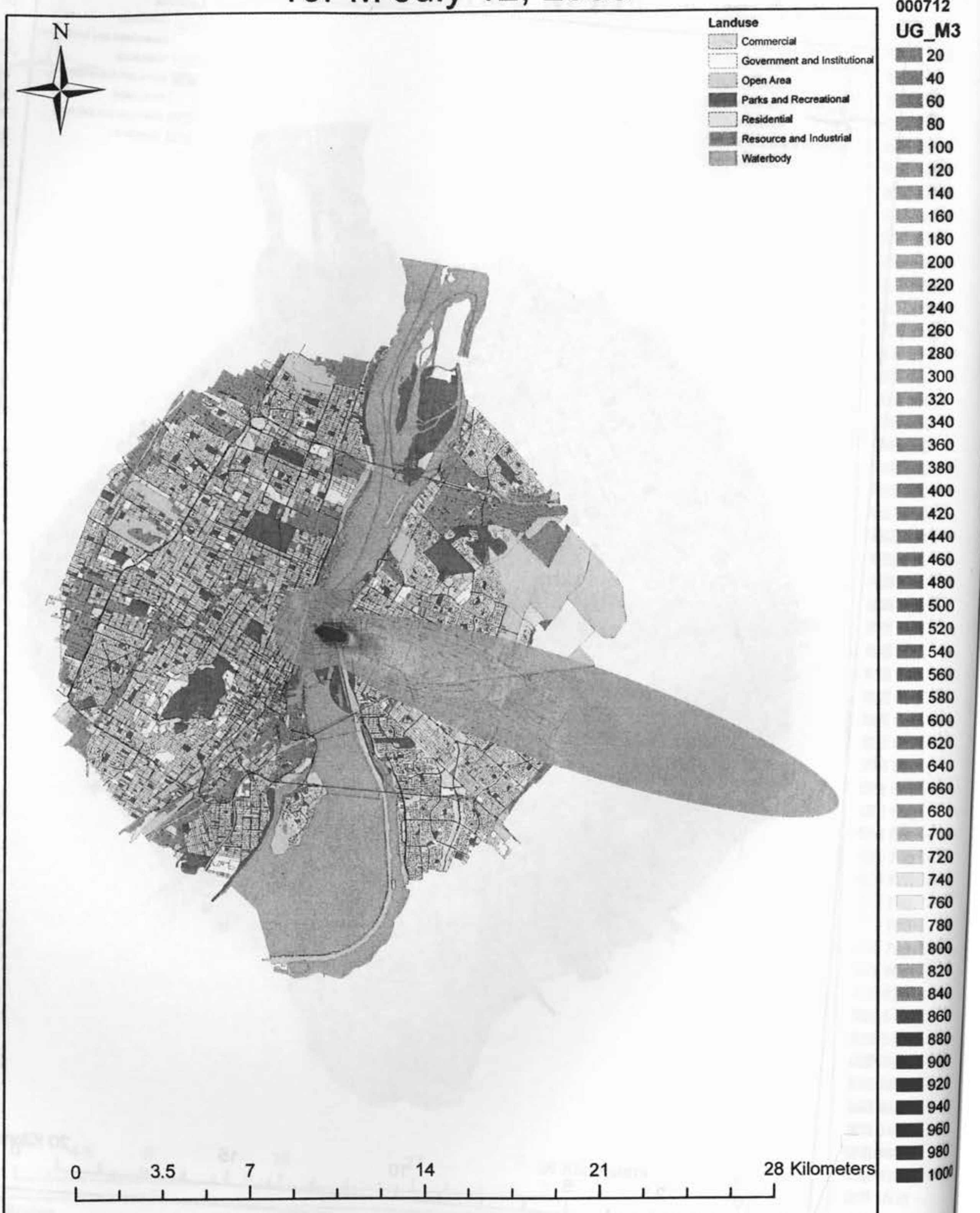
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 25, 2000



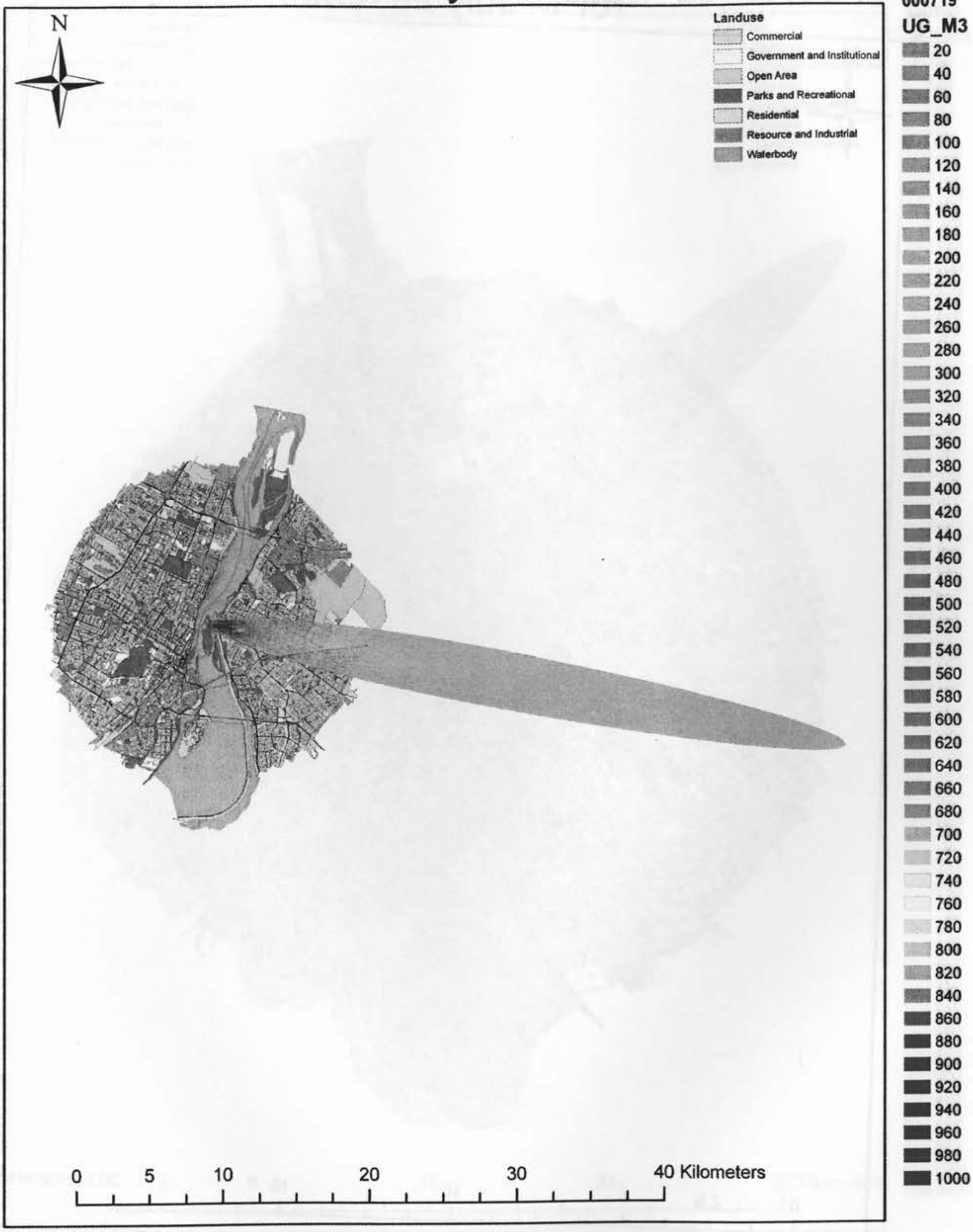
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 12, 2000



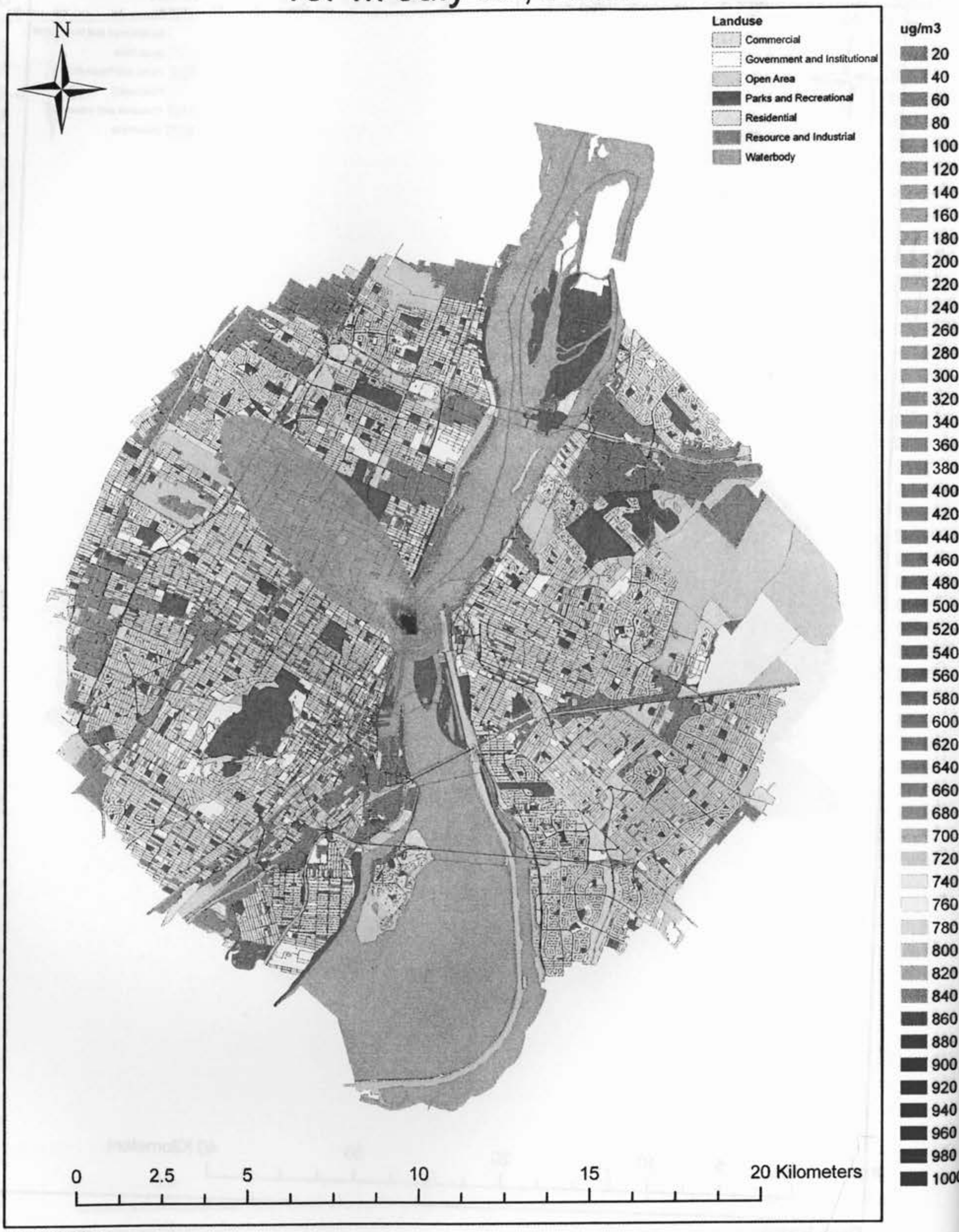
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 19, 2000



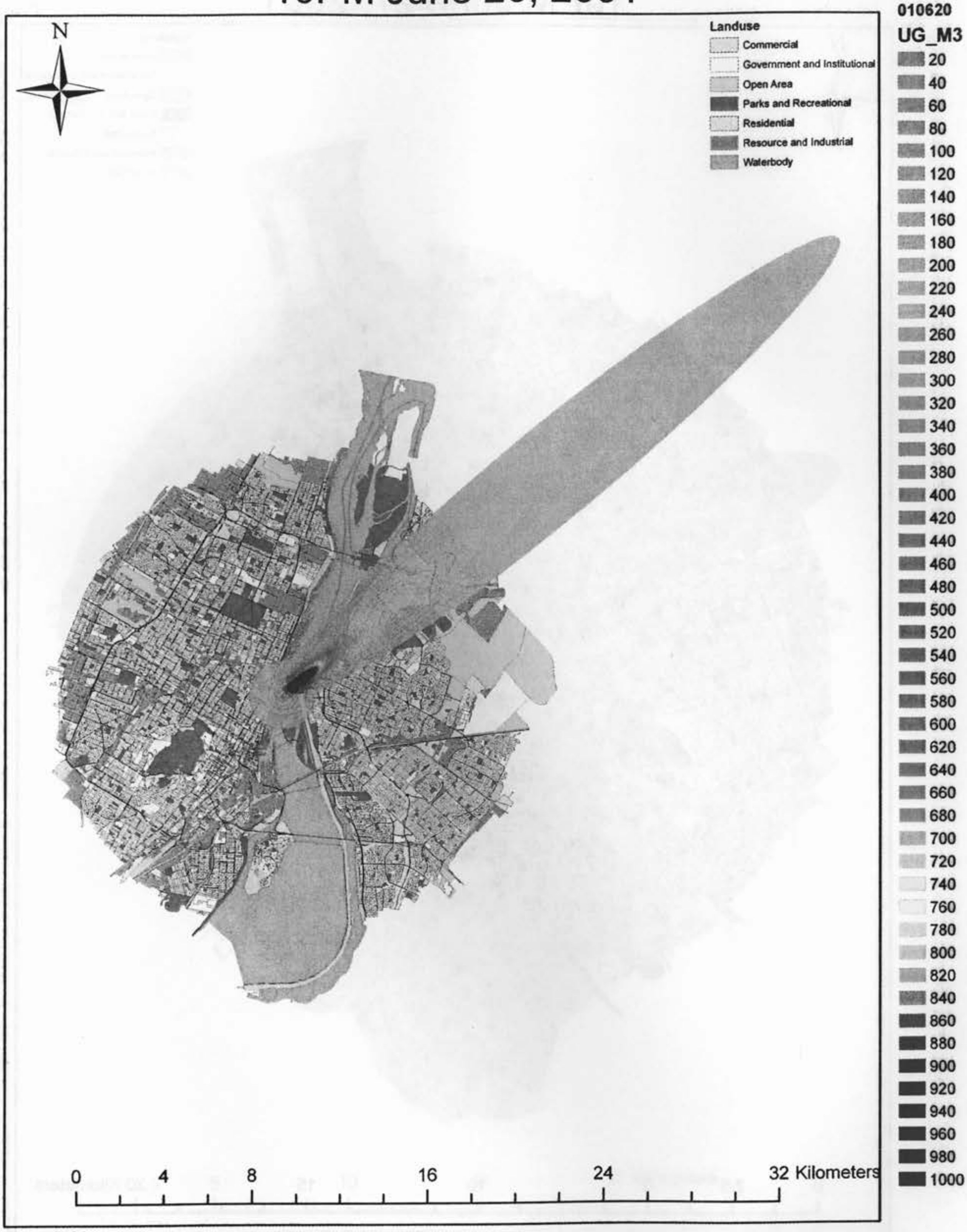
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 26, 2000



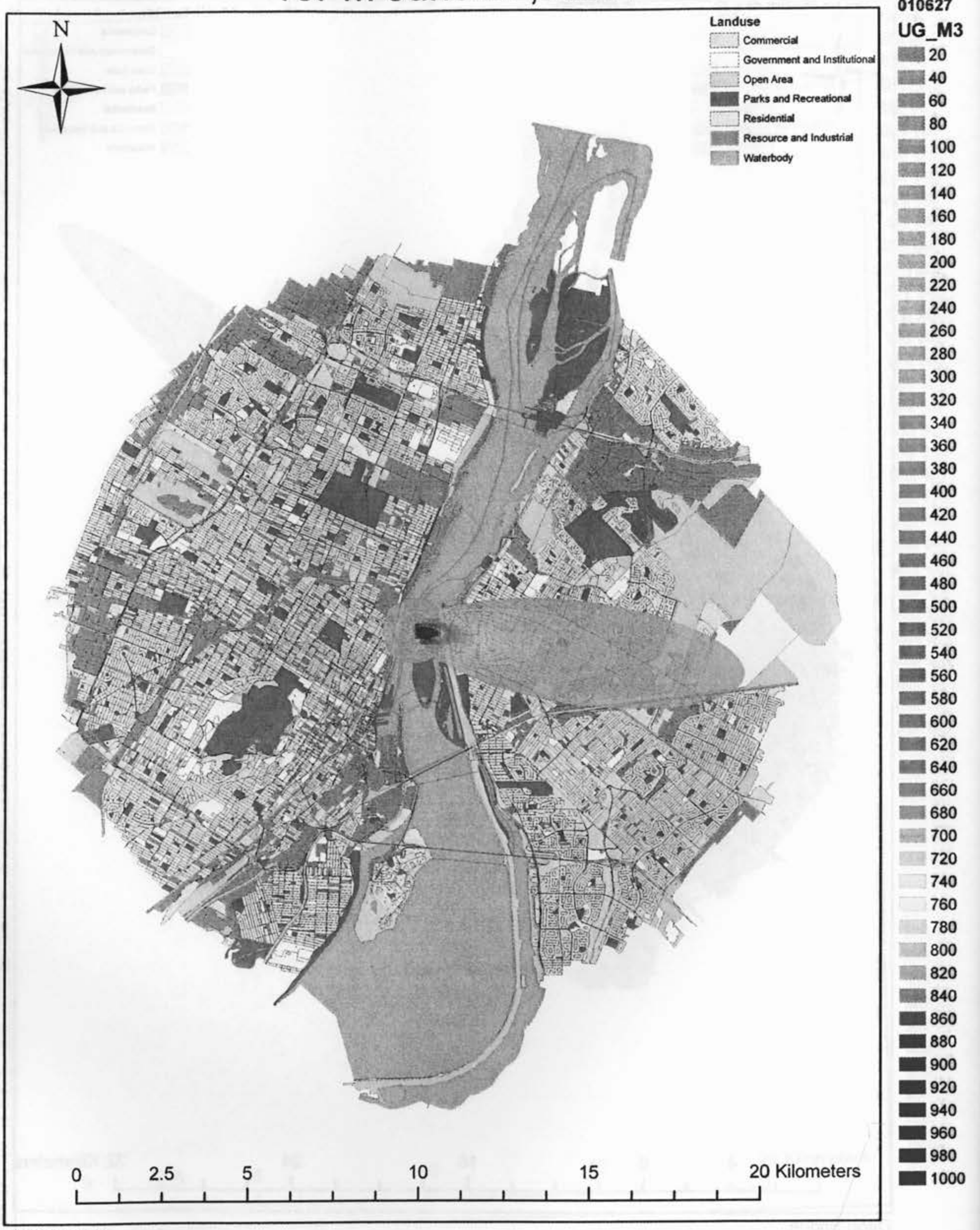
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 20, 2001



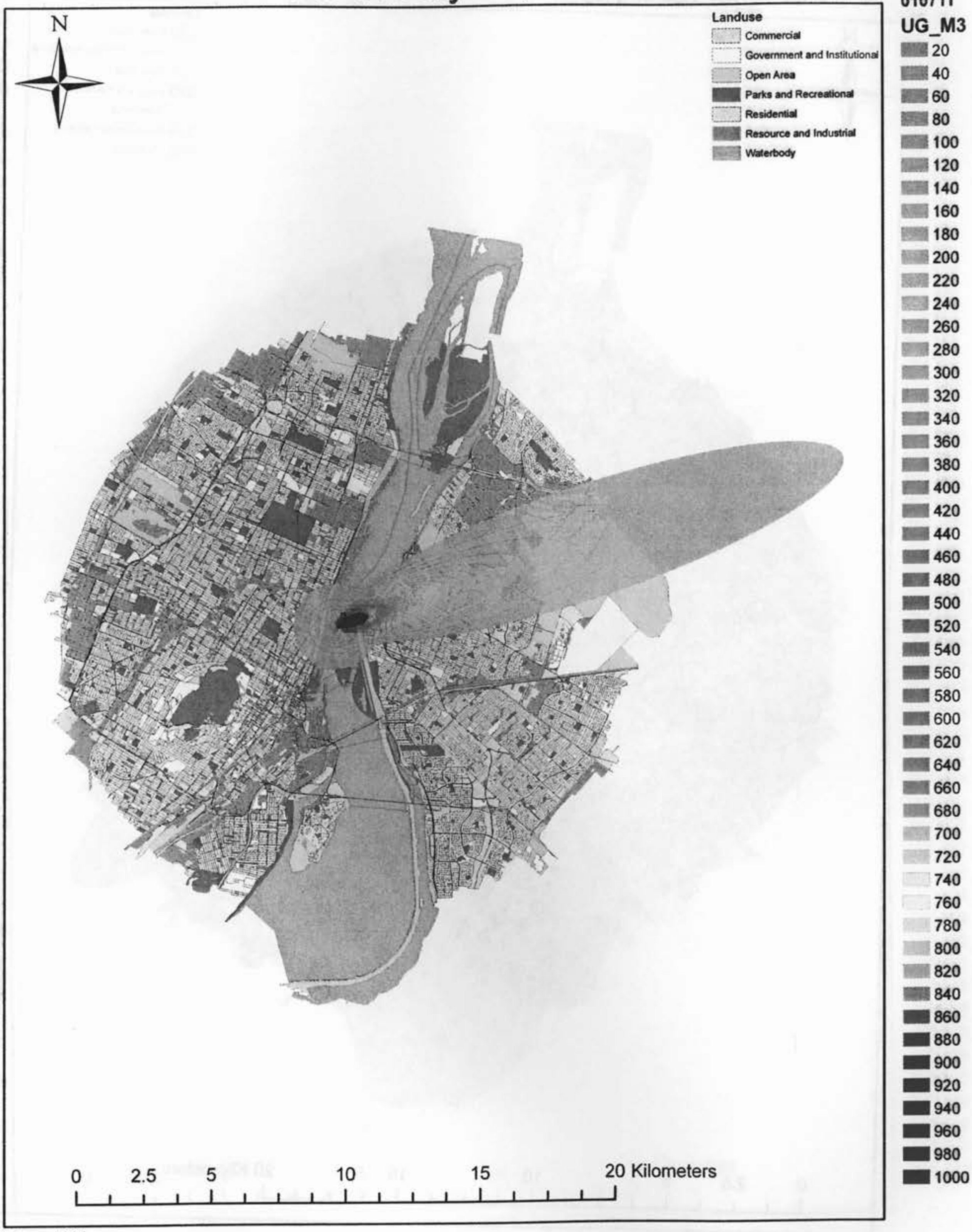
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 27, 2001



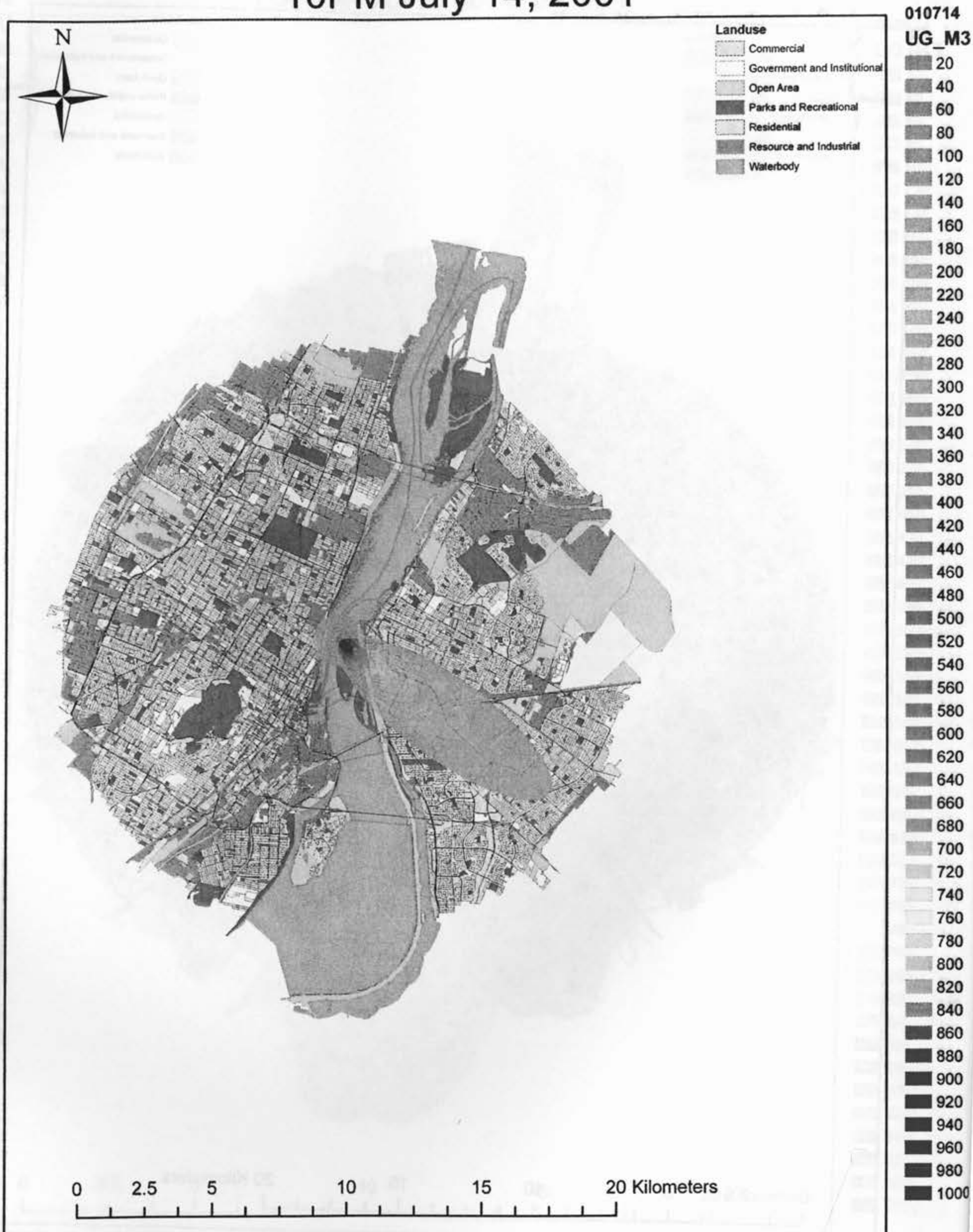
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 11, 2001



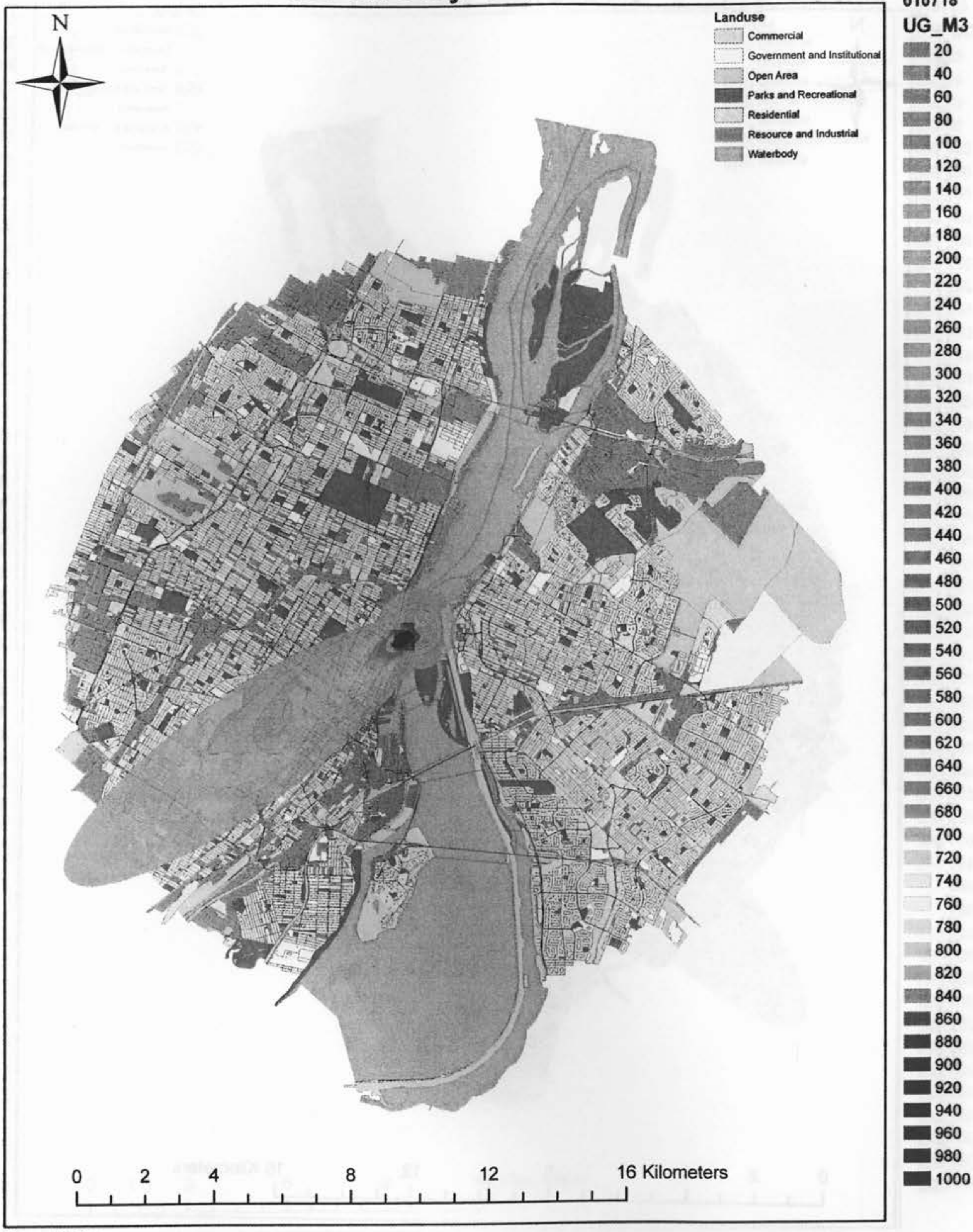
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 14, 2001



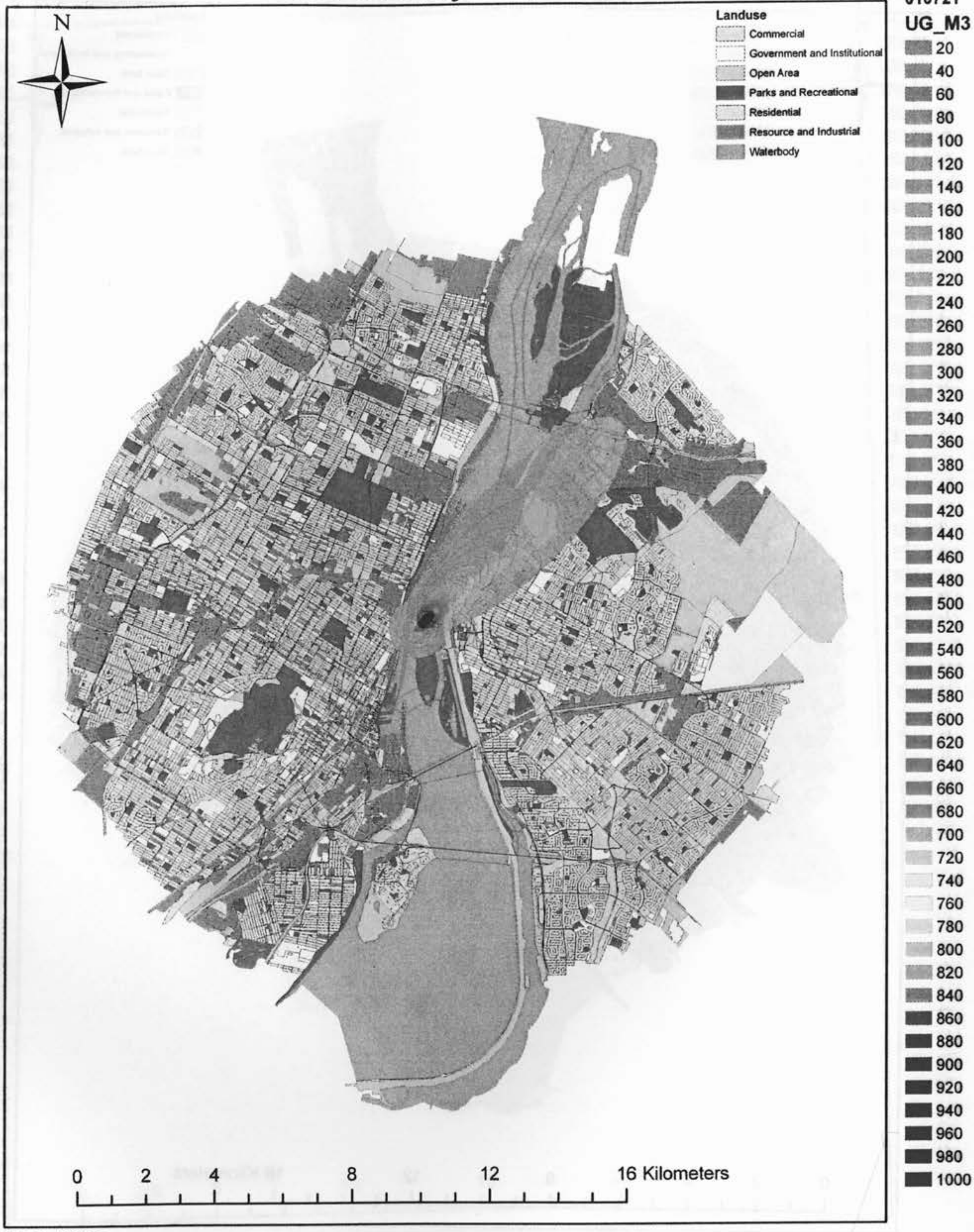
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 18, 2001



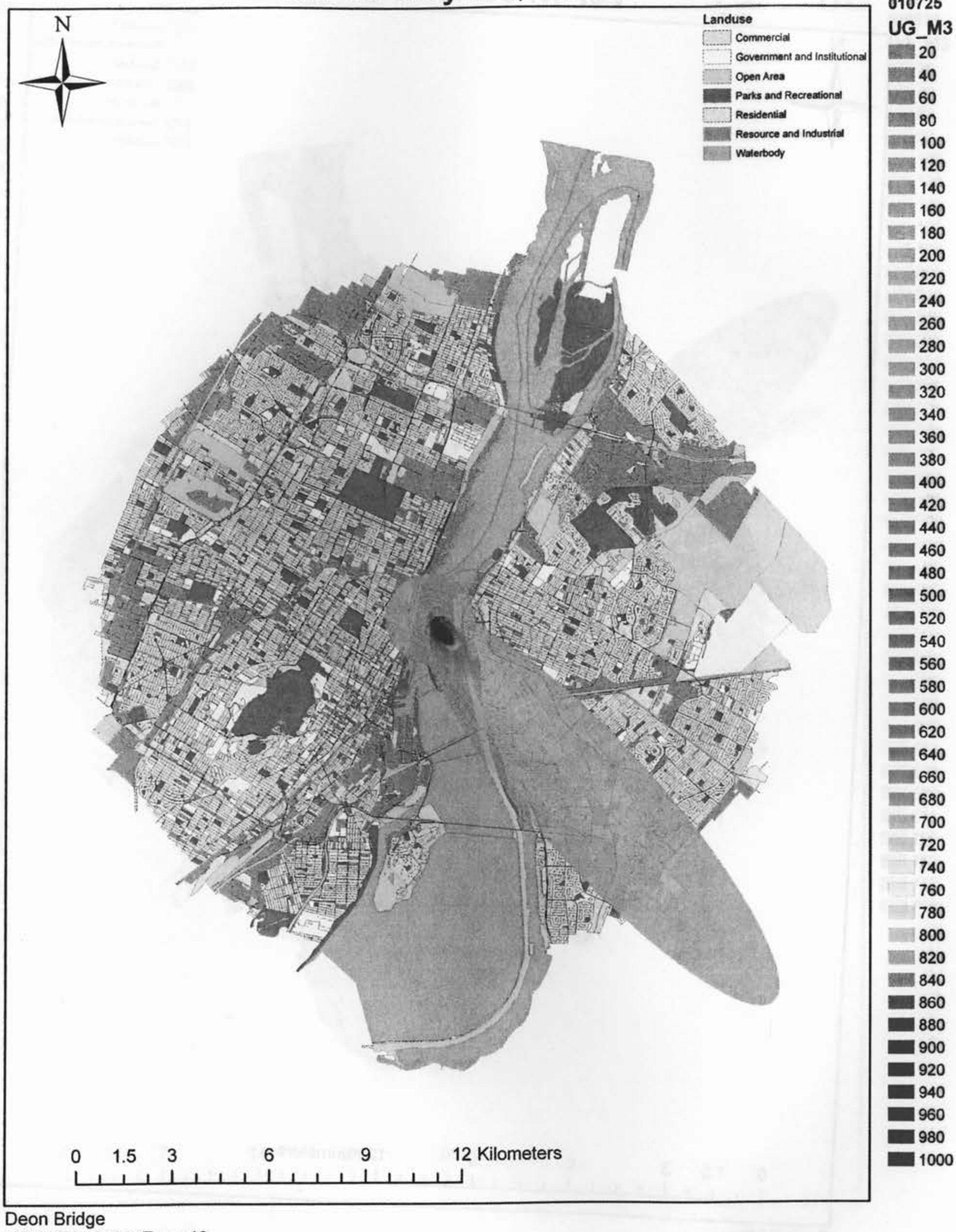
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 21, 2001



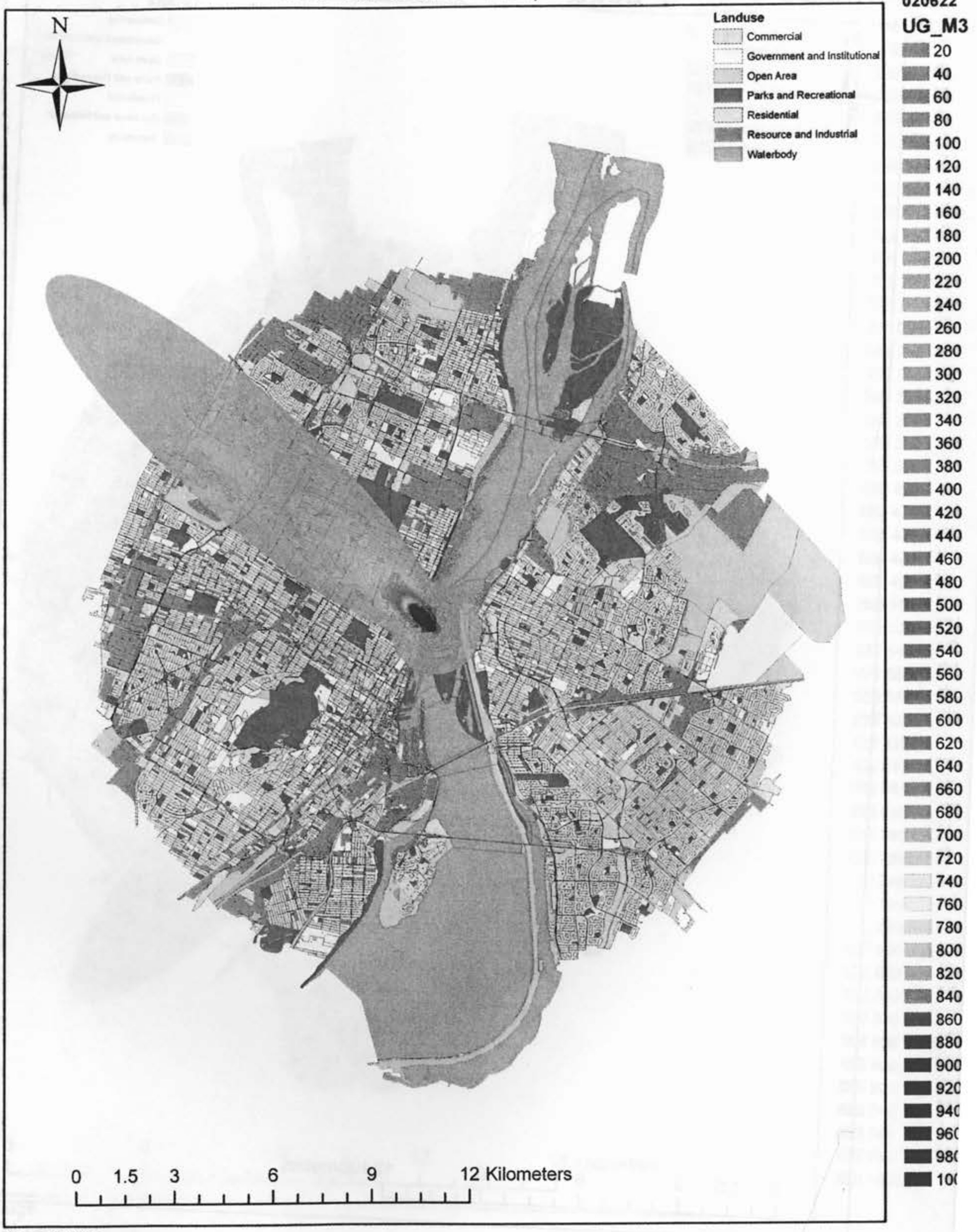
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 25, 2001



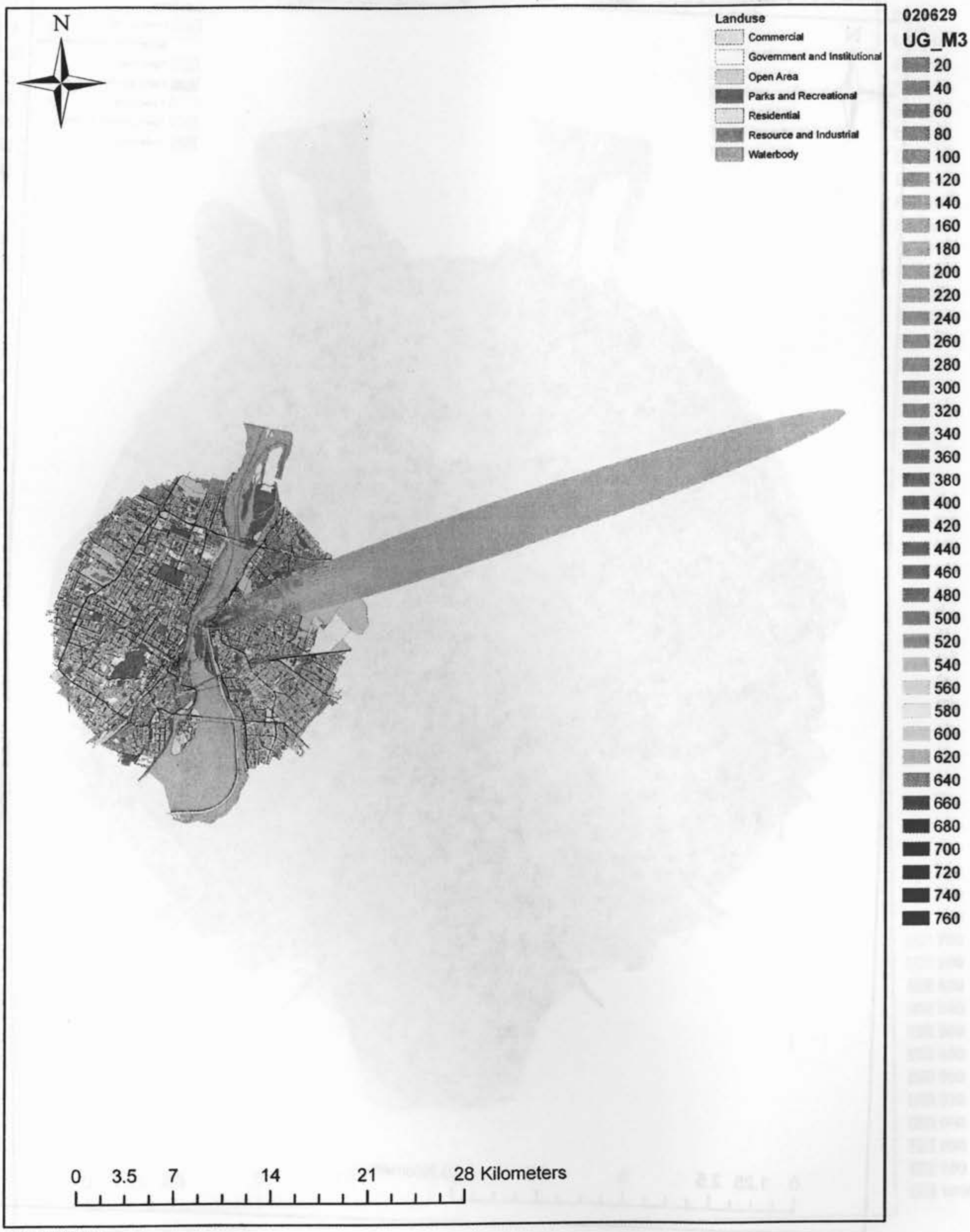
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 22, 2002



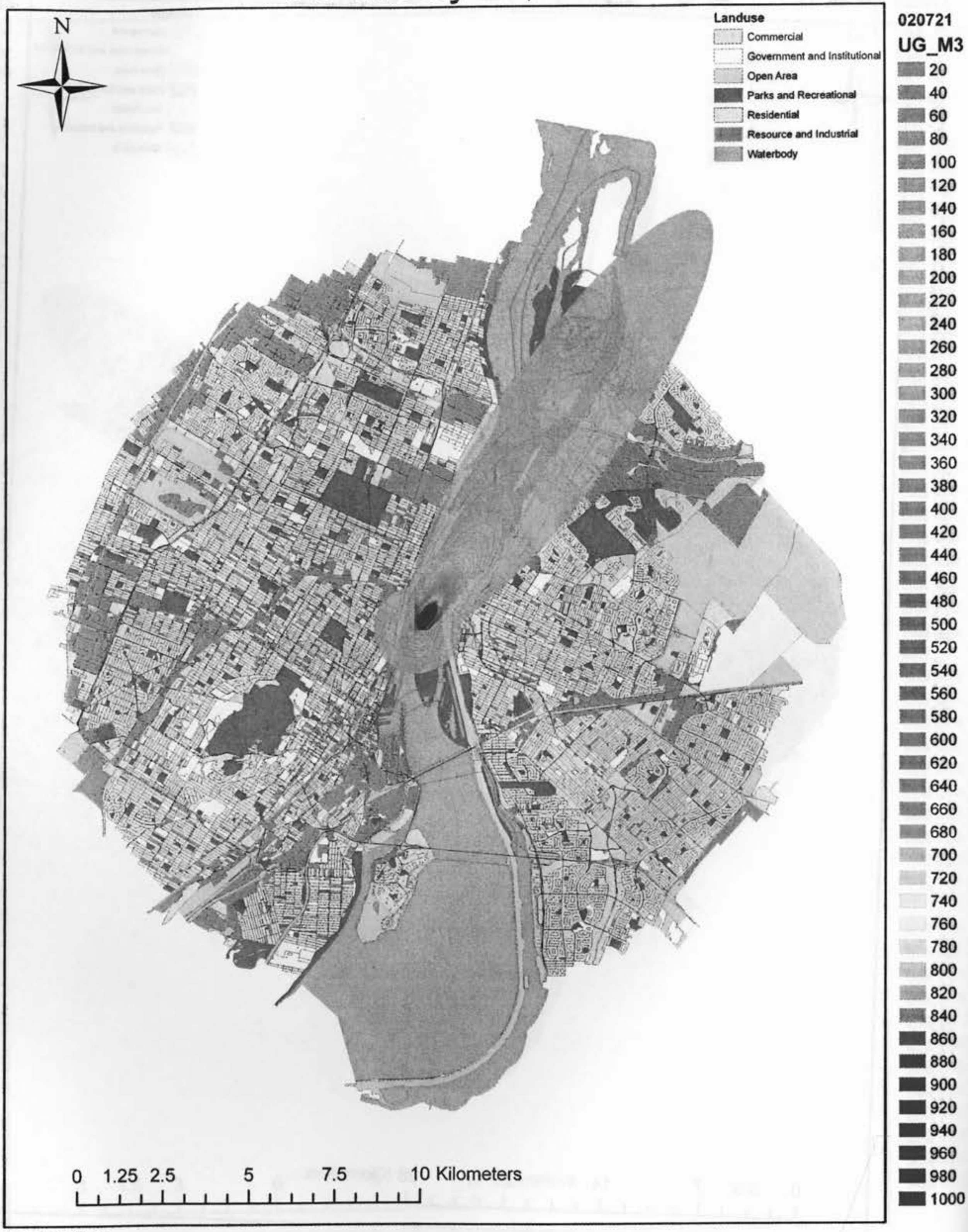
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 29, 2002



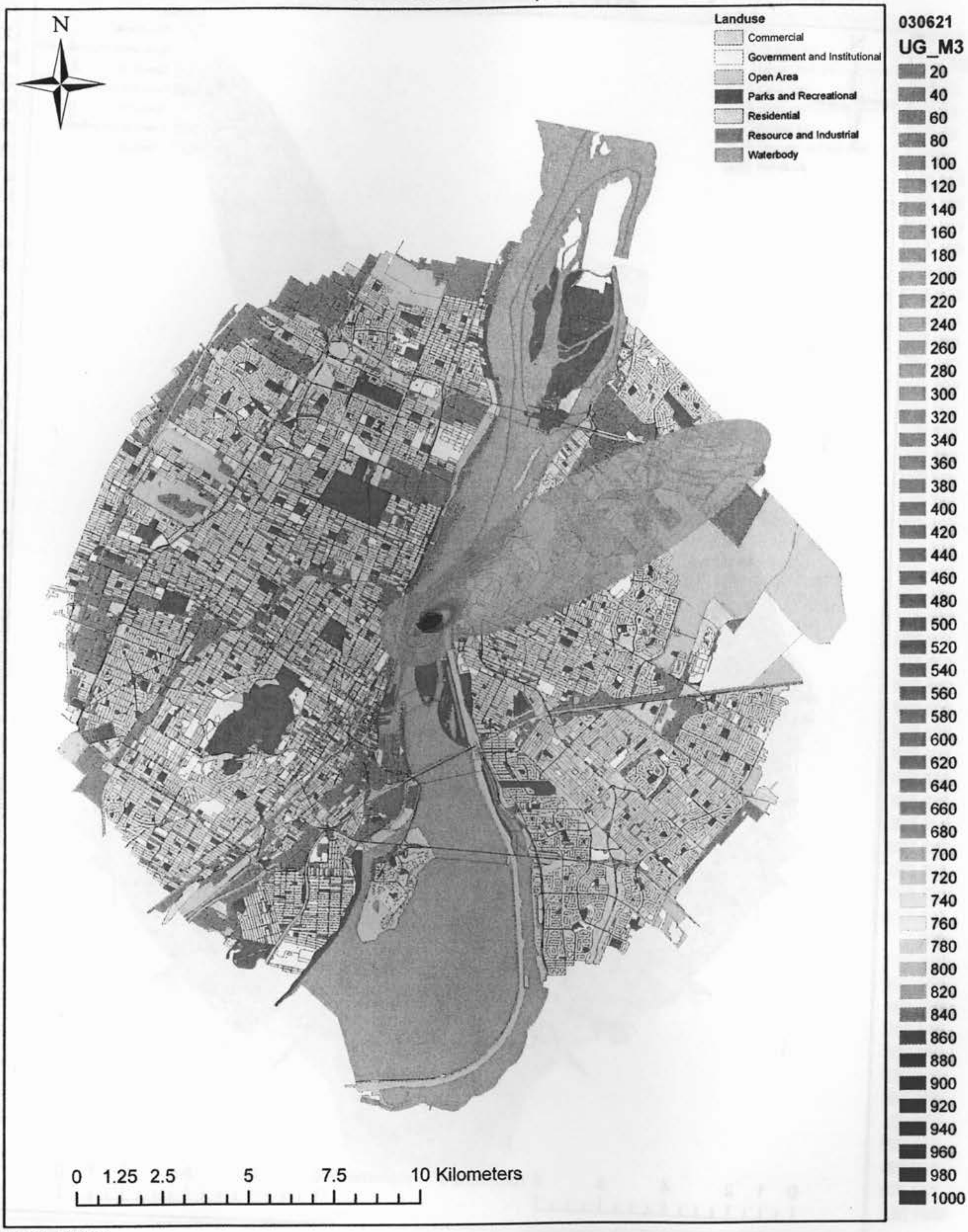
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 21, 2002



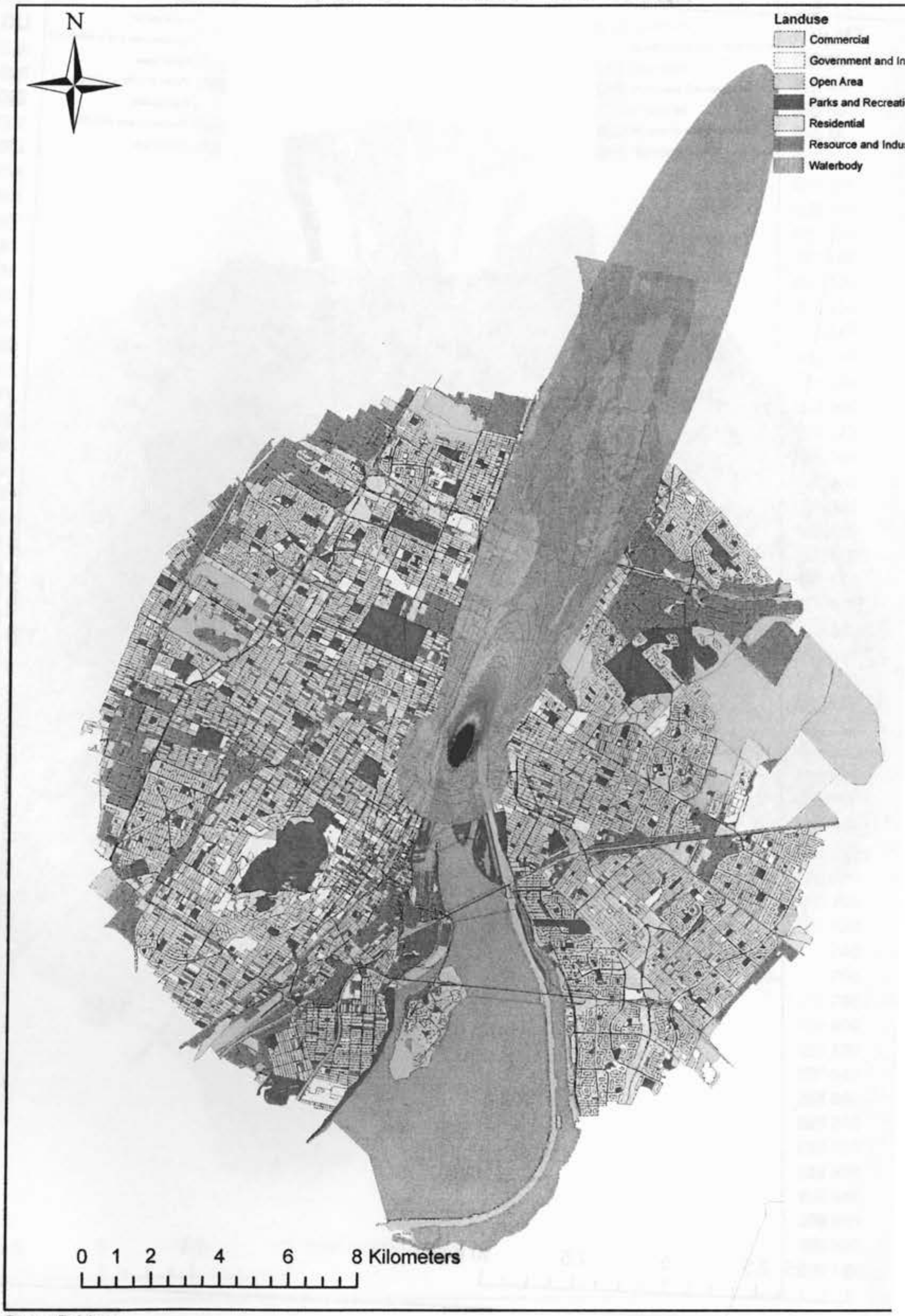
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 21, 2003



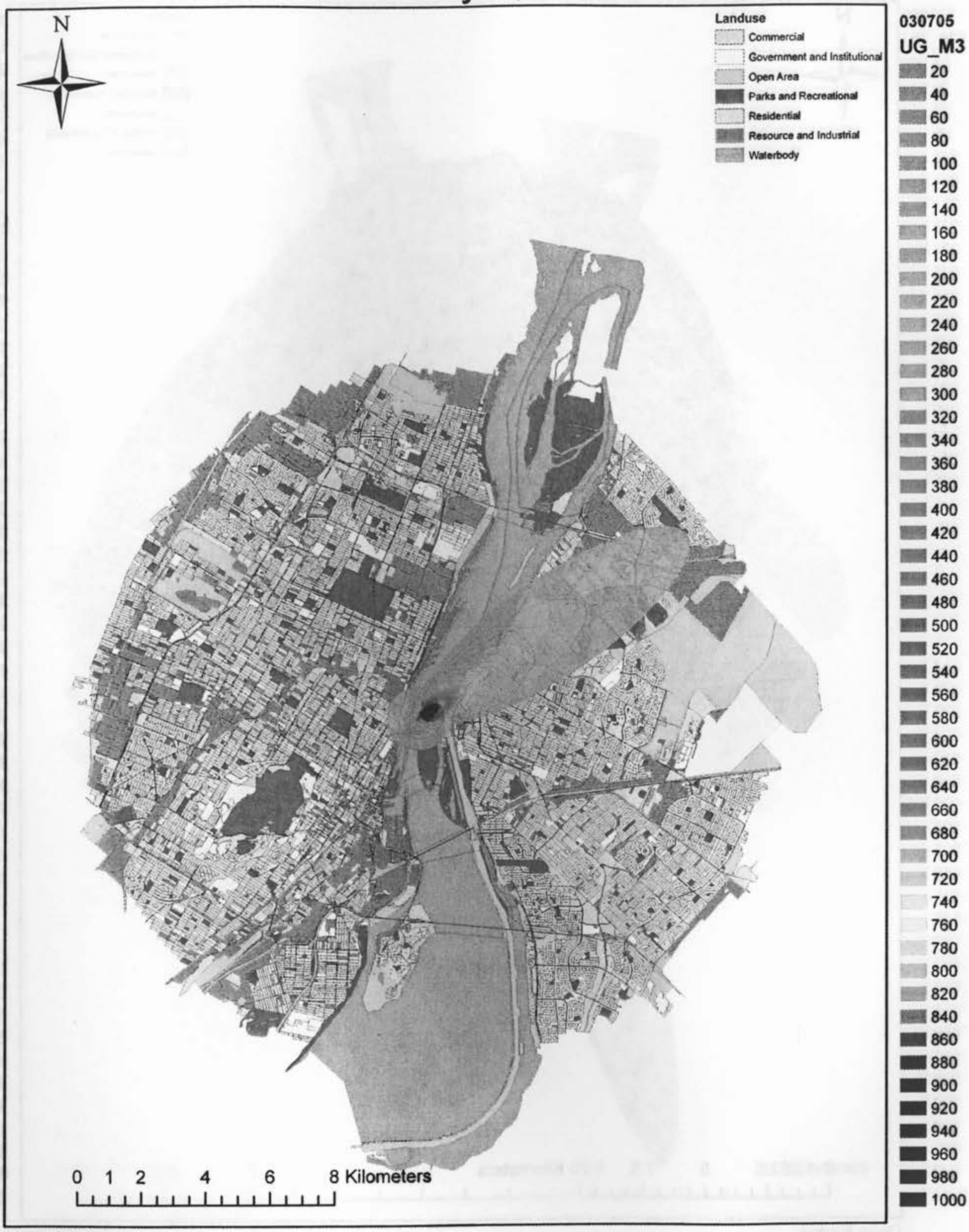
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Mo
10PM June 28, 2003



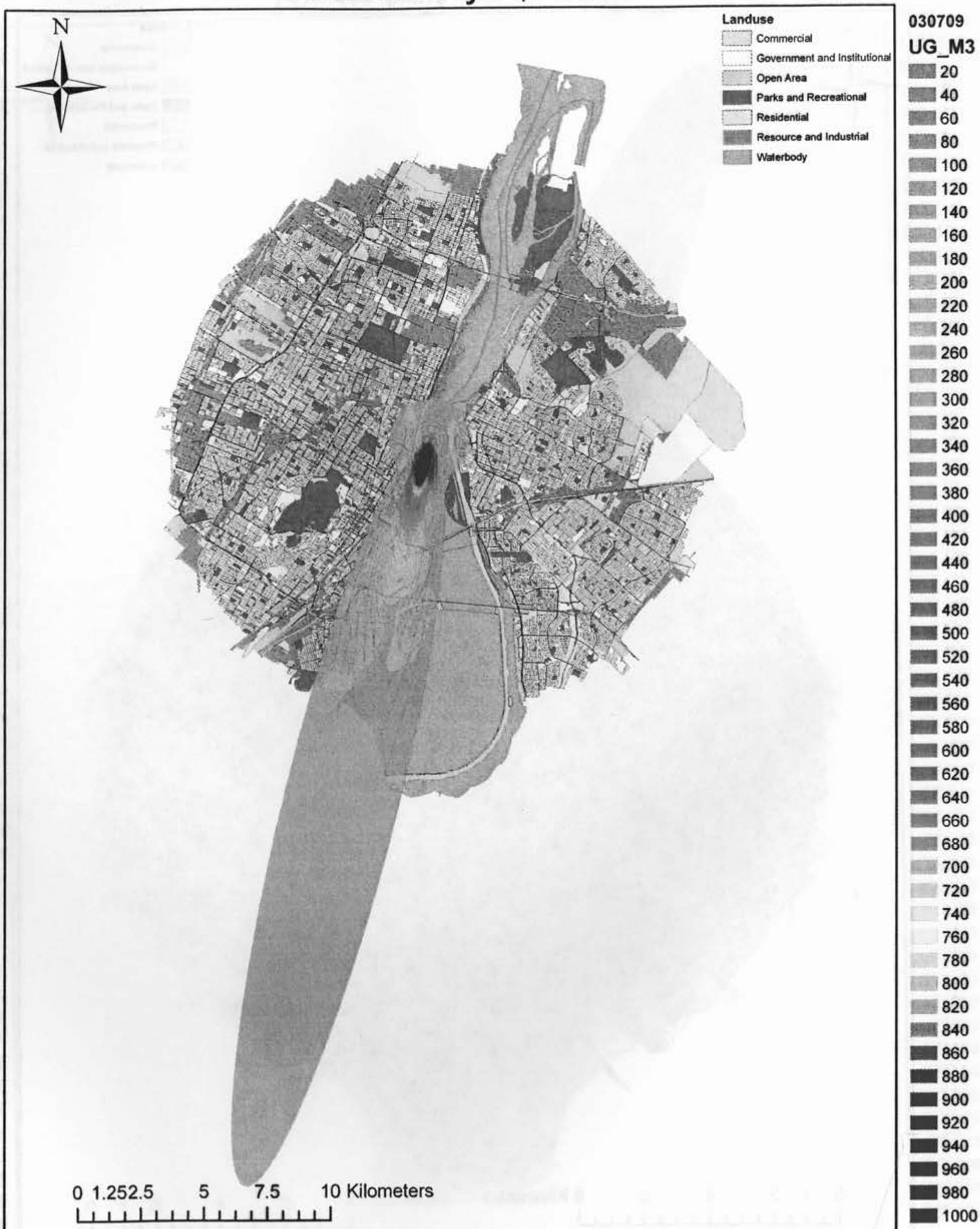
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

M2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 5, 2003



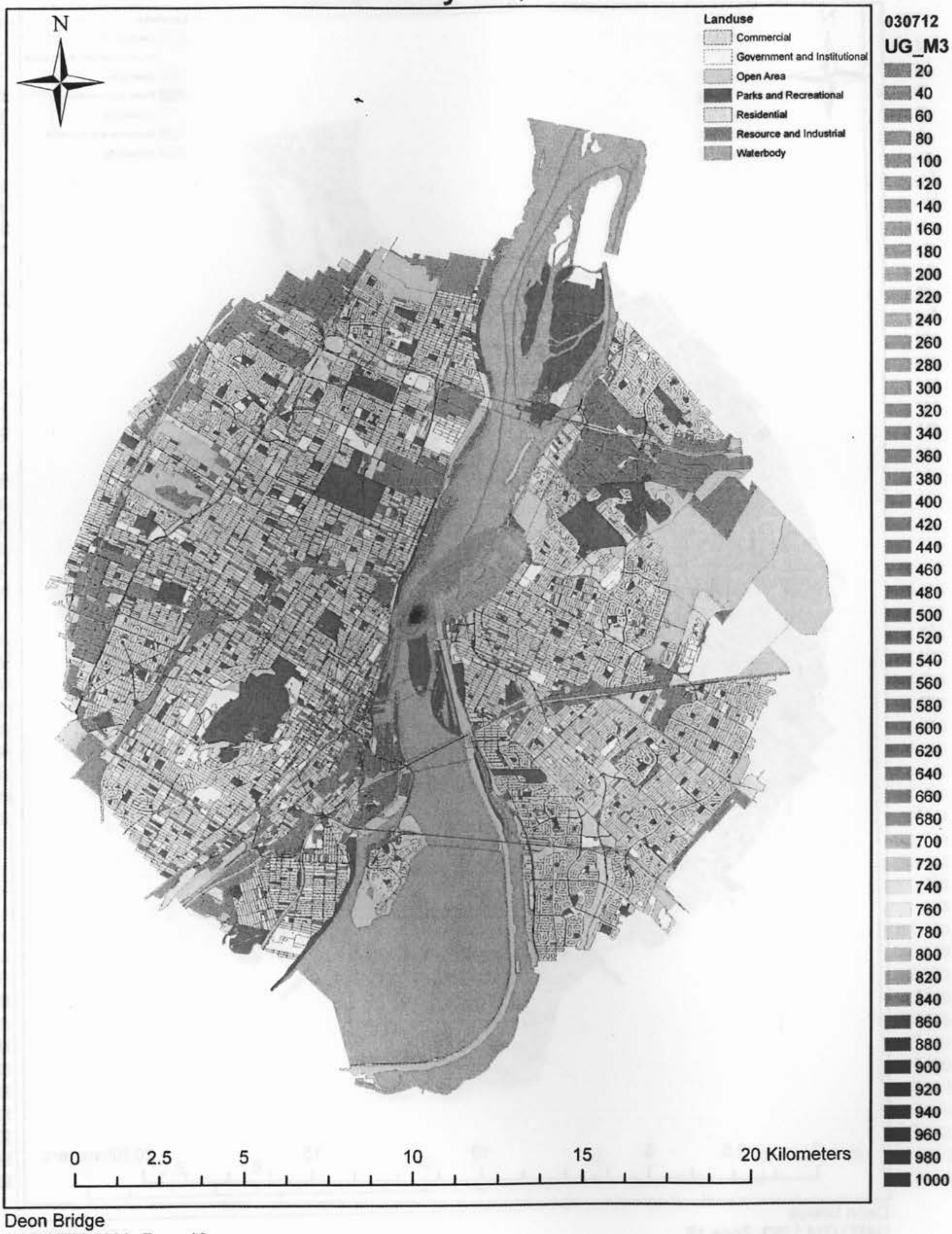
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 9, 2003



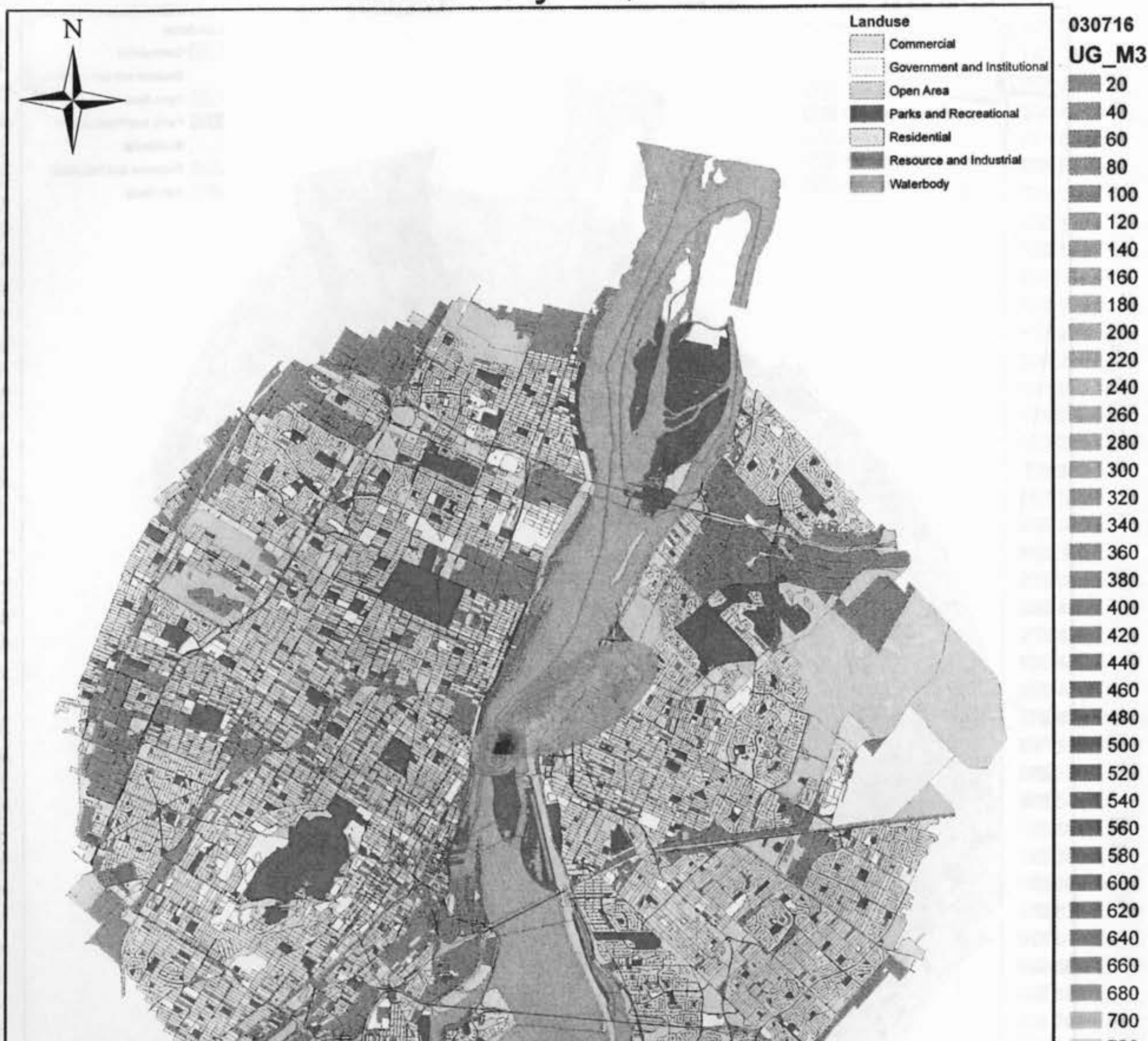
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 12, 2003



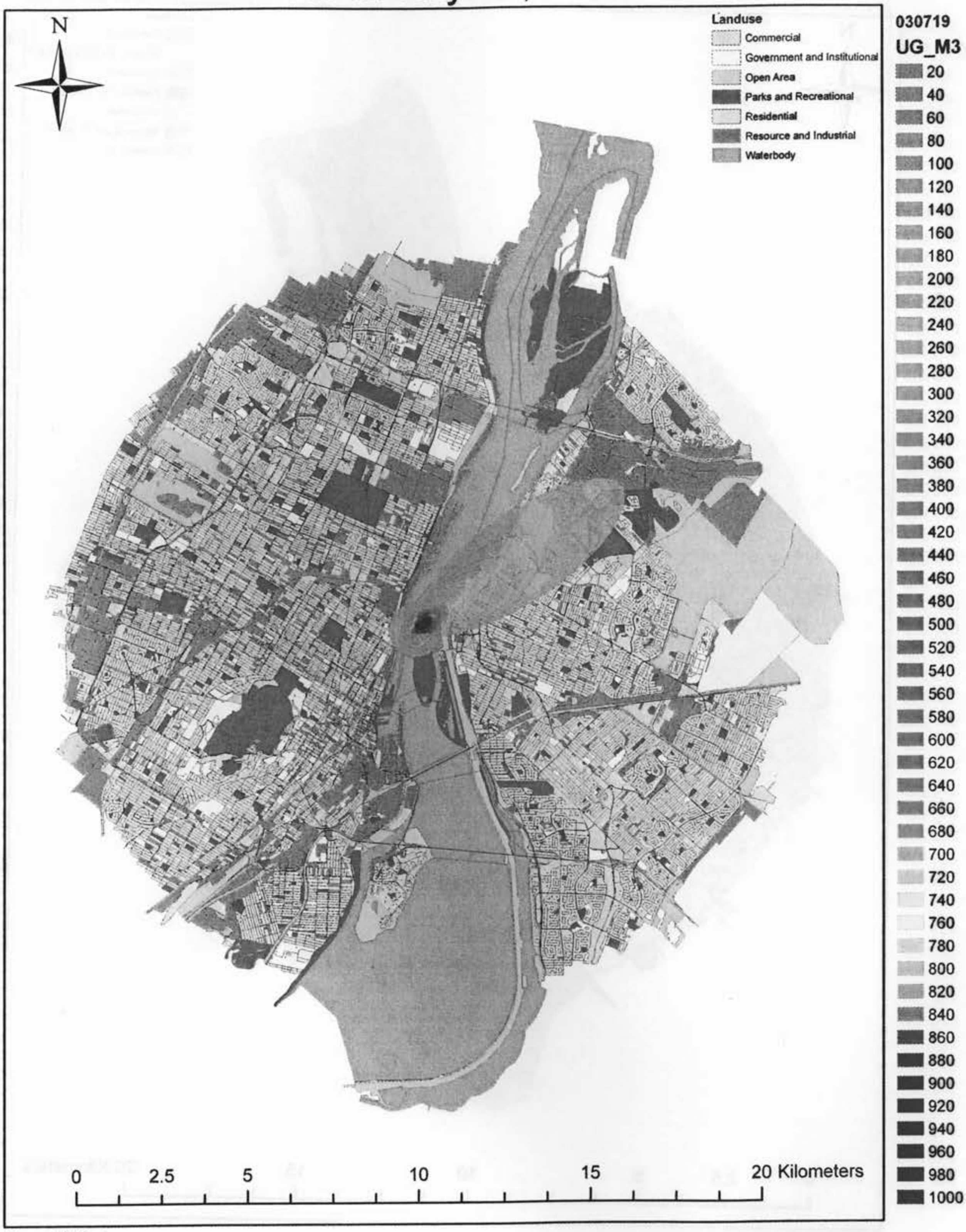
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 16, 2003



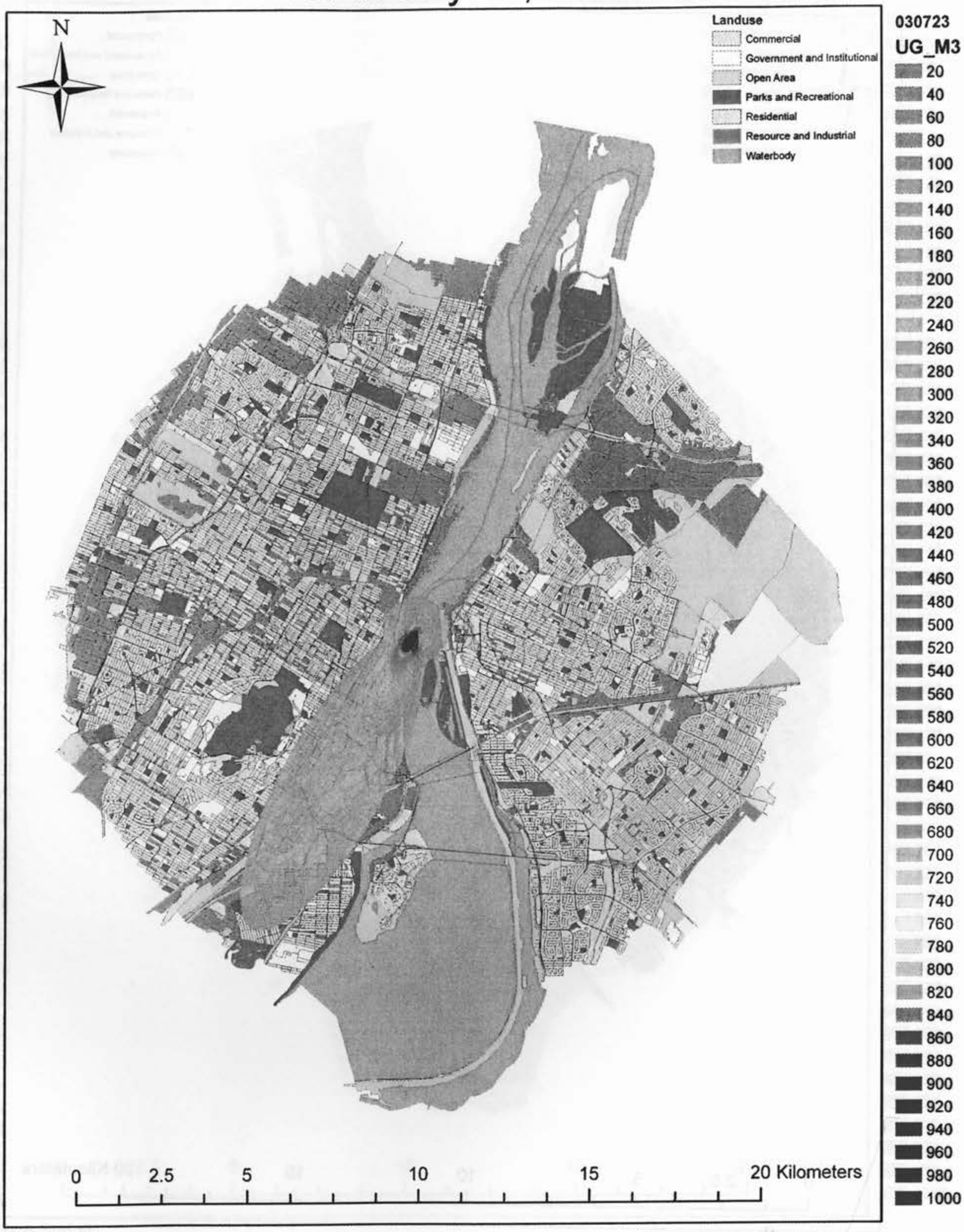
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 19, 2003



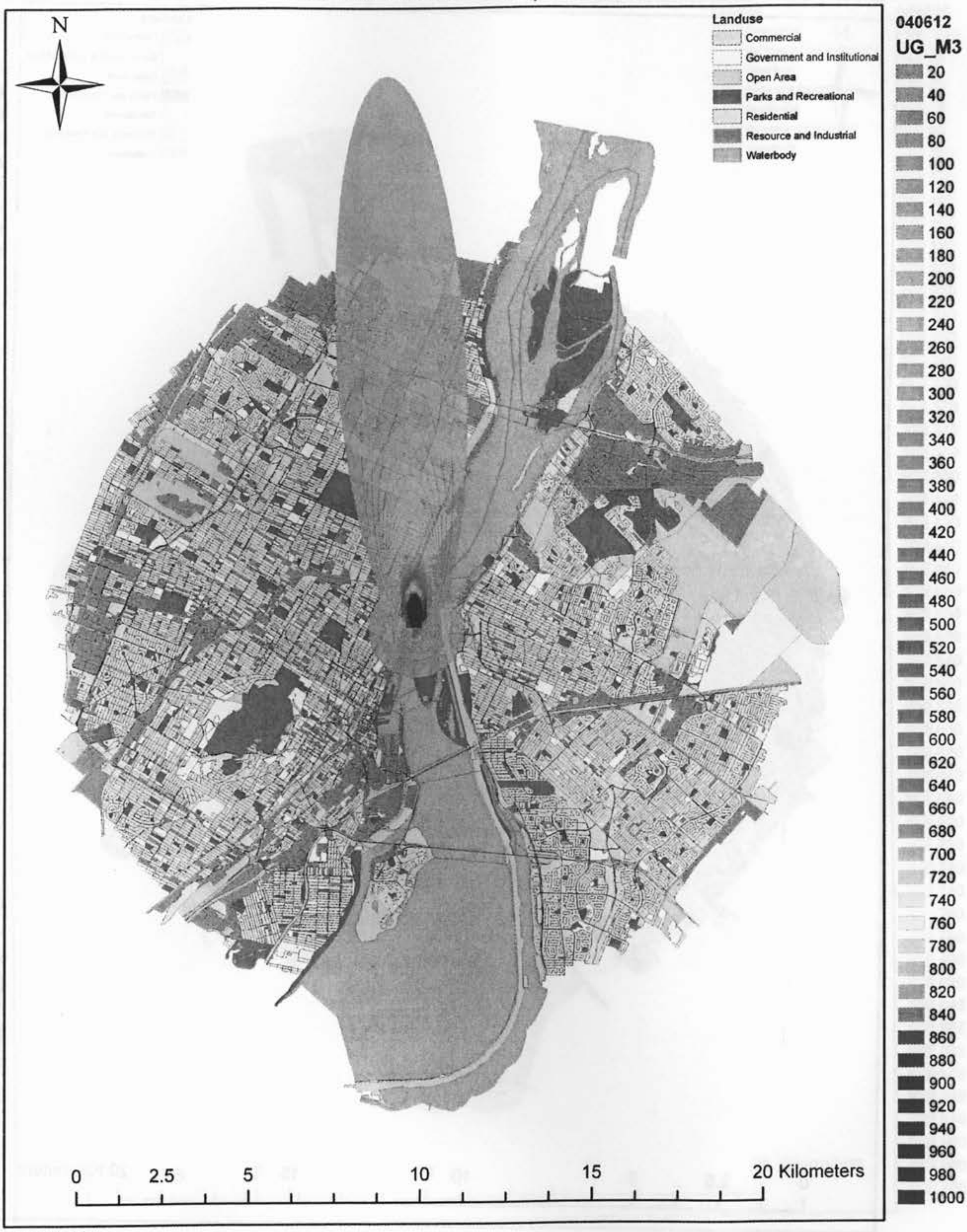
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 23, 2003



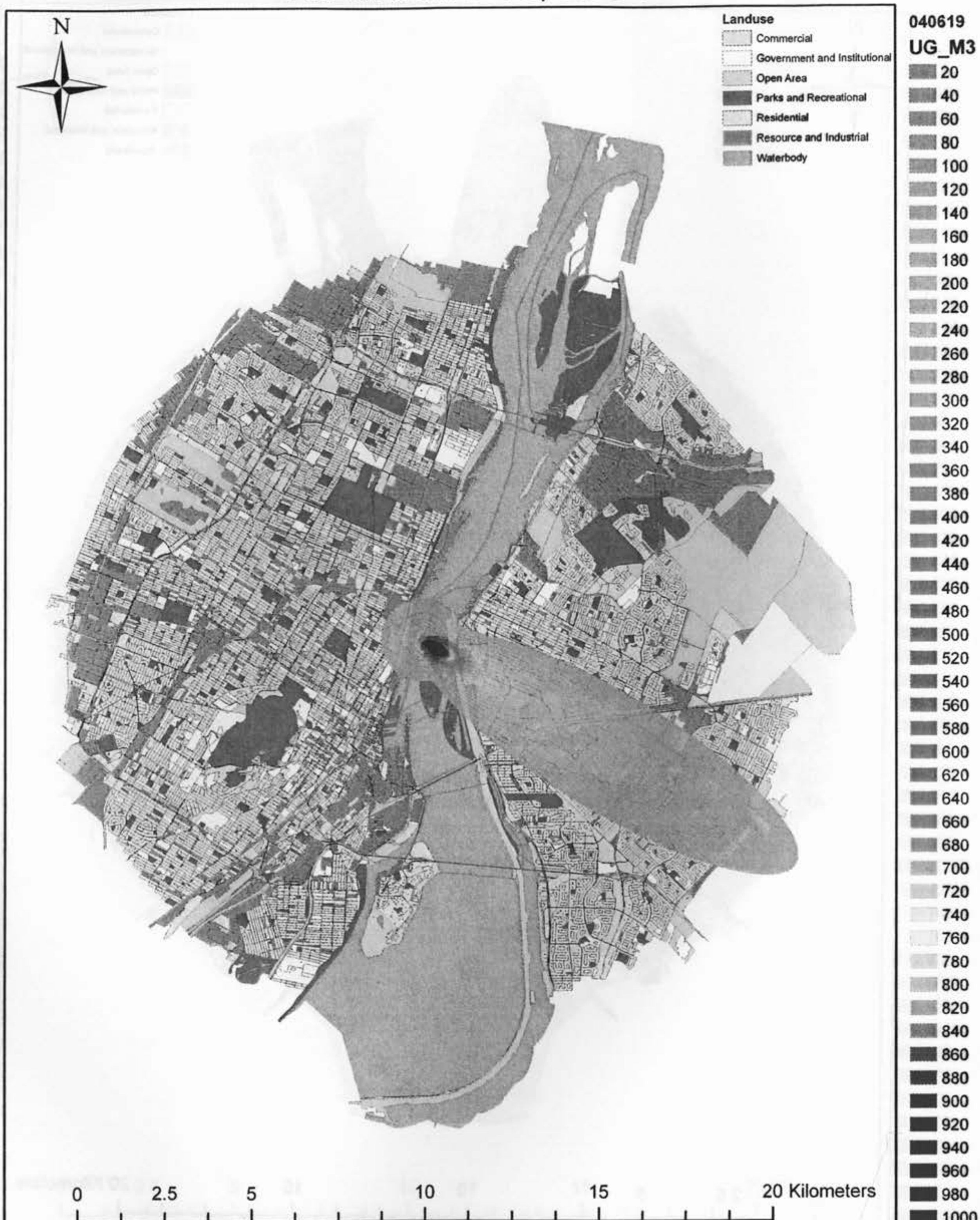
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 12, 2004



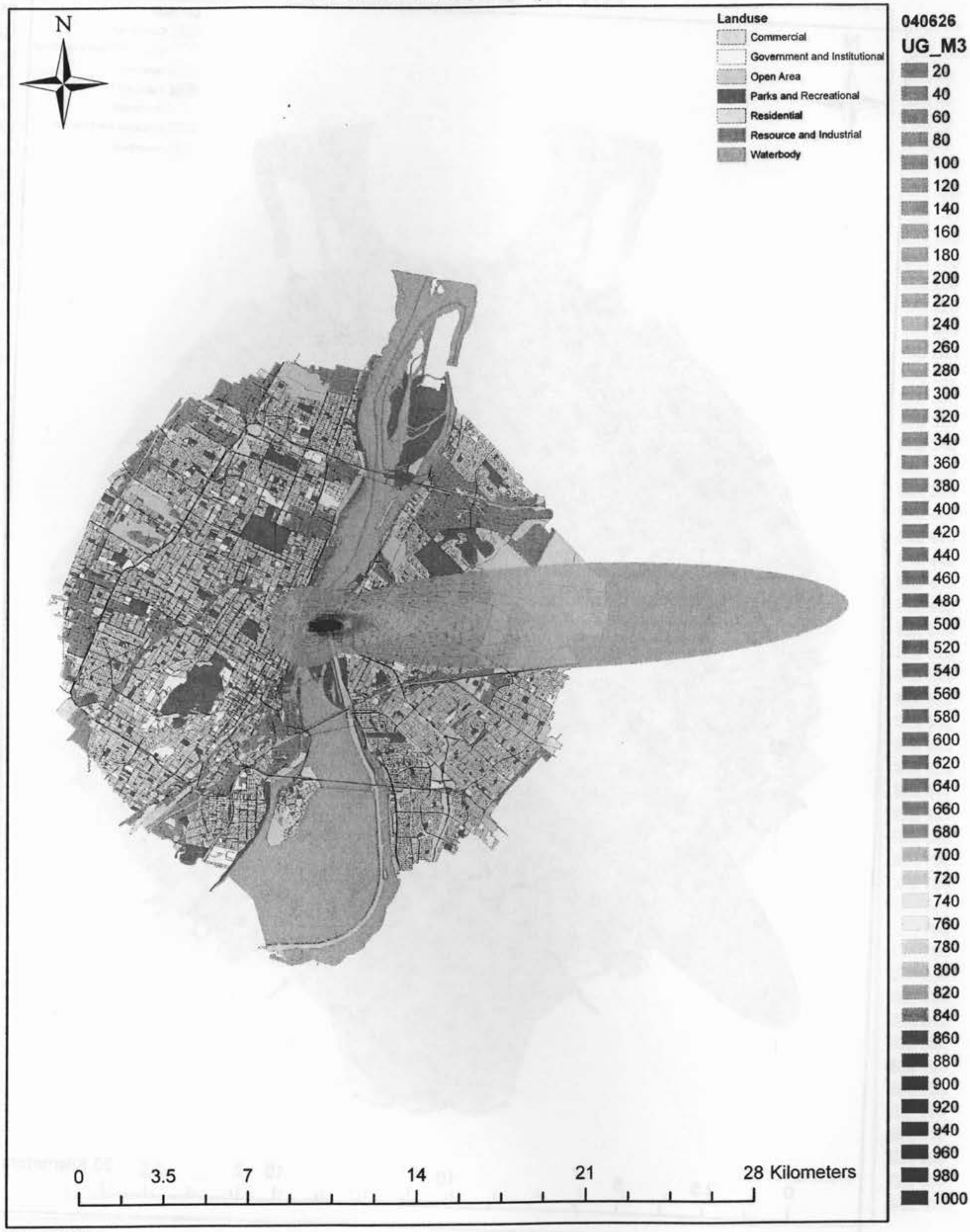
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 19, 2004



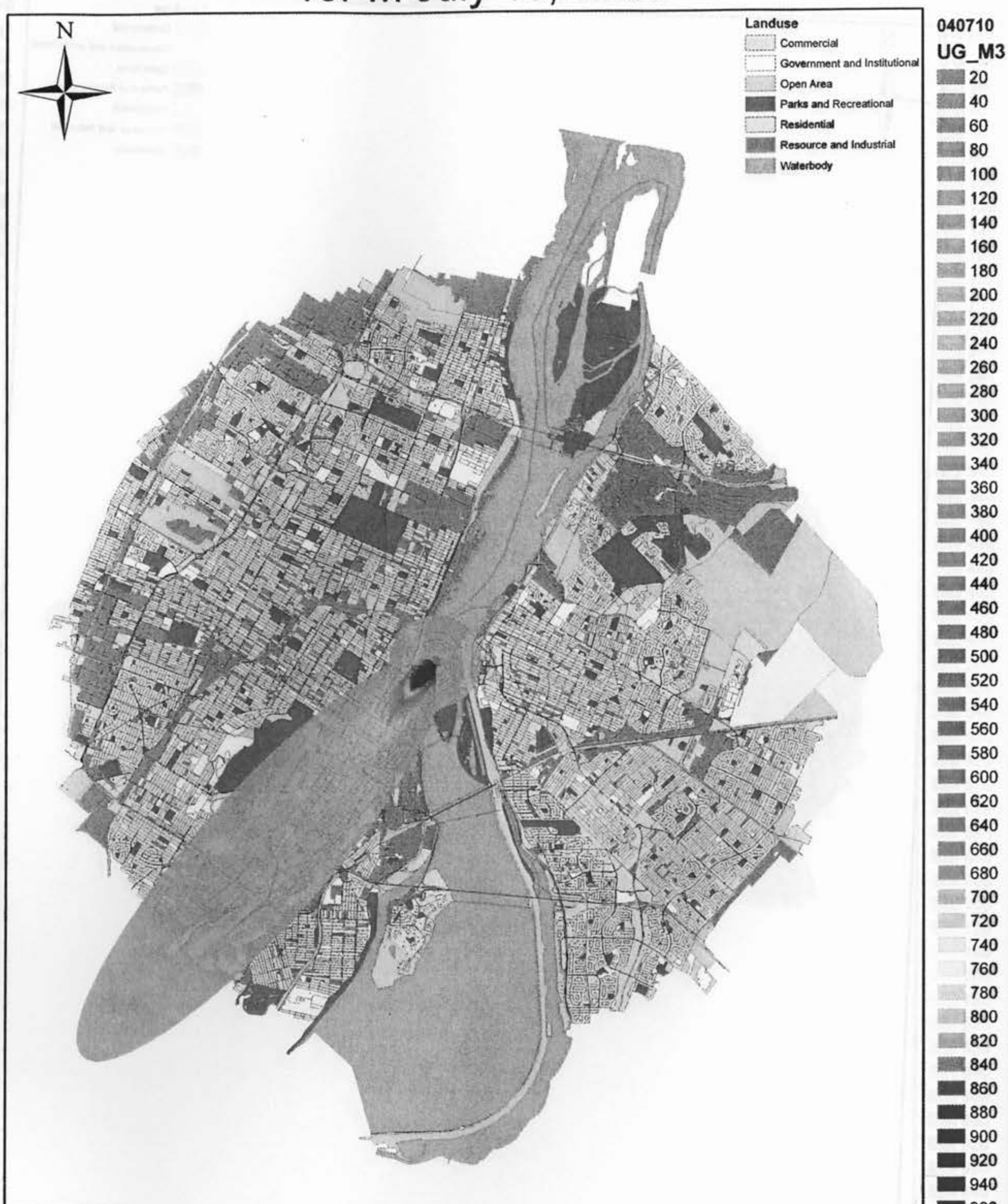
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM June 26, 2004



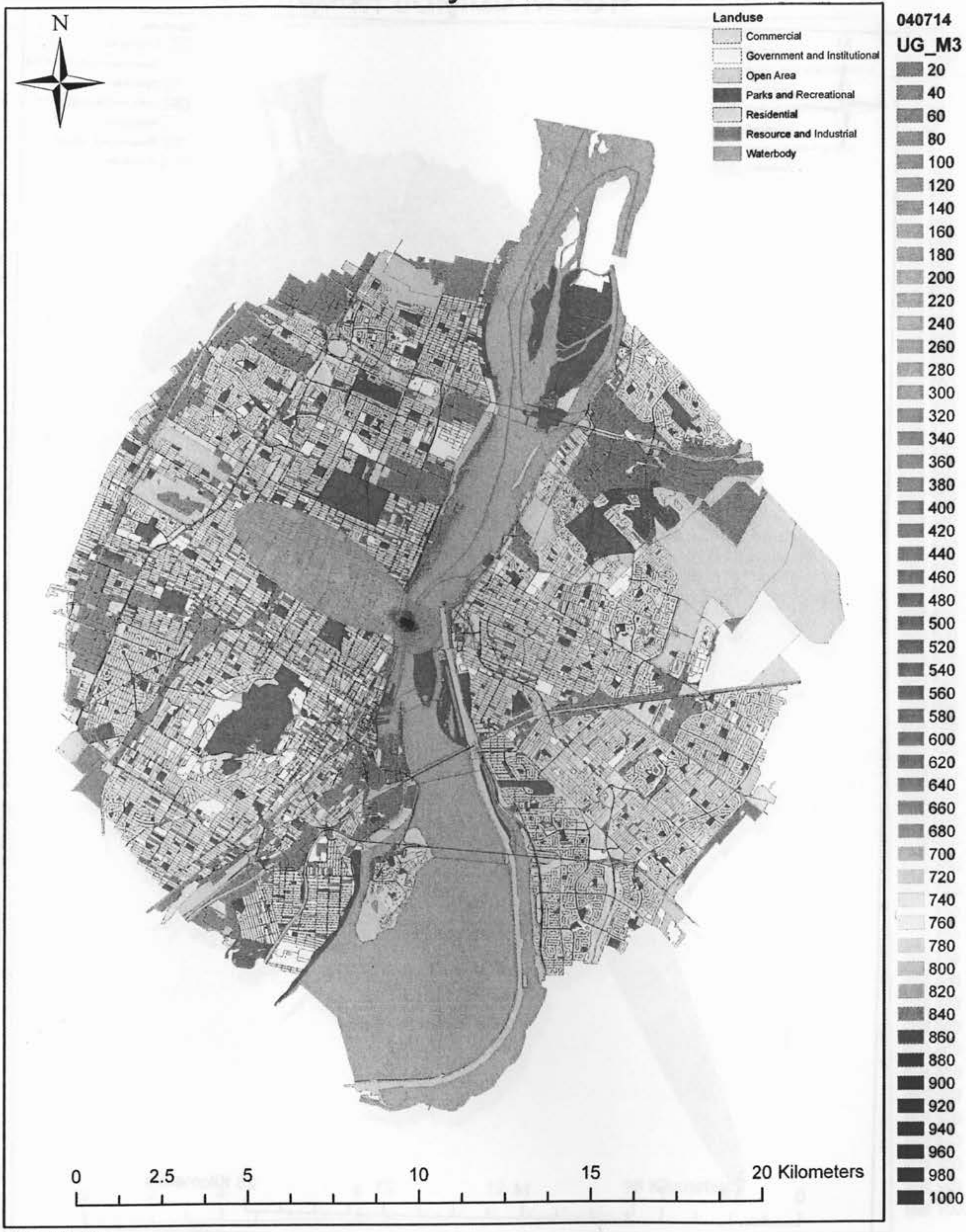
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 10, 2004



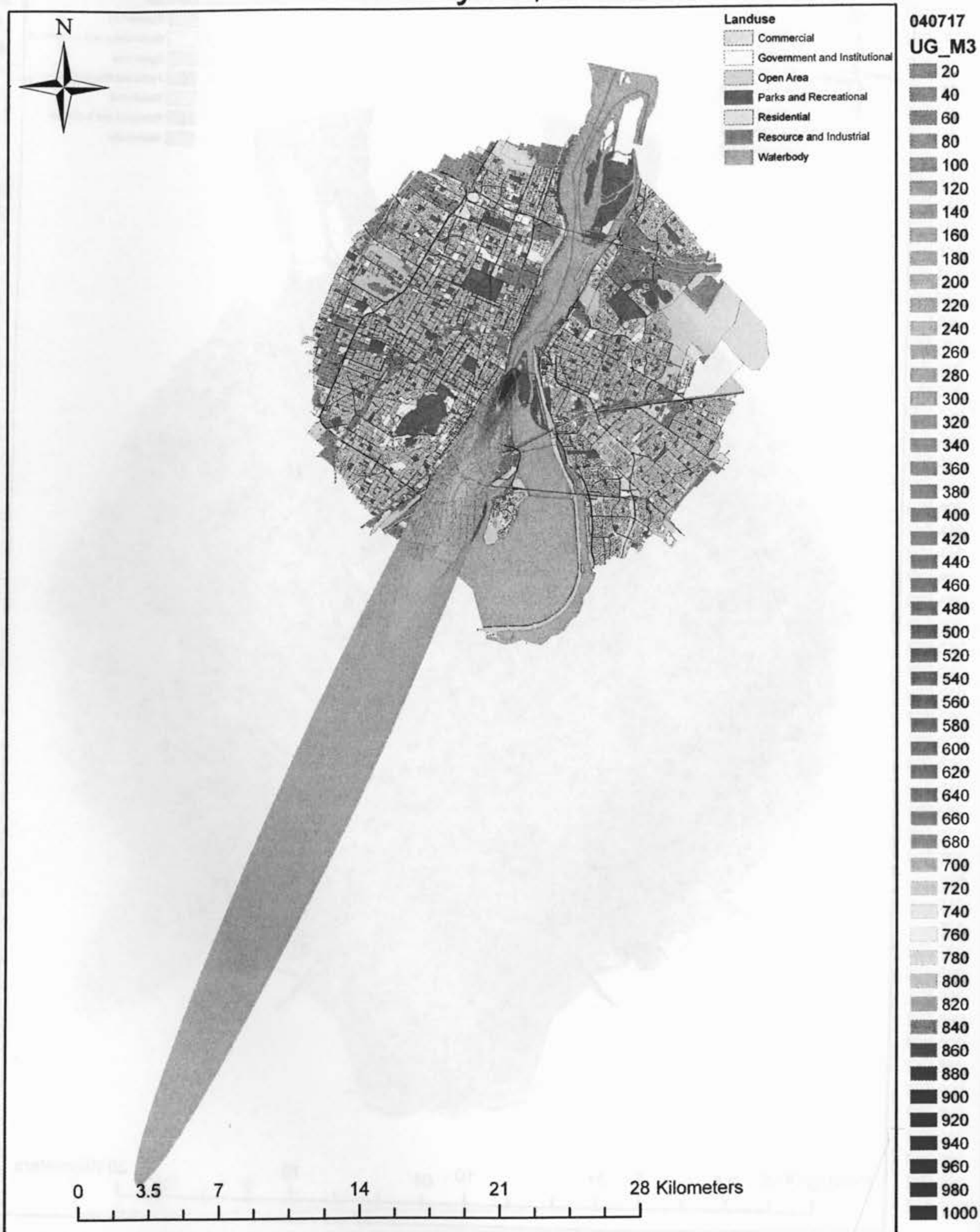
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 14, 2004



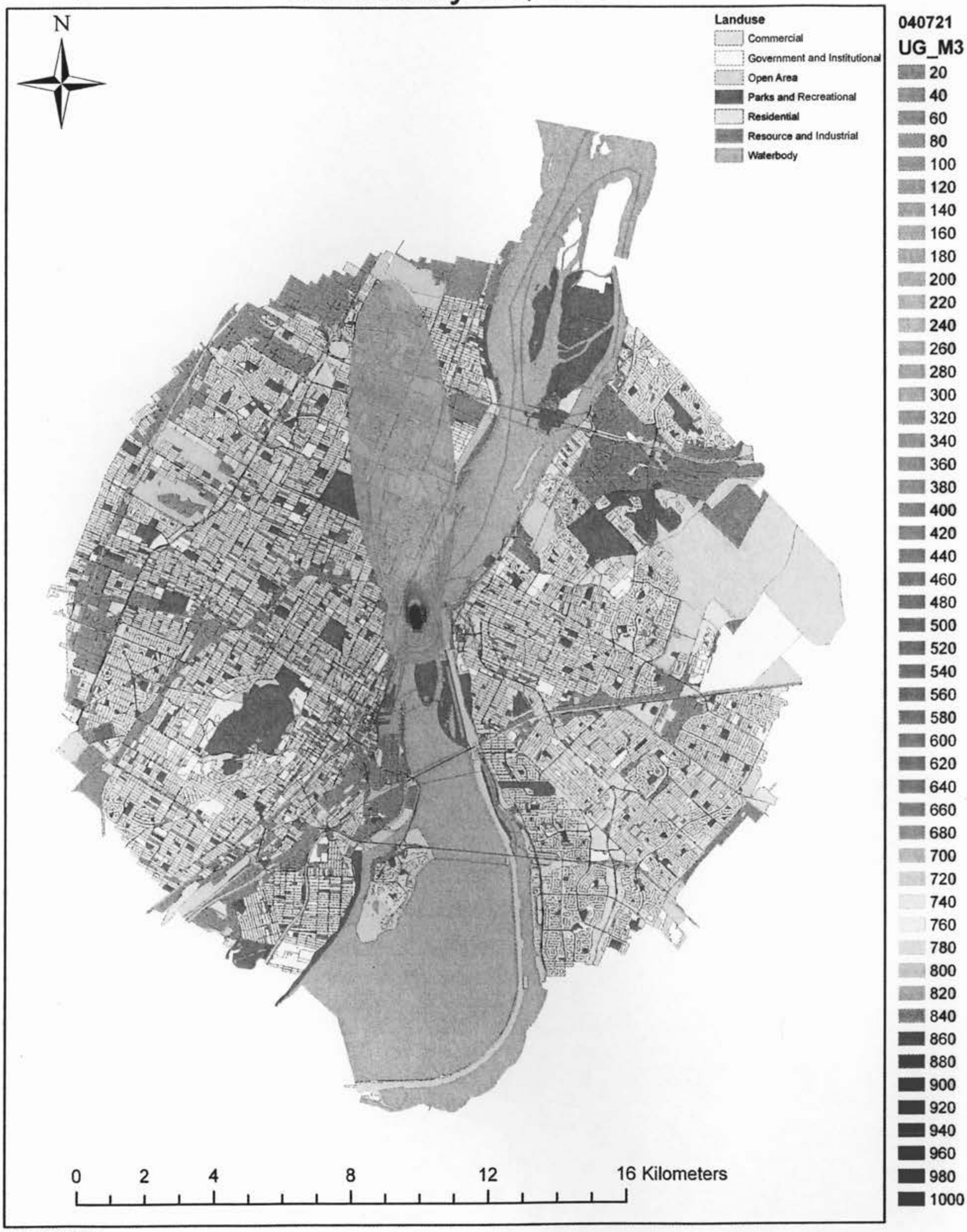
Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 17, 2004



Deon Bridge
NAD UTM 1983, Zone 18
January 2009

PM2.5 Plume from La Ronde Fireworks Event, Montreal, 10PM July 21, 2004



Deon Bridge
NAD UTM 1983, Zone 18
January 2009