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Air quality assessment for the proposed Miller Braeside quarry expansion in Canada: TSP

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Abstract This study aims to address the potential air quality impact of a proposed expansion of the Miller Braeside quarry in Ontario, Canada. The main focus of this assessment is on the potential impacts of the total suspended particulates (TSP) emissions. The CALPUFF dispersion modeling system was utilized to assess the maximum ground level concentrations of TSP emitted from the proposed quarry site. The emissions for 4 days in the year 2013 were examined, where each day represented a different season. The results of the dispersion models were evaluated against the TSP concentration limits set by the Ontario Ministry of Environment (MOE). All simulated 1-h average TSP concentrations were found to significantly exceed Ontario's 1-h TSP limit. Similarly, the simulated 24-h average TSP concentrations on the days representing the winter, summer, and autumn seasons were found to be well above Ontario's 24-h TSP limit. Potential regions nearby the quarry that may be affected by adverse TSP emissions were determined to generally be within the most concentrated region of the TSP plume trajectories. Since the quarry is situated in close proximity to many residential areas, expansion of the Miller Braeside quarry is not recommended as its high TSP concentration levels will pose as a severe hazard to human health.

Keywords TSP · Particulate matter · Air quality · Dispersion · Quarry · Canada

Introduction

Total suspended particulates (TSP) are particles with an aerodynamic diameter of less than 50 μm. These particles can be suspended in the atmosphere or transported over long distances (Ferris at al. 1979; Miller et al. 1979). Quarrying is the process of extracting valuable stones from a quarry (Bada et al. 2013). The operations of the quarry employ a variety of different techniques and several types of equipment to obtain stones, sand, gravel, or minerals either from the ground or by digging and cutting rocks. They typically involve the following major operations: hot-mix asphalt paving material production, concrete batch processing, aggregate extraction and crushing, quarrying, and miscellaneous ancillary activities. These quarrying activities have several adverse impacts on air quality, including the release of air pollutants such as TSP into the environment (Bada et al. 2013; Nartey et al. 2012).

In recent years, there has been an increase in awareness of the environmental impacts of the quarrying industry. As a result, the dusts emitted from quarry operations have begun to be more widely quantified (Hall et al. 2000; Olusegun et al. 2009; Tartakovsky et al. 2013). When such operations are monitored, the most common measure of impact is TSP, which represents the total concentration of suspended particulate matter in the atmosphere. It consists of particles with a diameter of less than 10 μm, which are usually termed as PM_{10} or coarse particles. Depending on the concentration of particulate within the region, PM_{10} has the potential to cause serious adverse effects on human health, such as respiratory and cardiovascular problems, harming the lung tissues, and lung cancer. As the concentration and length of exposure to particulates increase, residents within the exposed region will

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experience increasingly more serious adverse health effects. In particular, the elderly, children, and people with existing health problems such as asthma, chronic lung, and heart disease are the most affected by high concentrations of particulate (Bada et al. 2013; Nartey et al. 2012; Seaton et al. 1995; Valavanidis et al. 2008). Particles of aerodynamic diameters of less than 2.5 μm, also known as fine particle matter or $PM_{2.5}$, are a public health risk due to their ability to travel all the way down a person's lungs to the alveoli. $PM_{2.5}$ is known to have substantially greater toxicity than larger particles and an acute effect on all causes of mortality, such as respiratory and cardiovascular mortality (Franklin et al. 2007).

The impact of TSP is usually estimated using emission factors for the mineral industry. Typical emission sources include the dust generated from excavations, quarry, drilling, grinding, gathering, conveyance, and truck loading. In order to be able to determine the effect of TSP at offsite locations and nearby residential areas, it is necessary to employ dispersion modeling software (e.g., CALPUFF, AERMOD). Such models allow the determination of the maximum TSP concentrations and the minimum quarrying distances established for public protection. Tartakovsky et al. (2013) used a combination of the AERMOD and CALPUFF dispersion modeling systems to determine the concentrations of TSP emitted from a region of complex terrain for the years 2010 and 2011. The emission site of interest was the Chanaton quarry located in western Galilee. Nartey et al. (2012) examined the concentrations of PM_{10} dust emissions released from the quarry site as a result of limestone extraction between January and October 2011. The impact of PM_{10} concentrations on the Lower Manya Krobo District communities located in eastern Ghana was examined and compared against other nearby communities. Bada et al. (2013) assessed the different air pollutants present in the drilling emissions released from quarry activities and the pollutants that reach the Jagun village nearby. The quarry site of interest in this study is owned by FW SAN HE CONCEPTS LIMITED and is located in the Odeda Local Government Area, Ogun State, Nigeria. Tao et al. (2007) examined the correlation between visibility and the chemical composition of $PM_{2.5}$ near the South China Institute of Environmental Sciences' monitoring station in Guangzhou, China. The visibility impairment effect of each $PM_{2.5}$ water-soluble ionic species and carbonaceous content were assessed for the spring season in 2007. Valavanidis et al. (2008) assessed the relationship between particulate matter and human health. It determined the impact of PM size, composition, and carcinogenic mechanisms on its toxicity to humans. Franklin et al. (2007) examined the relation between $PM_{2.5}$ concentrations and both all-cause and specific-cause mortality throughout the years 1997 to 2002 in 27 US communities.

AERMOD is a steady state Gaussian plume model that is recommended to assess contaminant dispersion on a short-range transport basis. It has certain limitations. For example, this model assumes a straight line trajectory for contaminant dispersion and does not incorporate curved or variable trajectories. Additionally, AERMOD assumes a uniform atmosphere across the whole domain. Furthermore, it is not accurate when applied to calm conditions that are characterized by low wind speeds. AERMOD also does not retain the memory of any contaminant emissions that have occurred in the previous hours. On the other hand, CALPUFF is considered a long-range transport model that is recommended to be used when evaluating impacts on receptors that are located over 50 km away from the emission source. Some advantages of CALPUFF include its allowance for non-straight line trajectories, its consideration of a non-uniform atmosphere across the domain, its accuracy in calm conditions, and its ability to retain the memory of contaminant emissions from previous hours (Bluett et al. 2004). Using CALPUFF will also ensure that the dispersion is assessed further away from the emissions sources as well as nearer to them.

The objective of this study is to assess the impacts on air quality if the proposed expansion of the Miller Braeside quarry in Canada were to be approved. The concentration and dispersion of TSP around the quarry site were modeled for four reference days in the year 2013, with each day representing a different season. The CALPUFF dispersion modeling software was used along with the anticipated TSP emission data of the expanded quarry site to determine the general TSP air quality impacts during each season of the year. The results of the study will have an interest to the residents in the area and relevant permitting authorities in the area. The study makes useful contributions on demonstrating the application of air quality models for potential impacts that could be adopted by others.

Materials and methods

Description of study area

The proposed site of the Miller Braeside quarry expansion is located in the township of McNab/Braeside in the county of Renfrew, Ontario, Canada. This expansion will increase the total removal of aggregate and allow the addition of a hot-mix asphalt plant and a ready-mix concrete plant in the quarry. According to Statistics Canada (2013c), in the year 2011, there were 7371 residents living in the township of McNab/Braeside. This township is located immediately south of the Ottawa River, embodies the White Lake, and is intersected by the Madawaska River. It has a land area of 255.74 km^2, which is mainly used for a mixture of residential, agricultural, and recreational purposes, in addition to a few industrial companies

Table 1 Model input information for the study area

Parameter	Braeside quarry expansion
Projection	LCC
LCC latitude of origin	45.467° N
LCC longitude of origin	74.442° W
Latitude 1	10° N
Longitude 2	50° N
False easting	0
False northing	0
Continent/ocean	North America
Geoid-ellipsoid	North American 1983: GRS 80
Region	Canada
DATUM code	NAR-B
X (easting)	−100 km
Y (northing)	−100 km
Number of X grid cells	200
Number of Y grid cells	200
Grid spacing	1 km
Number of vertical layers	9
Cell face heights (m)	0, 20, 50, 100, 150, 200, 300, 500, 1000, 2000
Base time zone	UTC-05:00 eastern time US and Canada)
UTM zone	18
Hemisphere	Northern
UTM X location of source	387.255 km
UTM Y location of source	5035.804 km

LCC Lambert conformal conic, *UTM* Universal Transverse Mercator

located throughout the township. The climate of the study area can be found in Statistics Canada (2013a).

Table 2 Information about the surface station used to obtain surface meteorological data

Parameter	Value
Station name	Ottawa International Airport climate station
UTM latitude	45.316667° N (45°19′00.000″ N)
UTM longitude	75.666667° W (75°40′00.000″ W)
X location on grid	15 km
Y location on grid	−10 km
Elevation	114 m
Climate ID	6106001
WMO ID	71628
TC ID	YOW

ID identifier, *WMO* World Meteorological Organization, *TC* Transport Canada, *UTM* Universal Transverse Mercator, *YOW* Ottawa International Airport

The corporation most highly affected by emissions from the proposed expansion or even the present quarry site is the Arnprior Golf Club, which is located only 2.3 km to the east of the quarry, and the Arnprior Golf Club at Sand Point, which is located within 2 km north of the quarry. The closest residential area to the Miller Braeside quarry is the village of Braeside, which is located within 3 km southeast of the quarry site. Braeside is a dissolved municipality with 191 residents living in an area of 1.86 km^2 (Statistics Canada 2013b). Located further southeast, within 8 km of the quarry site, is the town of Arnprior, which contains the closest hospital to the township of McNab/Braeside, the Arnprior and District Memorial Hospital which is situated 7.3 km away. With only a total land area of 13.04 km^2, the town of Arnprior was recorded to contain a population of 8114 residents in 2011, which is greater than the entire population recorded for the township (Statistics Canada 2013a). In addition, nearby the quarry site in the southwest direction lies the city hall of the township of McNab/Braeside, situated 5.5 km away, and the McNab Public School, situated 6.8 km away. Across the Ottawa River, within 6 km north of the quarry site also lies the settlement of Norway Bay, which is part of the municipality of Bristol in Quebec, Canada.

CALPro modeling system

CALPro is non-steady-state modeling software produced by the Atmospheric Studies Group and distributed by TRC. The software consists of three main components: CALMET, CALPUFF, and CALPOST, in addition to a pre-processing system. The pre-processing system consists of processors for geophysical (including land use and terrain), precipitation, overwater, and surface and upper air meteorological data. The CALMET processing system is used to produce a 3D meteorological model. It is a diagnostic model that requires the combined input of geophysical data along with either

Table 3 Information about the Radiosonde station used to obtain upper air meteorological data

Parameter	Value
Station name/location	Maniwaki, PQ, Canada
UTM latitude	46.38° N
UTM longitude	75.97° W
X location on grid	40 km
Y location on grid	95 km
Elevation	170 m
WBAN	04734
WMO ID	71722
INIT	YMW

WBAN upper air station number, *ID* Identifier, *WMO* World Meteorological Organization, *INIT* Initial name, *YMW* upper air station name

Table 4 Input data for emission sources (Church and Trought Inc. 2009)

Point sources (stacks)										
Source description	General location	X (m)	Y (m)	HAG (m)	Temp (K)	Exit velocity (m/s)	Inside diameter (m)	TSP emission rate (g/s)		
Drum mixer baghouse	HMA	−764.0	168	10.7	422	45.7	0.77	0.68800		
RMC boiler	RMC	−694.4	−52.8	5.0	523	1.40	0.30	0.00188		
Crusher generator	Crushing	−409.6	−169.6	4.3	799	86.3	0.25	0.42200		
Line source (road)										
Source description	General location	Length of side (m)	Release HAG (m)	X coord node (m)	Y coord node (m)	X coord node (m)	Y coord node (m)	TSP emission rate (g/s)		
Unpaved haul road	Along pit	3.0	3.96	−669.0	−93.8	−473.0	−279.0	9.88		
Area sources (storage piles)										
Source description	General location	SW corner-X coord (m)	SW corner-Y coord (m)	Center-X coord (m)	Center-Y coord (m)	HAG (m)	Length (m)	Width (m)	Rotation angle (deg)	TSP emission rate (g/s)
HMA silo and loadout	HMA	−784.5	154.5	−782.0	157.0	18.29	4.27	3.66	90	0.0281
Cement silo #1 (cement)-larger	RMC	−704.0	−56.0	–	–	20	4.57	4.57	−60	0.00623
Cement silo #2 (slag)-smaller	RMC	−688.0	−57.6	–	–	14	3.51	3.35	−60	0.00623
Cold feed bin	RMC	−672.0	−89.0	−671.5	−86.0	4	3.05	1.83	−60	0.0950
Weight hopper	RMC	−691.2	−60.8	–	–	4	9.14	3.66	−60	0.1000
Primary crusher	Pit	−390.4	−190.4	–	–	4	12.5	3.66	−60	0.0759
Primary screen	Pit	−388.8	−168.0	–	–	4	10.06	3.66	30	0.1370
Secondary crusher	Pit	−400.0	−161.6	–	–	4	12.19	3.66	30	0.0416
Screen plant	pit	−376.0	−161.6	–	–	4	13.11	3.66	−60	0.0812
Crushing storage piles	Pit	–	–	−444.8	−188.8	10	8	8	–	7.4900
Blasting	Pit	−405.0	−291.0	−370.5	−255.0	15	99	5	43	6.8500
Drilling	Pit	−405.0	−291.0	−370.5	−255.0	15	99	5	43	0.00722

prognostic or observational data. The input of observational data requires surface and upper air meteorological data to be run using their respective pre-processors and their output files to be inputted into CALMET. On the other hand, prognostic data produced into gridded wind fields, such as Weather Research and Forecasting model (WRF), Fourth-Generation Penn State/NCAR Mesoscale model (MM4), and Fifth-Generation Penn State/NCAR Mesoscale model (MM5), can be inputted into CALMET in one of three ways: initial guess, Step 1 wind field, and observational data. CALPUFF can stimulate the dispersion and transformation process of multiple pollutants within various atmospheric layers. It requires the input of the CALMET 3D model. The output air quality dispersion model is then inputted into CALPOST for a summary of the simulation results. Additional details about the model can be found in Abdul-Wahab et al. (2011a, b), (2012), (2013), (2014) and Prueksakorn et al. (2014). Table 1 shows the model input information for the study area.

Surface meteorological data

The surface meteorological data used in this study was retrieved from the Government of Canada website (climate.weather.gc.ca). Climate data was obtained on an hourly basis from the Ottawa International Airport climate station for four different meteorological conditions. The first data set represents the winter season and consists of climate data obtained for the modeling period from 00 h00 Eastern Time on January 11, 2013 to 23 h00 Eastern Time on January 13, 2013. The second data set represents the spring season and consists of climate data obtained for the modeling period from 00 h00 Eastern Time on April 14, 2013 to 23 h00 Eastern Time on April 16, 2013. The third data set represents the summer season and consists of climate data obtained for the modeling period from 00 h00 Eastern Time on July 10, 2013 to 23 h00 Eastern Time on July 13, 2013. The forth data set represents the autumn season and consists of climate data obtained for the modeling period from 00 h00 Eastern Time on November 16, 2013 to 23 h00 Eastern Time on November 18, 2013. The surface station at the Ottawa International Airport was selected due to its location being relatively close to the proposed Braeside quarry expansion. Since this station is located approximately 20 km from the Braeside quarry, its surface meteorological data is considered representative of the quarry site. The extracted hourly meteorological data consists of the following information: temperature (°C), precipitation (mm), station pressure (mbar), relative humidity (%), wind direction (°), wind speed (m/s), cloud cover (tenths), and cloud height (ft). For each one of the four meteorological conditions, data was prepared in a format that could be run using CALPro's SMERGE program to produce a SURF.DAT file suitable for input into CALMET. Information pertaining to the Ottawa International Airport climate station is summarized in Table 2.

Upper air meteorological data

The upper air meteorological data used in this study was retrieved from the Radiosonde Database website that is developed and run by the Earth System Research Laboratory at the National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/raobs/). Twelve-hour interval data was obtained from the Maniwaki upper air climate station for the four different meteorological conditions mentioned previously. The first data set consists of data obtained for the modeling period from 00 h00 Eastern Time on January 11, 2013 to 12 h00 Eastern Time January 13, 2013. The second data set consists of data obtained for the modeling period from 00 h00 Eastern Time on April 14, 2013 to 12 h00 Eastern Time on April 16, 2013. The third data set consists of data obtained for the modeling period from 00 h00 Eastern Time on July 10, 2013 to 12 h00 Eastern Time July 12, 2013. The fourth data set consists of data obtained for the modeling period from 00 h00 Eastern Time on November 16, 2013 to 12 h00 Eastern Time on November 18, 2013. The Maniwaki upper air climate station was selected because it is located

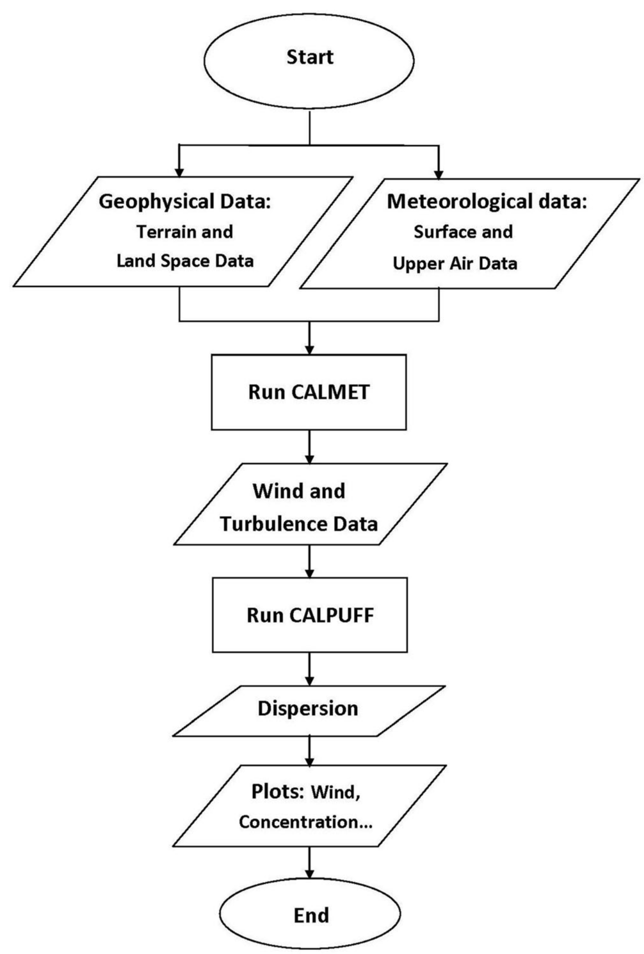

Fig. 1 Flowchart for the CALPUFF modeling steps

relatively close to the emission sources of the proposed quarry. For each one of the four meteorological conditions, hourly upper air meteorological data was prepared in a format that could be run using CALPro's READ62 program to produce a UP.DAT file suitable for input into CALMET. Information pertaining to Maniwaki upper air climate station is summarized in Table 3.

Emission data

This investigation utilizes emission data taken from a case study performed by Church and Trought Inc. (2009), which assesses the dispersion of pollutants emitted from the Braeside quarry expansion facility. Emissions are released from the Braeside quarry

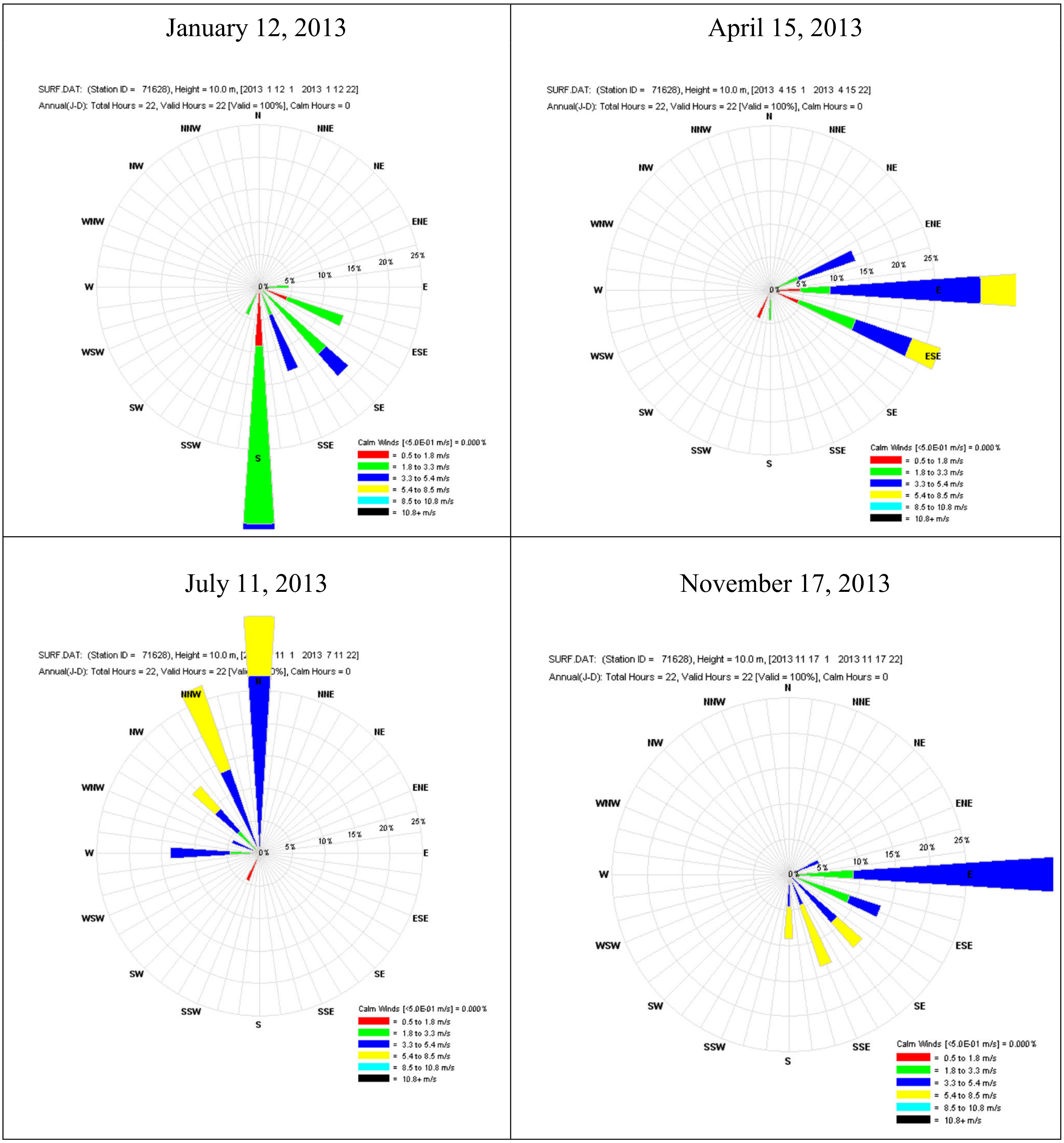

Fig. 2 Windrose for the study area on January 12, 2013; April 15, 2013; July 11, 2013; and November 17, 2013

expansion facility by means of various types of sources, including point source, line source, and area source. Point source emissions are emissions that are collected and discharged through an exhaust stack. In addition to these existing emission sources, the expanded quarry will allow the inclusion of major operations such as a hot-mix asphalt plant, ready-mix concrete plant, aggregate extraction and crushing, and fugitive dust emissions from quarry roads and storage piles. In particular, the contaminant of focus in this study is TSP. Table 4 contains a summary of all TSP emission data and sources on the proposed site used in this study. This emission data was entered into CALPUFF and ran for each of the four meteorological conditions.

Operation of CALPro

Figure 1 illustrates a flowchart for the CALPUFF modeling steps. In this study, the CALPUFF modeling system (CALPro Plus version 6.9.10.25.2007) running on a Pentium (Intel (R) Core (TM), Processor 3.2 GHz, 4.0 GB of Ram, 32-bit operating system) was used for simulation of the dispersion of TSP. This model was used to produce hourly contour plots of the TSP plume trajectories throughout the day and for a summary of the top 20 highest 1-h and 24-h average TSP concentrations. The model was used for all TSP sources on-site. Its predicted 24-h TSP concentrations is then compared to Ontario's Ministry of Environment (MOE) 24-h concentration criterion, whereas its predicted 1-h TSP concentrations are converted to their 30-min equivalent values and then compared against Ontario's MOE 30-min concentration criterion.

Results and discussions

Figure 2 shows a wind rose for each of the four seasonal meteorological conditions examined in this study. This wind rose illustrates the distribution of wind speed and direction at a specific location. This wind rose plots the daily wind frequency by the wind direction, with the colored bands indicating wind speed range. The length of each spoke indicates the wind frequency blowing from that particular direction. The multiple colored bands on a spoke show the different wind speed ranges that occurred in that direction throughout the day and the fraction of those winds that blew at a certain speed. Thus, the longest spoke in the rose indicates the wind direction with the greatest frequency and the longest colored band on the spoke indicates its main wind speed.

Table 5 List of the top 20 1-h and 24-h average TSP concentrations simulated on January 12, 2013 from 00:00 to 23:00

	1-h average TSP concentrations			24-h average TSP concentrations	
	Time (HH:MM)	Concentration (μg/m^3)	Coordinates (km)	Concentration (μg/m^3)	Coordinates (km)
1	18:00	934.9	−1.500, 2.500	132.9	−1.500, 2.500
2	01:00	876.7	−2.500, −0.500	69.5	−1.500, 1.500
3	17:00	627.2	−1.500, 2.500	63.5	−2.500, 2.500
4	21:00	594.0	−2.500, 2.500	56.7	−2.500, 0.500
5	19:00	569.9	−2.500, 0.500	55.3	−2.500, −0.500
6	16:00	496.4	−1.500, 1.500	54.6	−0.500, 0.500
7	04:00	462.4	−1.500, 2.500	40.0	−1.500, 3.500
8	02:00	430.3	−2.500, 0.500	37.4	−3.500, 1.500
9	22:00	368.9	−1.500, 2.500	36.1	−4.500, 0.500
10	03:00	368.9	−2.500, 2.500	36.0	−2.500, 3.500
11	02:00	368.3	−6.500, 0.500	32.8	−3.500, 3.500
12	02:00	358.4	−3.500, 0.500	32.6	−3.500, 0.500
13	21:00	345.2	−4.500, 4.500	31.3	−3.500, 4.500
14	18:00	342.4	−1.500, 3.500	30.8	−5.500, 0.500
15	02:00	333.4	−4.500, 0.500	30.7	−2.500, 5.500
16	06:00	331.4	−4.500, 1.500	30.1	−2.500, 4.500
17	12:00	321.3	−0.500, 0.500	29.3	−4.500, 1.500
18	20:00	300.6	−5.500, 4.500	27.3	−3.500, 5.500
19	01:00	294.0	−3.500, −0.500	27.3	−1.500, 0.500
20	20:00	292.5	−4.500, 2.500	27.0	−4.500, 4.500

Winter

From Fig. 2, it can be seen that for the winter day of January 12, 2013, wind only blows from the SSW to E directions. Majority of the wind blows from the S to ESE directions, while the dominant wind direction comes from the S. For majority of the day, this northbound wind has a speed ranging from 1.8 to 3.3 m/s, with the second most prominent wind speed ranging from 0.5 to 1.8 m/s. Table 5 lists the top 20 highest 1-h and 24-h average concentrations of TSP simulated for the winter period of January 12, 2013 from 00 to 23 h00. The highest 24-h average TSP concentration of 132.9 μg/m^3 is significantly greater than the second and third highest TSP concentrations of 69.5 and 63.5 μg/m^3, respectively, almost double their concentrations. These top 3 highest 24-h average concentrations all occur NW to NNW of the quarry as suggested by the wind rose in Fig. 2. The highest 24-h average concentration occurs at a location 1.5 km west and 2.5 km north of the quarry. The second and third highest 24-h average concentrations occur, respectively, 1.5 and 2.5 km both west and north of the quarry.

Figure 3 shows four contour plots illustrating the plume trajectory of the top 4 h in which TSP concentrations were the highest during the winter period of January 12, 2013 from 00 to 23 h00. As a result of the dominant northbound wind, all four contour plots have plume trajectories primarily extending north of the quarry. Table 5 shows that the top 4 highest 1-h average TSP concentrations are greater than 555 μg/m^3. Further examination of both Table 5 and Fig. 3 illustrates that at 01 h00, TSP has just begun to disperse outwards from the quarry. Thus, the second highest 1-h concentration of 876.7 μg/m^3, which occurs 2.5 km west and 0.5 km south of the quarry, is a result of TSP accumulation nearby the quarry prior to dispersion. This can be seen in the contour plot where

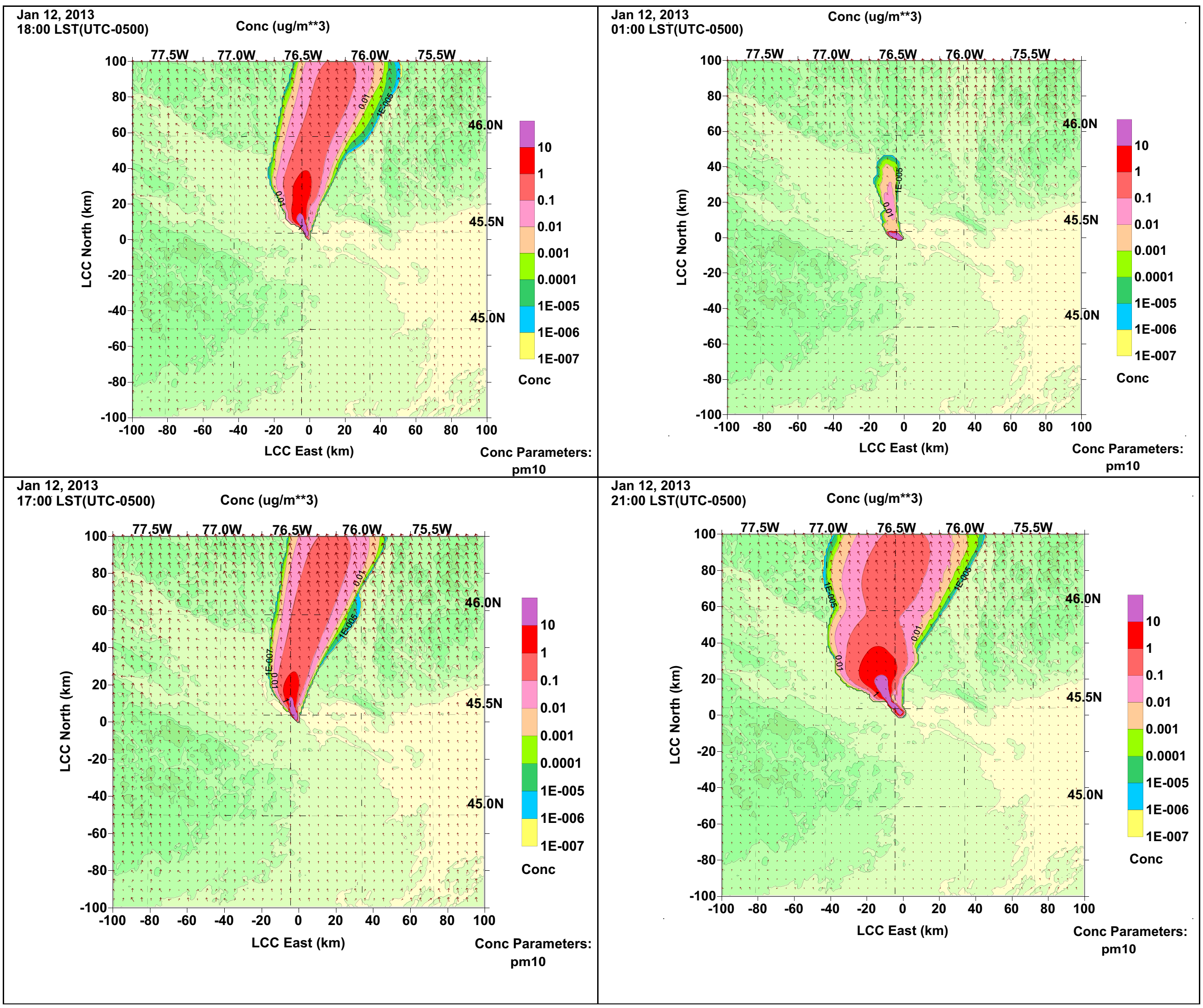

Fig. 3 Contour plots showing the plume trajectory of the first (*top left*), second (*top right*), third (*bottom left*), and fourth (*bottom right*) highest 1-h average TSP concentrations on January 12, 2013

the portion of the plume with a concentration greater than 10 disperses 10 km west of the quarry. The highest and third highest 1-h concentrations of, respectively, 934.9 and 627.2 μg/m^3 occur only 1 h apart from each other at 18 and 17 h00, respectively. They both also occur at the same location as the highest 24-h average concentration, 1.5 km west and 2.5 km north of the quarry. In both contour plots, the portion of the plume with a concentration greater than 10 extends 15 km northwards. Originally at 17 h00, the portion with a concentration ranging from 1 to 10 had dispersed 27 km northwards but by 18 h00, it further expanded to 40 km northwards. The fourth highest 1-h concentration of 594.0 μg/m^3 occurs at 21 h00 and at the same location as the third highest 24-h average concentration, 2.5 km west and north of the quarry. By this time, the plume trajectory of TSP has expanded both northwards and outwards. From the contour plot, the portion of the plume with a concentration greater than 10 disperses in the NW direction, 15 km west and 22 km north, while the surrounding portion of the plume with a concentration ranging from 1 to 10 is NW of the quarry and has a radius of about 20 km. These wind directions all correspond with the predominant wind directions indicated by the wind rose in Fig. 2. Wind is seen to be predominately coming from the S to ESE directions, with the dominant wind heading northbound.

From this analysis, it is evident that residents living north of the quarry would be most affected by TSP emissions on the winter day of January 12, 2013. This includes residents of Norway Bay, located 6 km north of the quarry, and visitors to the Arnprior Golf Club at Sand Point located only 2 km north of the quarry. Both these locations fall well within the portion of the plume with a concentration greater than 10. This has major negative impacts on residents living anywhere north of the quarry. As seen in Fig. 3, throughout the day the plumes continue to disperse further northwards and outwards, even affecting residents to the east and west of the quarry.

Spring

From Fig. 2, it can be seen that for the spring day of April 15, 2013, wind only blows from the SSW to ENE directions. Majority of the wind blows from the ESE to ENE directions, while the dominant wind direction comes from the E. For majority of the day, this westbound wind has a speed ranging from 3.3 to 5.4 m/s. The wind from the ESE direction, which has the second highest frequency, is also seen to have a strong impact. The most frequent wind speed ranges from 1.8 to 3.3 m/s, while its second most prominent wind speed is only slightly less frequent than the first and ranges from 3.3 to 5.4 m/s. Table 6 lists the top 20 highest 1-h and 24-h average concentrations of

Table 6 List of the top 20 1-h and 24-h average TSP concentrations simulated on April 15, 2013 from 00:00 to 23:00

	1-h average TSP concentrations			24-h average TSP concentrations	
	Time (HH:MM)	Concentration (μg/m^3)	Coordinates (km)	Concentration (μg/m^3)	Coordinates (km)
1	03:00	1467.9	−1.500, −1.500	82.0	−2.500, −0.500
2	04:00	853.1	−2.500, −0.500	80.3	−1.500, −0.500
3	05:00	798.5	−2.500, −0.500	70.4	−1.500, −1.500
4	20:00	473.2	−2.500, −1.500	47.5	−3.500, −1.500
5	05:00	412.9	−4.500, −0.500	39.2	−2.500, −1.500
6	05:00	394.0	−3.500, −0.500	33.2	−6.500, −2.500
7	22:00	381.5	−3.500, −1.500	32.1	−3.500, −0.500
8	17:00	380.0	−1.500, −0.500	27.8	−4.500, −1.500
9	01:00	365.3	−0.500, 1.500	26.5	−2.500, −2.500
10	21:00	332.8	−3.500, −1.500	24.3	−2.500, 0.500
11	22:00	310.9	−6.500, −2.500	24.3	−3.500, −2.500
12	22:00	286.8	−1.500, −0.500	23.8	−4.500, −0.500
13	04:00	272.4	−3.500, −2.500	21.3	−0.500, 1.500
14	03:00	262.9	−2.500, −2.500	18.4	−7.500, −2.500
15	21:00	262.7	−1.500, −0.500	18.0	−4.500, −2.500
16	18:00	240.3	−1.500, −0.500	17.8	−5.500, −2.500
17	04:00	239.3	−2.500, −2.500	16.7	−3.500, 0.500
18	04:00	224.5	−3.500, −0.500	15.2	−1.500, 4.500
19	05:00	220.9	−7.500, −2.500	14.3	−5.500, −0.500
20	05:00	214.7	−5.500, −0.500	14.2	−5.500, −3.500

TSP simulated for the spring period of April 15, 2013 from 00 to 23 h00. The highest and second highest 24-h average TSP concentrations of 82.0 and 80.3 μg/m^3 are notably greater than the third highest TSP concentrations of 70.4 μg/m^3 by around 10 μg/m^3. These top 3 highest 24-h average concentrations are all determined to be greater than 50 μg/m^3 and occur SW to W of the quarry as suggested by the wind rose in Fig. 2.

Figure 4 shows four contour plots illustrating the plume trajectory of the top 4 h in which TSP concentrations were the highest during the spring period of April 15, 2013 from 00 to 23 h00. As a result of the most prominent winds coming from the ESE to ENE directions, all four contour plots have plume trajectories primarily extending WSW to WNW of the quarry. Table 5 shows that the top 4 highest 1-h average TSP concentrations are greater than 450 μg/m^3. Further examination of both Table 6 and Fig. 4 illustrates that the top 3 highest 1-h average concentrations all sequentially occur 1 h after each other starting from 03 h00. Since TSP disperses very slowly outwards from the quarry on this day, the top 3 highest 1-h average concentrations are all a result of TSP accumulation nearby the quarry. The highest 1-h concentration at 03 h00 reached an exceptionally high TSP concentration of 1467.9 μg/m^3, which is the highest 1-h average TSP concentration determined out of the 4 days analyzed in this study. In the contour plot, the portion of the plume with a concentration greater than 10 has a radius of 12 km west of the quarry and is surrounded by the portion of the plume with a concentration ranging from 1 to 10 and that is of a 20-km radius. The second and third highest 1-h concentrations of, respectively, 853.1 and 798.5 μg/m^3 occur during the following hours of 04 and 05 h00, respectively. They both occur at the same location as

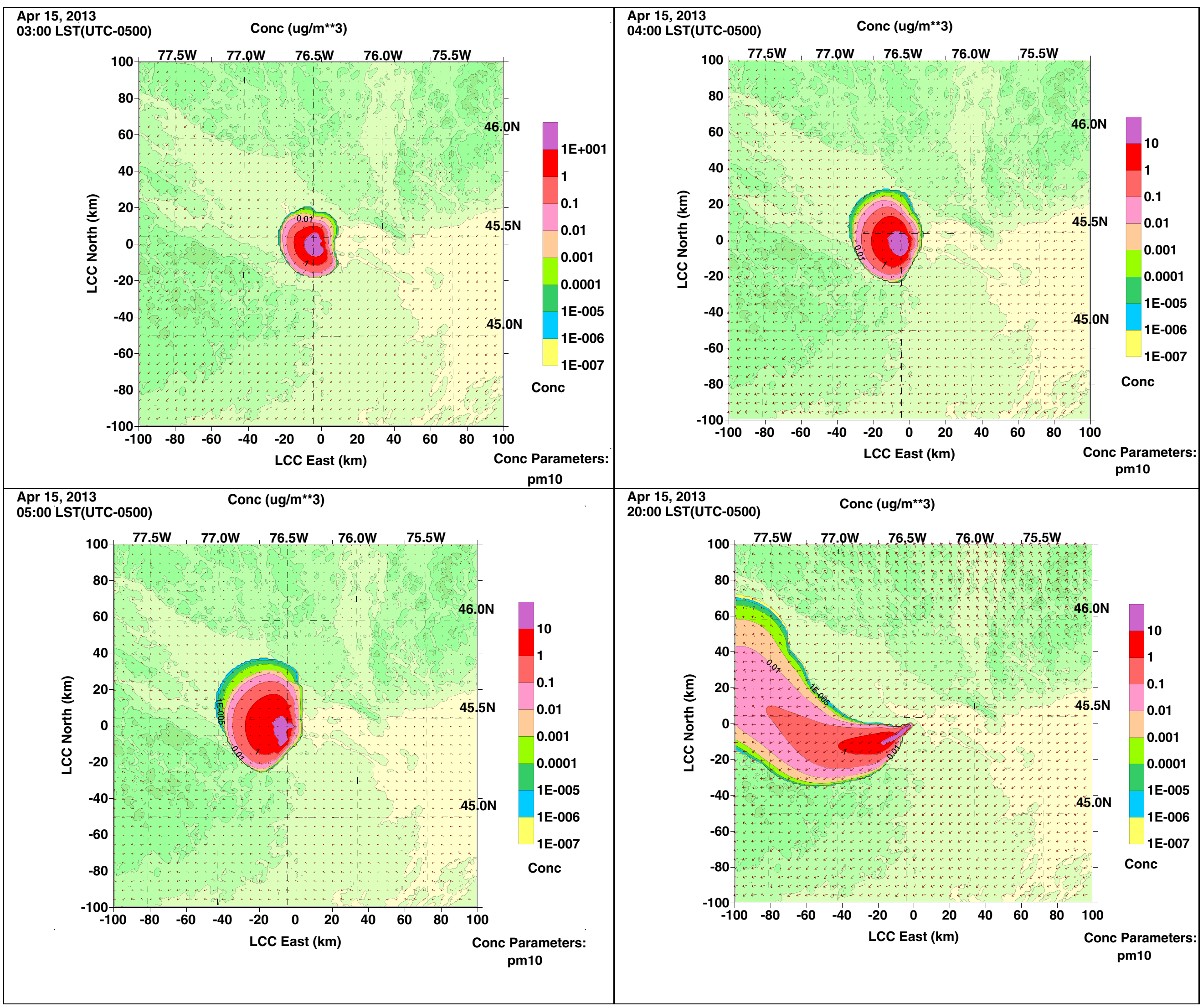

Fig. 4 Contour plots showing the plume trajectory of the first (*top left*), second (*top right*), third (*bottom left*), and fourth (*bottom right*) highest 1-h average TSP concentrations on April 15, 2013

the highest 24-h average concentration, 2.5 km west and 0.5 km south of the quarry. In the 04 h00 contour plot, the portion of the plume with a concentration greater than 10 still has a radius of 12 km west of the quarry, but by 05 h00, it has stretched southwards till it had a length of 15 km and width of about 5 km. At 04 h00, the surrounding portion of the plume with a concentration ranging from 1 to 10 expanded to a length of 30 km and a width of 20 km, and then further enlarged to a length of 32 km and a width of 30 km by 05 h00. The fourth highest 1-h concentration of 473.2 μg/m^3 occurs near the end of the day at 20 h00 and at a location 2.5 km west and 1.5 km south of the quarry. Due to the changing direction of the wind far north of the quarry, the plume trajectory of TSP near the quarry is dispersed in the SW direction, while further away from the quarry it is dispersed in the NW direction. From the contour plot, the portion of the plume with a concentration greater than 10 disperses in the SW direction, 20 km west and 10 km north, while the surrounding portion of the plume with a concentration ranging from 1 to 10 is SW of the quarry and has a length of about 10 km and a width of about 33 km. These wind directions all correspond with the predominant wind directions indicated by the wind rose in Fig. 2. Wind is seen to be predominately coming from the ENE to ESE directions, with the dominant wind heading westbound.

From this analysis, it is evident that residents living SW to NW of the quarry would be most affected by TSP emissions on the spring day of April 15, 2013. This includes the city hall of the township of McNab/Braeside, situated 5.5 km SW of the quarry, and the McNab Public School, situated 6.8 km SW of the quarry. Since this region consists of both a city hall and a school, there must be a moderate population of residents living nearby. It is also important to note that this region falls within the portion of the plume with a concentration greater than 10. This would have serious negative impacts on residents living anywhere SW to NW of the quarry, namely children, which is one of the categories of people most adversely affected by TSP.

Summer

From Fig. 2, it can also be seen that for the summer day of July 11, 2013, wind only blows from the SSW to N directions. Majority of the wind blows from the W to N directions, while the dominant wind direction comes from the N. For majority of the day, this southbound wind has a speed ranging from 3.3 to 5.4 m/s, with the remainder of the day having a faster wind speed ranging from 5.4 to 8.5 m/s. The wind from the NNW direction, which has the second highest frequency, is also seen to have a strong impact. For slightly over half the day, its wind

Table 7 List of the top 20 1-h and 24-h average TSP concentrations simulated on July 11, 2013 from 00:00 to 23:00

	1-h average TSP concentrations			24-h average TSP concentrations	
	Time (HH:MM)	Concentration (μg/m^3)	Coordinates (km)	Concentration (μg/m^3)	Coordinates (km)
1	19:00	838.2	−0.500, −0.500	146.1	−0.500, −0.500
2	01:00	475.5	0.500, 0.500	28.4	0.500, −3.500
3	18:00	410.5	−0.500, −0.500	26.0	0.500, −4.500
4	17:00	410.5	−0.500, −0.500	25.2	−0.500, −1.500
5	07:00	369.8	−0.500, −0.500	20.9	0.500, 0.500
6	08:00	362.3	−0.500, −0.500	19.6	2.500, −0.500
7	03:00	358.6	2.500, −0.500	19.3	−0.500, −5.500
8	20:00	318.2	0.500, −3.500	16.4	1.500, 0.500
9	12:00	307.5	−0.500, −0.500	16.1	2.500, 0.500
10	21:00	300.7	0.500, −4.500	14.8	3.500, −0.500
11	03:00	297.5	3.500, −0.500	11.9	0.500, −6.500
12	18:00	284.0	−0.500, −1.500	11.5	0.500, −1.500
13	01:00	241.7	1.500, 0.500	10.9	0.500, −2.500
14	00:00	241.3	2.500, 0.500	10.1	1.500, −8.500
15	21:00	236.4	0.500, −3.500	10.0	1.500, −9.500
16	03:00	194.8	4.500, −0.500	9.3	4.500, −0.500
17	01:00	178.8	3.500, 1.500	9.0	3.500, 1.500
18	22:00	175.2	0.500, −5.500	9.0	1.500, −10.500
19	21:00	165.0	1.500, −8.500	8.7	−0.500, −2.500
20	16:00	161.7	−0.500, −0.500	8.3	1.500, −11.500

speed ranges from 3.3 to 5.4 m/s, while the remainder of the day has a faster wind speed ranging from 5.4 to 8.5 m/s. Table 7 lists the top 20 highest 1-h and 24-h average concentrations of TSP simulated for the summer period of July 11, 2013 from 00 to 23 h00. The highest 24-h average TSP concentration of 146.1 μg/m^3 is the highest 24-h average TSP concentration determined out of the 4 days analyzed in this study. It is also significantly greater than the second and third highest TSP concentrations of 28.4 and 26.0 μg/m^3, respectively, over five times their concentrations. These top 3 highest 24-h average concentrations all occur SW to SE of the quarry as suggested by the wind rose in Fig. 2. The highest 24-h average concentration occurs at a location 0.5 km west and south of the quarry, the second highest concentration occurs 0.5 km east and 3.5 km south of the quarry, and the third highest concentration occurs 0.5 km east and 4.5 km south of the quarry.

Figure 5 shows four contour plots illustrating the plume trajectory of the top 4 h in which TSP concentrations were the highest during the summer period of July 11, 2013 from 00 to 23 h00. As a result of the dominant wind coming from the north, the contour plots during the later hours of the day have plume trajectories extending SSW to SSE of the quarry. Table 7 shows that the top 4 highest 1-h average TSP concentrations are greater than 400 μg/m^3. Further examination of both Table 7 and Fig. 5 illustrates that throughout the day, the portion of the plume with a concentration greater than 10 is very small and does not disperse far from the quarry. Thus, almost all of the top 20 highest 1-h TSP concentrations occur nearby the quarry. The first, third, and fourth highest 1-h average concentrations all occur at the same location and 1 h apart from each other, with the fourth highest concentration occurring at 17 h00, the

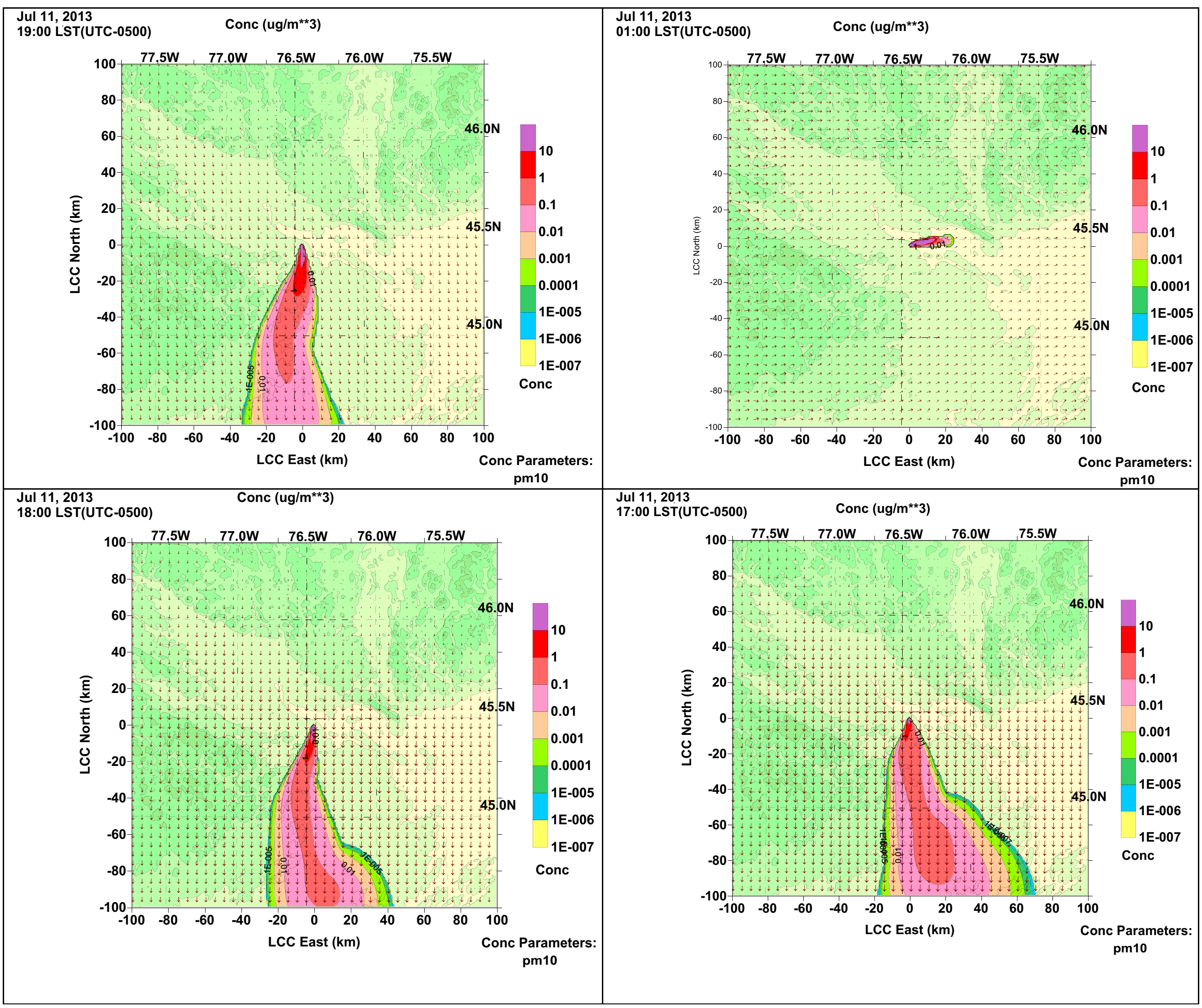

Fig. 5 Contour plots showing the plume trajectory of the first (top left), second (*top right*), third (*bottom left*), and fourth (*bottom right*) highest 1-h average TSP concentrations on July 11, 2013

third highest concentration occurring at 18 h00, and the first highest concentration at 19 h00. At 01 h00, TSP has just begun to disperse outwards from the quarry in the east direction as a result of the eastward wind at the time. Thus, the second highest 1-h concentration of 475.5 μg/m^3, which occurs 0.5 km north and east of the quarry, is a result of TSP accumulation nearby the quarry. This can be seen in the contour plot where the portion of the plume with a concentration greater than 10 disperses about 15 km east of the quarry. The third and fourth highest 1-h concentrations, at 18 and 17 h00, respectively, have the same concentration of 410.5 μg/m^3 and occur at the same location of 0.5 km west and south of the quarry. In the 17 h00 contour plot, the portion of the plume with a concentration greater than 10 disperses about 4 km south of the quarry, which further stretches to 10 km south of the quarry by 18 h00. The portion of the plume with a concentration ranging from 1 to 10 dispersed 12 km SSW to SSE by 17 h00, which further expands to 20 km S to SSE of the quarry by 18 h00. The highest 1-h concentration at 19 h00 reaches 838.2 μg/m^3 and also occurs 0.5 km west and south of the quarry. In the contour plot, the portion of the plume with a concentration greater than 10 disperses 13 km S to SSW of the quarry, while the portion with a concentration ranging from 1 to 10 is 22 km in length and 12 km in width.

From this analysis, it appears that only residents living in close proximity of the quarry would be affected by the most heavily concentrated TSP emissions on the summer day of July 11, 2013. The Arnprior Golf Club is located only 2.3 km east of the quarry and falls within the portion of the TSP plume that has a concentration greater than 10 during the earlier hours of the day. There are no major residential areas or buildings immediately SSW to SSE of the quarry. However, there may be a few families living relatively close to this region of the quarry. In addition, southeast of the quarry lies the village of Braeside, which is home to 191 residents, within 3 km away and the town of Arnprior, which is home to 8114 residents, within 8 km away. Arnprior contains the closest hospital to the township of McNab/Braeside, the Arnprior and District Memorial Hospital, which is situated 7.3 km away. Towards southwest of the quarry lies the city hall of the township of McNab/Braeside 5.5 km away and the McNab Public School 6.8 km away. The presence of a city hall and school indicate this is a relatively populated region. If the portion of the plume with a concentration greater than 10 expanded further in the SW or SE directions, many residents, including children living

Table 8 List of the top 20 1-h and 24-h average TSP concentrations simulated on November 17, 2013 from 00:00 to 23:00

	1-h average TSP concentrations			24-h average TSP concentrations	
	Time (HH:MM)	Concentration (μg/m^3)	Coordinates (km)	Concentration (μg/m^3)	Coordinates (km)
1	03:00	1147.8	−1.500, −0.500	140.9	−1.500, −0.500
2	05:00	764.4	−1.500, −0.500	39.0	−2.500, −0.500
3	07:00	595.7	−1.500, −0.500	36.6	−3.500, −1.500
4	06:00	440.6	−3.500, −1.500	28.1	−4.500, −1.500
5	06:00	361.1	−1.500, −0.500	26.0	−2.500, 1.500
6	21:00	349.5	−2.500, 1.500	26.0	−5.500, −1.500
7	03:00	330.5	−2.500, −0.500	21.4	−3.500, −0.500
8	04:00	304.2	−3.500, −2.500	21.2	−6.500, −2.500
9	03:00	266.8	−3.500, −0.500	18.1	−7.500, −2.500
10	04:00	266.4	−2.500, −1.500	17.9	−2.500, −1.500
11	03:00	257.8	−4.500, −0.500	17.2	−6.500, −1.500
12	20:00	257.2	−1.500, 1.500	16.9	−8.500, −2.500
13	22:00	239.4	−2.500, 1.500	16.7	−4.500, −0.500
14	01:00	220.7	−5.500, 2.500	16.0	−3.500, 1.500
15	00:00	214.2	−3.500, 1.500	16.0	−1.500, 1.500
16	17:00	211.7	−1.500, 2.500	14.8	−11.500, −3.500
17	07:00	207.9	−2.500, −0.500	14.6	−5.500, 2.500
18	03:00	199.4	−5.500, −0.500	14.4	−10.500, −3.500
19	06:00	186.8	−4.500, −1.500	14.4	−3.500, 2.500
20	21:00	177.1	−3.500, 2.500	14.2	−5.500, −2.500

nearby, would suffer from serious adverse TSP effects and even the Arnprior and District Memorial Hospital would be located within the affected region.

Autumn

From Fig. 2, it can be seen that for the autumn day of November 17, 2013, wind only blows from the S to ENE directions. Majority of the wind blows from the SSE to E directions, while the dominant wind direction comes from the E. For majority of the day, this westbound wind has a speed ranging from 3.3 to 5.4 m/s, with the remainder of the day having a slower wind speed ranging from 1.8 to 3.3 m/s. Table 8 lists the top 20 highest 1-h and 24-h average concentrations of TSP simulated for the autumn period of November 17, 2013 from 00 to 23 h00. The highest 24-h average TSP concentration of 140.9 μg/m^3 is significantly greater than the second and third highest TSP concentrations of 39.0 and 36.6 μg/m^3, respectively, slightly below four times their concentrations. These top 3 highest 24-h average concentrations all occur W to WSW of the quarry as suggested by the wind rose in Fig. 2. The highest 24-h average concentration occurs at a location 1.5 km west and 0.5 km south of the quarry, the second highest concentration occurs 2.5 km west and 0.5 km south of the quarry, and the third highest concentration occurs 3.5 km west and 1.5 km south of the quarry.

Figure 6 shows four contour plots illustrating the plume trajectory of the top 4 h in which TSP concentrations were the highest during the autumn period of November 17, 2013 from 00 to 23 h00. Table 8 shows that the top 4 highest 1-h average TSP concentrations are greater than 400 μg/m^3. Further examination of both Table 8 and Fig. 6 illustrates that the second, third, and fourth highest 1-h average concentrations all occur 1 h apart from each other, with the second highest

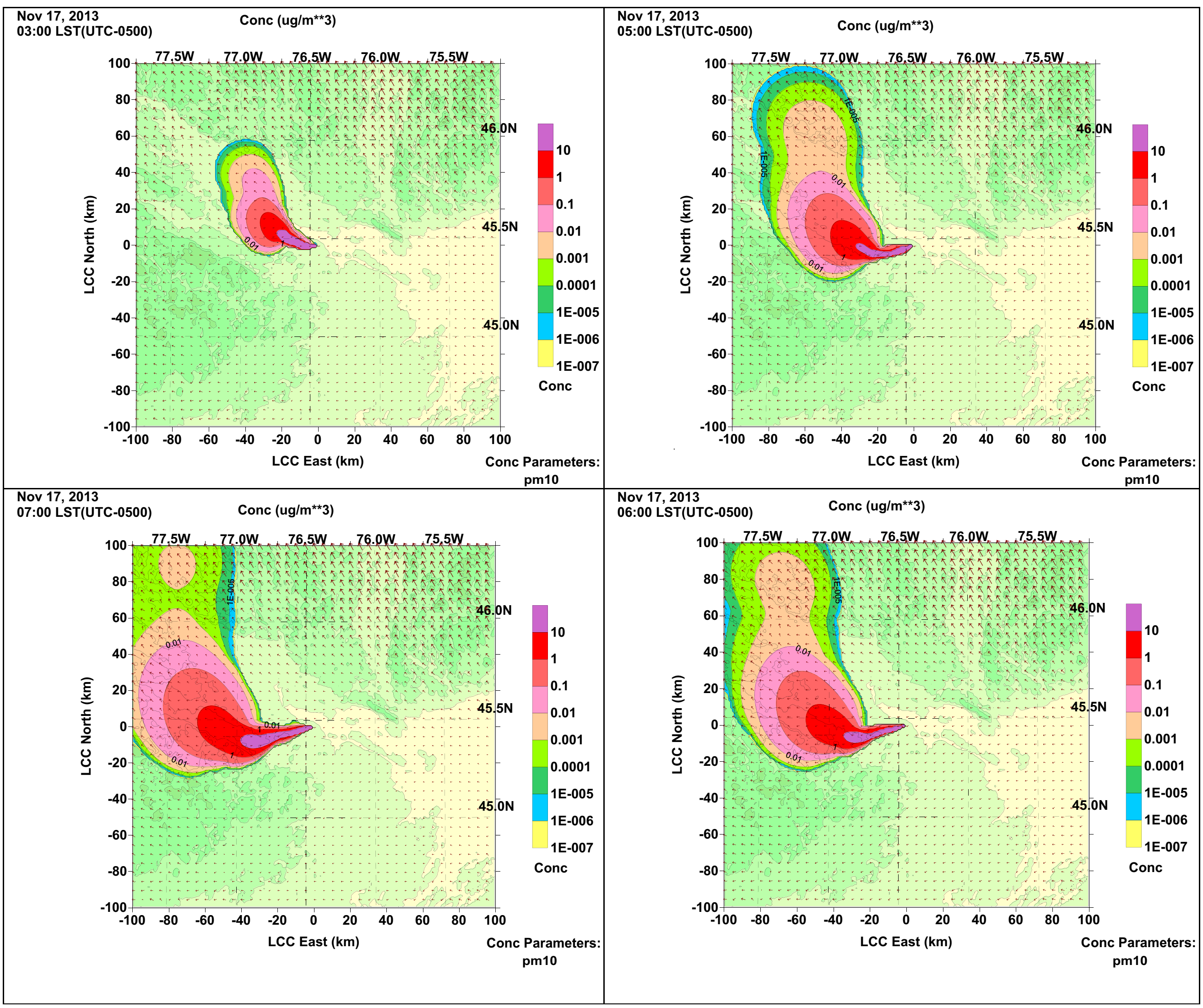

Fig. 6 Contour plots showing the plume trajectory of the first (*top left*), second (*top right*), third (*bottom left*), and fourth (*bottom right*) highest 1-h average TSP concentrations on November 17, 2013

Table 9 Maximum highest 30-min and 24-h concentrations of TSP with their corresponding criterion limits

Date	Maximum highest 30-min concentration, CALPUFF (μg/m^3)	30-min criterion (μg/m^3)	Maximum highest 24-h concentration, CALPUFF (μg/m^3)	24-h criterion (μg/m^3)
January 12, 2013	1135.15	100	132.86	120
April 15, 2013	1782.32		82.01	
July 11, 2013	1017.74		146.07	
November 17, 2013	1393.65		140.9	

concentration occurring at 05 h00, the fourth highest concentration occurring at 06 h00, and the third highest concentration occurring at 07 h00. The highest 1-h TSP concentration of 1147.8 μg/m^3 occurs at 03 h00, 2 h prior to the second highest concentration. The contour plot illustrates that the portion of the plume with a concentration greater than 10 disperses about 25 km in the WNW direction, while the portion with a concentration ranging from 1 to 10 surrounds it with a radius of about 15 km. The top 3 highest 1-h TSP concentrations all occur at the same location as the highest 24-h TSP concentration, 1.5 km west and 0.5 km south of the quarry. The second and third highest 1-h concentrations have concentrations of 764.4 and 595.7 μg/m^3, respectively. The fourth highest 1-h concentration of 440.6 μg/m^3 occurs at the same location as the third highest 24-h concentration, 3.5 km west and 1.5 km south of the quarry. In the 05, 06, and 07 h00 contour plots, the plume trajectories initially disperse from the quarry in the WSW direction but are then blown NW of the quarry. The portion of the plume with a concentration greater than 10 disperses overall 32 km west of the quarry by 05 h00, which further expands and is blown to 35 km WSW of the quarry by 06 h00 and 40 km WSW of the quarry by 07 h00. The surrounding portion of the plume with a concentration ranging from 1 to 10 follows the trajectory of the overall plume in dispersing WSW and then NW of the quarry. By 05 h00, this portion of the plume dispersed to a radius of about 20 km, which further expands and is blown to a length of 21 km and width of 25 km by 06 h00 and a length of 25 km and width of 30 km by 07 h00.

From this analysis, it is evident that residents living WSW close to the quarry and NW slightly further from the quarry would be most affected by TSP emissions on the autumn day of November 17, 2013. Although there are no major buildings or residential areas within this region, slight changes in the wind direction can cause the wind to blow in the SW or N directions. Southwest of the quarry lies the city hall of the township of McNab/Braeside 5.5 km away and the McNab Public School 6.8 km away. Similarly, north of the quarry lies the Arnprior Golf Club at Sand Point within 2 km away, while the settlement of Norway Bay lies across the Ottawa River within 6 km away. Since the portion of the plume with a concentration greater than 10 disperses far from the quarry, it would encompass the regions stated above if the plume were shifted or expanded SW or N of the quarry. This has major negative impacts on residents living anywhere SW to N of the quarry.

Comparison with Ontario regulation

Ontario's has two criterions for the TSP average concentration, a 30-min limit and a 24-h limit. Since only the highest 1-h and 24-h average TSP concentrations were determined from this study, it is necessary to convert the highest 1-h concentrations to its 30-min concentration equivalents. The following equation was used for this purpose (Ontario Provincial Government 2005):

$$(\text{30-minute concentration}) = (\text{1-hour concentration}) \times (1\ \text{h}/0.5\ \text{h})^{0.28}$$

Table 9 shows a comparison of the highest 30-min and 24-h average TSP concentrations for each of the 4 days examined in this study compared to Ontario's MOE TSP criterions for 30-min and 24-h. The MOE in Ontario has 30-min and 24-h maximum TSP concentration criterions of 100 and 120 μg/m^3, respectively. The maximum 30-min average TSP concentrations determined for the 4 days analyzed in this study all significantly exceed Ontario's 30-min criterion. Likewise, the 24-h average TSP concentrations on January 12, July 20, and November 17 of 2003 are all well above Ontario's 24-h criterion. The 24-h average TSP concentration on April 15, 2003 is well below Ontario's 24-h criterion. However, given that quarry emission levels will vary on a day-to-day basis, changes in the seasonal weather may cause TSP concentration levels to even exceed the highest concentration levels determined in this study.

Conclusions

From the results of this study, the spring day of April 15, 2003 was determined to have the highest 1-h average TSP concentration, while the summer day of July 11, 2003 was determined to have the highest 24-h average TSP concentration out of all 4 days analyzed. In the year 2003, the highest 30-min average TSP concentrations on January 12, April 15, July 11, and November 17 were determined to, respectively, be 1135.15, 1782.32, 1017.74, and 1393.65 $\mu g/m^3$. These TSP concentrations all significantly exceed Ontario's MOE 30-min criterion of 100 $\mu g/m^3$. Likewise, in the year 2013, the highest 24-h average TSP concentrations on January 12, April 15, July 11, and November 17 were determined to, respectively, be 132.86, 82.01, 146.07, and 104.9 $\mu g/m^3$. The TSP concentrations on January 12, July 11, and November 17 are all well above Ontario's MOE 24-h criterion of 120 $\mu g/m^3$, while the concentration on April 15 is well under this limit. Taking these 4 days as a representation of each season, it can be concluded that overall the predicted maximum TSP levels are not within the limits of the applicable standards. In addition, it should be noted that with the changing seasonal weather, TSP concentrations may even exceed the concentrations determined in this study and disperse further from the quarry. During the hours or days where TSP concentrations are high, citizens residing, working, or touring nearby the quarry would experience serious adverse TSP effects. In particular, children, the elderly, and citizens allergic to TSP experience the most hazardous effects of TSP. Unfortunately, many residential areas, in addition to both a hospital and school, are found to be located within close proximity to the quarry.

Recommendations

Overall, it is recommended that the Miller Braeside Quarry adjust their emission settings to meet the Ontario's regulated TSP concentration criterion. The quarry could try to use cleaner alternative fuel sources to reduce their emissions of TSP and other pollutants. They could also install air filters and regularly change the filters to efficiently filtrate TSP and other pollutants from the gas emissions prior to releasing it from the boundaries of the quarry. Additionally, it is recommended that the dust management plan suggested by Miller Paving Limited be implemented to further reduce TSP concentrations. Nevertheless, in its current proposed state, it is not recommended that the proposal for the expansion of the Miller Braeside Quarry be approved as a result of health and safety issues.

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