Studies that investigate the environmental health risks to Cairo residents invariably conclude that lead is one of the area’s major health hazards. Lead is a very toxic element that is capable of causing a variety of health effects at low dose levels. Long-term exposure to lead in humans results in effects upon the blood, central nervous system, blood pressure, kidneys, and metabolism. The principal routes of human exposure are ingestion and inhalation, both of which are encouraged through airborne lead.

Through the Cairo Air Improvement Project (CAIP), a lead emission inventory has been developed for the greater Cairo (GC) area. This inventory presents a current listing by major source of the annual lead emissions in the GC area. The inventory, and the associated database, may be used to develop effective regulatory and control strategies, assessing emissions trends, and conducting modeling exercises. This paper describes the development of the current lead emissions inventory (1999–2010), along with an approach to develop site specific emission factors and measurements to validate the inventory. This paper discusses the major sources of lead in the GC area, which include lead smelters, Mazout (heavy fuel oil) combustion, lead manufacturing batteries factories, copper foundries, and cement factories. Included will be the trend in the lead emissions inventory with regard to the production capacity of each source category. In addition, the lead ambient measurements from 1999 through 2010 are described and compared with the results of Source Attribution Studies (SAS) conducted in 1999, 2002, and 2010. Due to EEAA/CAIP efforts, a remarkable decrease in more than 90% in lead emissions was attained for 2007.

© 2013 Production and hosting by Elsevier B.V. on behalf of Cairo University.
effective regulatory and control strategies, assess emissions trends, and conduct modeling exercises.

Pure lead is a silvery-white metal that oxidizes and turns bluish-gray when exposed to air. Its properties include the following: a low melting point; ease of casting; high density; low strength; ease of fabrication; acid resistance; electrochemical reaction with sulfuric acid; chemical stability in air, water, and earth; and the ability to attenuate sound waves, atomic radiation, and mechanical vibration. Lead in its elemental or pure form rarely occurs in nature. Lead most commonly occurs as the mineral galena (lead sulfide \( \text{PbS} \)) and is sometimes found in other mineral forms [1–3].

For many of the uses in Cairo and elsewhere, lead must be hardened. Lead is hardened by alloying it with small amounts of arsenic, copper, antimony, or other metals. These alloys may then be used in manufacturing various lead-containing products. In addition to lead alloys, there are many lead compounds that may be used in the manufacture of lead-containing products.

Though lead has many uses, it is also a toxic material that can adversely affect the blood, nervous system, brain, and kidneys. The principal routes of human exposure are ingestion and inhalation. Manifestations of lead exposure include anemia, encephalopathy, and kidney damage. Studies that investigate the environmental health risks to Cairo residents invariably conclude that lead is one of the area's major health hazards [4]. Several references report ambient lead levels up to 10 \( \mu \text{g/m}^2 \) in many areas of Cairo and in the range of 10–50 \( \mu \text{g/m}^2 \) in industrial areas. Studies of blood lead levels in Cairo resident's report that some children, the most sensitive receptors in the population, have blood lead concentrations up to three times the "safe" level.

Though much has been done to reduce the ambient lead concentrations, there are further opportunities for improvement. In order to implement policies with a goal of reducing the amount of ambient airborne lead, it is necessary to have an accurate lead emissions inventory that details the primary sources of ambient lead. With this information, sources can be prioritized and corrective actions can first be taken where they will have the greatest positive effect. This work presents an important step in reducing health risks due to lead exposure was taken when an additive containing lead compounds was removed from gasoline sold in the GC area. This action reduced the exposure of the general public to lead emitted from mobile sources. Thus, stationary sources are thought to be the major remaining sources of lead emissions and are the main focus of this inventory.

Though the previously mentioned activities may each emit lead, it is beyond the scope of an initial emissions inventory to include every potential source of emissions. Rather, this emissions inventory will focus on the industries and activities that are felt to be most significant in the GC area. Based on monitoring data, preliminary emissions investigations, and the experience of the USEPA and local environmental professionals, it was felt that the most significant remaining sources of ambient lead emissions in Cairo are summarized in Table 2.

### Data collection

The secondary lead smelting, lead–acid battery, copper, and Portland cement production data given in this research were obtained using 1999 facility surveys. Mazout usage data were obtained from the Ministry of Petroleum [8,9]. Fig. 1 presents the GC area which involves most of lead pollution facilities in Egypt. The GC area involves major parts of three governorates (Cairo, Giza, and Kalubia). All the collected data are given in Table 3.

### Emissions estimation

An emission factor is a representative value that relates the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of lead emitted per metric ton of Mazout burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of the available data of acceptable quality and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average). In the absence of continuous emissions data, emission factors are frequently the best or only method available for estimating emissions, in spite of their limitations [8,9].

The general equation for emission estimation using an emission factor is:

\[
E = A \times EF \times \left(1 - \frac{ER}{100}\right)
\]

where \( E \), emissions; \( EF \), emission factor; \( A \), activity rate; and \( ER \), overall emission reduction efficiency, \%. The emissions reduction efficiency can be accounted for either using the ER term in the equation above or by developing emission factors that incorporate the emissions reduction (as is done for Portland cement kilns). Note that, although there are a small number of air pollution control devices installed at the facilities surveyed, these are by and large ineffective or inoperable. Thus, for most facilities, no emissions reduction efficiency has been used in estimating emissions. The one exception is the Portland cement industry, which has efficient and operational control devices. Emissions reductions due to the use of
Emissions of lead were calculated for each source using emission factors from three sources:

- Compilation of Air Pollutant Emission Factors, Fifth Edition, AP-42, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.
- Source tests performed in Cairo by the CAIP for the express purpose of developing emission factors.
- Mass balance using materials information.

It should be noted that emissions estimates rely not only upon the emission factors, but also upon reliable and accurate production data (“activity rate” in the equation above). The production data used to estimate emissions for this inventory came primarily from the facility surveys. The survey requested actual production data for 1999 and repeated in 2000, 2001, and 2007. It appears that the Egyptian government has to conduct major efforts to reduce lead concentrations in the ambient air of the GC area and to move the lead smelters outside the residential area. These efforts continued from 2001 through 2007 in complete cooperation with two USAID projects which area Cairo Air Improvement Project (CAIP) till 2003 and the Egyptian Environmental Policy Program (EEPP) till 2007 (the Life Lead Component).

Lead emission inventory for the Greater Cairo

Lead emission factor development for Mazout combustion

The emission factor for Mazout combustion was developed using an analysis of the fuel.

Samples of Mazout from the GC Area were collected and analyzed for lead content. These results are summarized in Table 4.

Though combustion technique will have an effect upon lead emissions because some lead may concentrate in any bottom ash or slag that may be generated, this effect is assumed to be negligible for Mazout combustion in the GC area. Rather, it has been assumed that 100% of the lead present in the fuel will be emitted. The emission factor used is the average of the sampled lead concentrations. Further work may focus on the different combustion techniques used and their effect upon total lead emissions.

Emission factor for Mazout combustion:

\[
\text{Emission factor for Mazout combustion:} \quad 114 \frac{\text{mg lead}}{\text{kg mazout combusted}} \times 0.89 \frac{\text{lb lead}}{1000 \text{ gal mazout combusted}}
\]

Though the USEPA has not developed emission factors for Mazout combustion, external combustion emission factors for residual oil #6 and waste oil have been developed.

These emission factors range from approximately 0.0015 lb of lead per thousand gallons of residual oil #6 combusted to 1.68 lb of lead per thousand gallons of waste oil combusted [10].

Lead emission factor developed for Portland cement manufacturing

The Portland cement manufacturing process can be divided into raw materials handling, kiln feed preparation, pyroprocessing, and finished cement grinding. The primary focus is upon emissions from the pyroprocessing operations (the kilns), which constitute the core of a Portland cement plant. Pyroprocessing in the GC area is accomplished using the wet and the dry processes. In the dry process, raw materials are fed into the rotary kiln in a dry state, whereas in the wet process, the raw materials are mixed with water to form a slurry before being fed into the kiln.
The USEPA AP-42 document provides emission factors for lead emissions from Portland cement kilns having either an electrostatic precipitator or a fabric filter control device [7].

The EPA Locating and Estimating (L&E) document [11] provides additional factors for kilns not having control equipment. The appropriate emission factor has been used for each kiln in the GC area.

Emission factors for Portland cement manufacturing:

- **Cement Kiln with fabric filter control:**
  \[ \frac{3.8 \times 10^{-5}}{1000 \text{ kg clinker produced}} \times 7.5 \times 10^{-3} \frac{\text{lb lead}}{\text{ton clinker produced}} \]

- **Cement Kiln with electrostatic precipitator control:**
  \[ \frac{3.6 \times 10^{-4}}{1000 \text{ kg clinker produced}} \times 7.1 \times 10^{-4} \frac{\text{lb lead}}{\text{ton clinker produced}} \]

There was some initial concern that the raw materials in Egypt may vary significantly in lead content from the raw materials used in the United States. If this were the case, it would not be appropriate to use the USEPA emission factor. Samples of Egyptian and U.S. cement were tested for lead con-

---

**Table 3** The most significant activities which have high lead emissions in the Greater Cairo area (GC).

| Activity                          | Governorate | No. of facilities | Total no. in 1999 | Total no. in 2010 |
|-----------------------------------|-------------|-------------------|-------------------|-------------------|
| Secondary lead smelter            | Cairo       | 7                 | 15                | Zero              |
|                                   | Giza        | 3                 |                   |                   |
|                                   | Kalubia     | 5                 |                   |                   |
| Secondary copper process          | Cairo       | 184               | 206               | 206               |
|                                   | Giza        | 8                 |                   |                   |
|                                   | Kalubia     | 14                |                   |                   |
| Lead–acid battery production      | Cairo       | 23                | 33                | 33                |
|                                   | Giza        | 10                |                   |                   |
|                                   | Kalubia     |                   |                   |                   |
| Portland cement magnification     | Cairo       | 3                 | 3                 | 3                 |
|                                   | Giza        | –                 |                   |                   |
|                                   | Kalubia     | –                 |                   |                   |

---

The USEPA AP-42 document provides emission factors for lead emissions from Portland cement kilns having either an electrostatic precipitator or a fabric filter control device [7].

The EPA Locating and Estimating (L&E) document [11] provides additional factors for kilns not having control equipment. The appropriate emission factor has been used for each kiln in the GC area.

Emission factors for Portland cement manufacturing:

- **Cement Kiln with fabric filter control:**
  \[ \frac{6.00 \times 10^{-2}}{1000 \text{ kg clinker produced}} \times 0.120 \]
  \[ \frac{\text{kg lead}}{\text{ton clinker produced}} \]

- **Cement Kiln with electrostatic precipitator control:**
  \[ \frac{3.6 \times 10^{-4}}{1000 \text{ kg clinker produced}} \times 7.1 \times 10^{-4} \frac{\text{lb lead}}{\text{ton clinker produced}} \]

There was some initial concern that the raw materials in Egypt may vary significantly in lead content from the raw materials used in the United States. If this were the case, it would not be appropriate to use the USEPA emission factor. Samples of Egyptian and U.S. cement were tested for lead con-
tent and were found to be similar. Thus, the use of the USEPA emission factor seems appropriate. The results of the testing are summarized in the Table 5.

Although the AP-42 emission factors have been used, it should be noted that they have a “D” rating indicating that EPA believes the emission factors to be below average in accuracy. This means that the data may have come from a limited number of facilities, and that there may be some reason to suspect that there is variability within the industry. Thus, the emission factor may not be representative of the industry as a whole. Further refinement of these emissions factors could occur as a result of a limited source-testing program in Egypt.

In addition, the USEPA AP-42 document provides an estimate of lead emissions from cement kilns, but does not provide lead emissions from related processes such as raw material and clinker grinding. Further research may establish whether these are significant sources of lead emissions in the GC area.

Results and discussion

Stationary source emissions

Secondary lead smelting

The secondary lead smelting industry produces elemental lead and lead alloys by reclaiming lead. The primary source of the reclaimed lead is scrap automobile and truck batteries. Smelting is the reduction of lead compounds to elemental lead and requires a higher temperature than that required for melting lead. Rotary furnaces are typically used for smelting scrap lead and producing secondary lead. After processing in the rotary furnace, the secondary lead is typically refined in a kettle to produce soft lead, or refined and alloyed to produce hard lead. The typical sequence of operations at an Egyptian secondary lead smelting operation includes scrap receiving and preparation, rotary furnace smelting, lead refining and alloying, and casting. Battery breaking is also performed at a number of facilities (primarily the Awadallah facilities) and is undoubtedly a source of lead emissions. However, because of the variable nature of emissions from battery breaking, USEPA has elected not to develop an emission factor for this process. Given the relatively minor amount of emissions from battery breaking, the lead emissions from this process are not accounted for in this work. However, in the future, it may be helpful to perform testing at an Awadallah facility and develop an emission factor. As battery breaking is performed primarily at the Awadallah facilities, an emission factor may be appropriate in Egypt while it may not be in the United States.

Rotary furnace smelting

A rotary furnace is typically a refractory-lined steel drum mounted on rollers with an electric motor to rotate the drum. Fuel is injected at one end of the drum, and the connection to the exhaust stack (if applicable) is often located at the same end. The furnaces are operated on a batch basis.

Emission factors were developed by CAIP through source testing at several facilities in Cairo. Two emission factors have been developed for this process. One is applicable at the Awadallah facilities, and the other is applicable at all other facilities. The Awadallah facilities produced nearly 75% of the total lead ingot from January 1999 through December 2001 and consistently showed lower emissions from their rotary furnaces [12]. It was felt that the most accurate portrayal of emissions from this process would result from separating the Awadallah facilities from the others. The emission factor for lead emissions from rotary furnaces at secondary lead smelters was applied directly to the annual production throughput to calculate annual emissions, as shown below. The production throughput for rotary furnaces is the amount of lead ingot produced.

Awadallah facilities

\[
\begin{align*}
(1999) & = 44,400 \frac{\text{metric tons ingots}}{\text{year}} \times 21.4 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 950,160 \frac{\text{kg lead emitted}}{\text{year}} \\
(2000) & = 23,500 \frac{\text{metric tons ingots}}{\text{year}} \times 21.4 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 502,900 \frac{\text{kg lead emitted}}{\text{year}} \\
(2001) & = 24,600 \frac{\text{metric tons ingots}}{\text{year}} \times 21.4 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 526,440 \frac{\text{kg lead emitted}}{\text{year}} \\
(2007) & = \text{Zero} \frac{\text{metric tons ingots}}{\text{year}} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} \Rightarrow \text{Zero} \frac{\text{kg lead emitted}}{\text{year}} \\
(2010) & = \text{Zero} \frac{\text{metric tons ingots}}{\text{year}} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} \Rightarrow \text{Zero} \frac{\text{kg lead emitted}}{\text{year}}
\end{align*}
\]

Other facilities

\[
\begin{align*}
(1999) & = 15,540 \frac{\text{metric tons ingots}}{\text{year}} \times 76.6 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 1,193,472 \frac{\text{kg lead emitted}}{\text{year}} \\
(2000) & = 12,770 \frac{\text{metric tons ingots}}{\text{year}} \times 76.8 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 980,736 \frac{\text{kg lead emitted}}{\text{year}} \\
(2001) & = 16,710 \frac{\text{metric tons ingots}}{\text{year}} \times 76.8 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 128,332 \frac{\text{kg lead emitted}}{\text{year}} \\
(2007) & = \text{Zero} \frac{\text{metric tons ingots}}{\text{year}} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} \Rightarrow \text{Zero} \frac{\text{kg lead emitted}}{\text{year}} \\
(2010) & = \text{Zero} \frac{\text{metric tons ingots}}{\text{year}} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} \Rightarrow \text{Zero} \frac{\text{kg lead emitted}}{\text{year}}
\end{align*}
\]

Kettle refining operations

After the secondary lead is produced from the rotary furnace, it is typically cooled into bars that are then used as the feed stream for the kettle refining process. In this process, large, open-top, heated kettles are used to melt and refine the secondary lead. In some cases, smaller cauldrons are used in lieu of kettles, but the principal of operation is the same. This is also the step in the process where other metals such as antimony can be added to produce a desired lead alloy.
Table 6 1999 (Panel a), 2000 (Panel b), 2001 (Panel c), 2007 (Panel d), 2010 (Panel e) lead emission summary. Estimate of lead emissions from major sources in the Greater Cairo area.

| Activity | Number of facilities | 1999 Production | 1999 Lead emissions (metric tons) | Percentage of total lead emissions (%) |
|----------|---------------------|----------------|----------------------------------|-----------------------------------------|
| Panel (a) |                     |                |                                  |                                         |
| Secondary lead smelting\(^a\) | 14 | 59,940 (metric tons lead ingot) | 2177 | 81.6 |
| Lead-acid battery production\(^a\) | 33 | 416,600 (batteries) | 3.41 | 0.13 |
| Secondary copper processing\(^a\) | 207 | 16,080 (metric tons) | 8.04 | 0.30 |
| Portland cement manufacturing\(^a\) | 3 | ~13,500,000 (metric tons cement) | 3.39 | 0.13 |
| Mazout combustion\(^b\) | Not applicable | 4,180,000 (metric tons Mazout consumed) | 477 | 17.9 |
| Total | 2669 | 100 |
| Panel (b) |                     |                |                                  |                                         |
| Secondary lead smelting\(^a\) | 14 | 36,270 (metric tons lead ingot) | 1504 | 79.45 |
| Lead-acid battery production\(^a\) | 34 | 386,613 (batteries) | 3.16 | 0.16 |
| Secondary copper processing\(^a\) | 207 | 12,864 (metric tons) | 6.43 | 0.33 |
| Portland cement manufacturing\(^a\) | 4 | ~10,859,420 (metric tons cement) | 2.89 | 0.15 |
| Mazout combustion\(^b\) | Not applicable | 3,304,600 (metric tons Mazout consumed) | 376.7 | 19.89 |
| Total | 1893 | 100 |
| Panel (c) |                     |                |                                  |                                         |
| Secondary lead smelting\(^c\) | Zero | Zero | Zero | 0 |
| Lead-acid battery production\(^c\) | 34 | 349,406 (batteries) | 2.86 | 1.26 |
| Secondary copper processing\(^c\) | 207 | 8.643 (metric tons) | 4.32 | 2.0 |
| Portland cement manufacturing\(^c\) | 4 | ~14,000,000 (metric tons cement) | 3.62 | 1.59 |
| Mazout combustion\(^b\) | Not applicable | 1,999,412 (metric tons Mazout consumed) | 250.7 | 27.34 |
| Total | 916.99 | 100 |
| Panel (d) |                     |                |                                  |                                         |
| Secondary lead smelting\(^c\) | Zero | Zero | Zero | 0 |
| Lead-acid battery production\(^c\) | 34 | 349,406 (batteries) | 2.86 | 1.26 |
| Secondary copper processing\(^c\) | 207 | 8.643 (metric tons) | 4.32 | 2.0 |
| Portland cement manufacturing\(^c\) | 4 | ~13,510,000 (metric tons cement) | 3.62 | 2.73 |
| Mazout combustion\(^b\) | Not applicable | 1,068,000 (metric tons Mazout consumed) | 121.75 | 91.85 |
| Total | 227.40 | 100 |
| Panel (e) |                     |                |                                  |                                         |
| Secondary lead smelting\(^c\) | Zero | Zero | Zero | 0 |
| Lead-acid battery production\(^c\) | 34 | 349,406 (batteries) | 2.86 | 1.26 |
| Secondary copper processing\(^c\) | 207 | 8.643 (metric tons) | 4.32 | 2.0 |
| Portland cement manufacturing\(^c\) | 4 | ~13,510,000 (metric tons cement) | 3.62 | 2.73 |
| Mazout combustion\(^b\) | Not applicable | 1,068,000 (metric tons Mazout consumed) | 121.75 | 91.85 |
| Total | 132.55 | 100 |

\(^a\) Production data source: CAIP survey.
\(^b\) Production data source: Ministry of Petroleum.
\(^c\) Production data source: EEAA survey.
Emission factors were developed by CAIP through source testing at several facilities in Cairo. The emission factor for lead emissions from kettle refining operations at secondary lead smelters was applied directly to the annual production throughput to calculate annual emissions, as shown below. The production throughput for refining kettles is equivalent to the amount of refined lead ingots produced. One facility does not use refining kettles, but only rotary furnaces, which is why the throughput for this process is lower than that for the rotary furnace.

\[
\begin{align*}
(1999) & : 51,540 \text{ metric ton ingots} \times 0.63 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 32,470 \frac{\text{kg lead emitted}}{\text{year}} \\
(2000) & : 31,192 \text{ metric ton ingots} \times 0.63 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 19,651 \frac{\text{kg lead emitted}}{\text{year}} \\
(2001) & : 34,311 \text{ metric ton ingots} \times 0.63 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 21,611 \frac{\text{kg lead emitted}}{\text{year}} \\
(2007) & : \text{Zero} \text{ metric ton ingots} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = \text{Zero} \frac{\text{kg lead emitted}}{\text{year}} \\
(2010) & : \text{Zero} \text{ metric ton ingots} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = \text{Zero} \frac{\text{kg lead emitted}}{\text{year}}
\end{align*}
\]

Casting

After the lead is refined in the refining/alloying kettles, it is typically poured into molds and allowed to cool. The pouring process is usually done by hand with one operator dipping a ladle into the refining kettle and pouring the molten lead into the mold. Another operator skims any impurities from the top of the molten lead as it cools and removes the hardened lead after the cooling process is complete. This is often the final product from a secondary lead smelter.

The USEPA believes that casting of lead is a comparatively small source of lead emissions because the temperature of molten lead is well below the fuming temperature of lead. Visual inspection of select casting operations in Cairo confirmed that only a negligible amount of lead fumes was visible during the casting operation. Thus, it was felt that the AP-42 emission factor for lead casting was appropriate for use in Cairo.

The emission factor for lead emissions from casting processes at secondary lead smelters was applied directly to the annual production throughput to calculate annual emissions, as shown below. The production throughput for casting operations is equivalent to the amount of lead ingots produced.

\[
\begin{align*}
(1999) & : 59,940 \text{ metric ton ingots} \times 0.0074 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 444 \frac{\text{kg lead emitted}}{\text{year}} \\
(2000) & : 36,270 \text{ metric ton ingots} \times 0.0074 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 268 \frac{\text{kg lead emitted}}{\text{year}} \\
(2001) & : 39,897 \text{ metric ton ingots} \times 0.0074 \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = 295.2 \frac{\text{kg lead emitted}}{\text{year}} \\
(2007) & : \text{Zero} \text{ metric ton ingots} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = \text{Zero} \frac{\text{kg lead emitted}}{\text{year}} \\
(2010) & : \text{Zero} \text{ metric ton ingots} \times \text{Zero} \frac{\text{kg lead emitted}}{\text{metric ton ingots}} = \text{Zero} \frac{\text{kg lead emitted}}{\text{year}}
\end{align*}
\]

A summary of 1999, 2000 emissions from this industry is provided in Table 6. Fig. 2, presents the lead emissions from different sources from 1999 through 2010 for secondary lead smelters and Mazout (heavy fuel oil) combustion, while Fig. 3 presents the lead emissions from the other sources which are lead acid batteries, secondary copper processing and cement factories.

From Table 6, it can be concluded easily that the main source of lead pollution is the lead smelters. Due to the huge efforts done through the past 10 years, the lead emissions from
smelters decreased dramatically from 2177 metric tons in 1999, to 1504 in 2000, to 654.8 in 2001 and reaches zero in 2007 and 2010. The elimination of smelting emission is due to closing all lead smelters from the residential area in the GC area and moving it to industrial area after modifying the engineering processes (preparing environmental impact assessment (EIA) studies and using up-to-date manufacturing processes).

It can be concluded too that the second major source of lead pollution is the Mazout combustion. It now can be considered as the major source of lead pollution in the GC area. The other sources of lead pollution are minor contributors for lead pollution and the sources are the lead acid batteries, secondary copper processing, and cement factories.

Ambient lead data in the Greater Cairo area

The annual average lead concentrations in the particulate matter PM$_{10}$ (Pb$_{10}$) concentration recorded during the period of 1999-2010 are shown in Fig. 4 in the GC area (annual averages of all monitoring sites) [13].

From the ambient lead concentrations in the GC area during the past few years, it can be concluded that the lead concentrations decreased a lot and its values are within the limits stated in the environmental law in Egypt (no. 4/1994) and law no. 9 for 2009 and its executive regulations of 1.5 µg m$^{-3}$.
Note that the concentrations of PM$_{10}$ and PM$_{2.5}$ approximately have not changed during the period from starting monitoring it in 1998–2010. This is due to the large increase in vehicles in the GC area, open burning processes for wastes, emissions from factories, and dramatic increase in the fall due to burning of the rice straw.

For Cairo City (Governorate), we can say that it is one of the world’s overpopulated cities, visited daily by not less than 1 million Egyptians, Arabs, and foreigners for treatment, tourism, work, or on commercial and economic business. The number of registered factories inside the city was 8536 in 2008 and the number of laborers was 51,998. In Giza city (which is part of the GC area), the number of registered factories was 2212 in 2008 and the number of laborers was 210,999. In Qaliubeya governorate (which is part of the GC area), the number of registered factories was 1762 in 2008 and the number of laborers was 212,003. This is according to the data of the Ministry of Industry and Mineral wealth. There are a huge number of industries in the GC area and causes lot of PM$_{10}$ and PM$_{2.5}$ emissions.

**Source Attribution Study (SAS) data in the Greater Cairo area**

To complete the Source Attribution Study (SAS), source emissions and representative ambient air samples for the GC area were collected. The source samples provide a “signature” that was defined by the chemical species present in the emissions and the relative concentrations of the different species. The Chemical Mass Balance (CMB) receptor model was used to fit the source signature profiles to the compositional profile of ambient samples. One output from the fitting program was an estimate of the relative attributions of the different source types (categories) to the observed ambient samples. Available data and accuracy of the source attributions as a

**Fig. 6** CAIP – source attribution study ambient monitoring sites for winter 1999, fall 1999, summer 2002, summer 2010, and fall 2010 – the yellow sites were added for 2002.
function of the number of source signatures was obtained, along with the concentrations of measured species. Fig. 3 presents the tasks involved in performing the SAS (Fig. 5).

Ambient SAS sampling monitoring sites

Representative sampling sites for the source attribution task were chosen (six in 1999, eight in 2002 and six in 2010). In 1999, knowledge about existing pollution sources in the GC area was used to choose six ambient SAS monitoring sites to represent activities in the area. These sites were chosen from existing CAIP Air Quality Monitoring Network sites in Kaha, El Qualaly, Zamalek, Shoubra el-Kheima, El-Massara, and Helwan. After using the CMB model, some uncertainties appeared due to the lack of appropriate source sample “signatures”.

Other source samples such as iron and steel, vegetative burning, and coke were identified and additional source samples collected. In addition, sources of air pollution that could contribute to air pollution criteria in the GC area were identified. Based on this analysis, two additional SAS ambient monitoring sites in the Basateen and Tebbin South areas were added (e.g., copper foundries located in Basateen and the many sources of pollution in Tebbin South such as the coke industry, iron and steel smelting, more than 100 brick factories, and some lead smelters). Ambient sampling was conducted during the winter of 1999 (February 21–March 3), fall of 1999 (October 27–November 27). In 2002, samples were collected during summer (June) in 2002. In 2010, sampling was conducted during (May 30–June 19), 2010 (summer) and (October 10–30), 2010 (fall) [14].

Source sampling (signature sampling)

Based on collaborative work between the Egyptian Environmental Affairs Agency (EEAA), CAIP, and the Desert Research Institute (DRI), the Air Quality Monitoring (AQM) team collected many samples from different source categories that could affect air pollution in the GC area.

These source categories were collected during three periods of time—originally in 1999, and then, due to uncertainties that appeared after using the CMB modeling, again during 2000 and 2002. Also, it was repeated in 2010 for the original monitoring sites of 1999.

- Shoubra el-Kheima, an industrial/residential area located downwind from many lead smelters and other industrial sources, was important in assessing the influence of CAIP initiatives to reduce lead emissions.
- El-Quallaly Square is located downtown and has high light- and heavy-duty (bus) traffic.
- Zamalek, a residential location, was chosen to represent a site with limited nearby sources of emissions.
- Basateen, a residential location, was added to expand the geographical distribution of the sites and evaluate the influence of nearby industrial activity on air quality. This site was added for the 2002 study.
- El-Massara is a residential area near a number of cement plants.
- Helwan is a residential area with limited nearby sources.
- Tebbin South is an industrial area with numerous brick kilns and some lead smelting activity. It is south of Helwan and CAIP wanted to evaluate the influence of emissions from Tebbin South on Helwan. This site was added for 2002 study.

Ambient sampling was conducted during winter (February 21–March 3) and fall (October 27–November 27) of 1999. In 2002, it was conducted during summer (June). In 2010, sampling was conducted during (May 30–June 19), 2010 (summer) and (October 10–30), 2010 (fall) [14].

Source attribution study of lead concentrations in June and October 2010 in the GC area.
Table 7 presents seasonally averaged PM$_{2.5}$ and PM$_{10}$ mass and lead concentrations at the five sampling sites from 1999 to 2010 [15]. PM$_{2.5}$ mass concentrations were significantly lower during fall 2010 compared with fall 1999. This is also the case for PM$_{10}$ mass at all sites except Helwan. Summer PM$_{2.5}$ concentrations were somewhat lower (within 20%) in 2010 compared with summer 2002. The difference was most dramatic at Shoubra (-37%). There is no significant trend for PM$_{10}$ between summer 2002 and summer 2010.

By contrast, lead concentrations decreased dramatically from 1999 to 2010 in both size fractions. The largest change was at Shoubra where PM$_{10}$ lead decreased from 33.7 μg/m$^3$ during winter, 1999, to 0.3 μg/m$^3$ during summer, 2010.

Fig. 7, presents the PM$_{10}$ Lead in SAS monitoring sites in the Greater Cairo area during SAS sampling period in 2010. Table 7 presents the trend in seasonal average concentrations for mass and lead in Cairo from 1999 to 2010. During June 2010, all SAS monitoring sites shows that the lead concentrations are less than the limit in Law 9, 2009, for protection of environment in Egypt (1.5 μg/m$^3$). During October (fall), the background site (Kaha), Helwan, El Qualaly, and Zamalek shows that the lead concentrations are less than the limit in Law 9, 2009. Shoubra industrial monitoring site shows slight increase during the last week of October 2010.

PM$_{10}$ lead at Shoubra also decreased significantly from 33.7 μg/m$^3$ to 12.7 μg/m$^3$ between winter and fall 1999. A similar decrease in roughly a factor of two and a half over this period occurred at El Qualaly. Large decreases in PM$_{10}$ lead between the summers of 2002 and 2010 were seen at Shoubra and El Qualaly.

**Conclusions**

This work presents the lead emissions inventory in the GC area for 1999, 2000, 2001, 2007, and 2010. This inventory gives a current listing by major source of the annual lead emissions in the GC area. The inventory, and the associated database, may be used to develop effective regulatory and control strategies, assess emissions trends, and conduct modeling exercises.

It can be concluded that when the lead smelters in the GC area were re-located to industrial areas outside of the urban area of the GC and modifications of processes and equipment implemented, the lead emissions are greatly decreased. So, from our study, lead smelters were the main source of lead pollution in the GC area until 2010. The second main source of lead pollution originally, and now the main source is Mazout combustion (heavy fuel oil). The remaining sources (Cement factories, copper foundries, and lead manufacturing battery factories) had minor contributions to lead pollution in the GC area.

Due to the efforts made by EEAA/CAIP regarding the re-location of lead smelters from the residential areas to designated industrial areas, and the studies related to the improvement of the industrial processes regarding this industry, the lead emissions inventory was remarkably decreased starting from 2000 and 2001 until completing the work by the end of 2010.

Using 1999 as the representative baseline year, the total percentage decrease in lead emission in 2000 was 29%. The percentage of decrease in lead emissions from secondary lead smelters was 31%, from lead–acid batteries was 7.3%, from secondary copper foundries was 20%, from Portland cement industries was 14.7%, and from Mazout combustion was 21%. Comparing 2001 and 1999, the total lead emission decreased by 65.6%. The percentage of decrease in lead emissions from secondary lead smelters was 69.9%, from lead–acid batteries was 13.8%, from secondary copper foundries was 28%, from Portland cement industries was 17.4%, and from Mazout combustion was 47.4%.

Between 2007 and 1999, the total lead emissions decreased 98.98%. The percentage decrease in lead emissions from secondary lead smelters was 100%, from lead–acid batteries was
16.13%, from secondary copper foundries was 46.27%, from Portland cement industries the concentration of lead increased by 6.78%, and from Mazout combustion the lead concentration was decreased by 54.6%.

The major source of lead pollution in the GC area in 2010 is Mazout combustion. The emission from it in 2010 was 121.75 metric tons which represent 91.85% of the total lead emissions in this year. The challenge now is to decrease Mazout use by switching to compressed natural gas (CNG) which is currently being implemented.

USAID, EEAA, CAIP, and Qaliubeya Governorate worked together to encourage private sector lead smelter owner (Awadulla) to relocate the largest lead smelter in Egypt to a designated industrial area. The smelter was completely re-located and it was retooled and started test operation on October 2002. Awadulla operated it continuously in the first quarter of 2003. This lead smelter was installed in an industrial area chosen after conducting an EIA for this area. CAIP is conducting source emissions tests there to calculate the emission factor. CAIP also had an ambient monitoring site colocated with the smelter. EEAA/CAIP is currently measuring the lead pollution in the work place (occupational exposure).

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

References

[1] The Merck index: an encyclopedia of chemicals, drugs, and biologicals, 10th ed. Rathway, New Jersey: Merck and Company; Inc.; 1976. p. 776.
[2] Greninger D, Kollonotsch V, Kline CH (Charles H. Kline & Co., Inc.). Lead chemicals. New York, New York: International Lead Zinc Research Organization, Inc. (ILZRO); 1975.
[3] Environmental Studies Department. Institute of Graduate Studies and Research, University of Alexandria (Egypt). A comparative study on the contribution of lead emission from motor vehicles to atmospheric pollution. A consultancy study for the ministry of petroleum, Cairo; 1996.
[4] Sessions SM, Gaffen S, Moore R, Efroymson F, El-Gohary M, Nasralla A, et al. “Comparing environmental health risks in Cairo, Egypt, volume 1: final report”; prepared for USAID/NE/DR/ENR by Chemonics International and its Associates, Cairo; 1994.
[5] Office of Air Quality Planning and Standards, Office of Air and Radiation, U.S. Environmental Protection Agency. Locating and estimating air emissions from sources of lead and lead compounds. North Carolina: Research Triangle Park; May 1998.
[6] Cabinet of Ministers, Egyptian Environmental Affairs Agency. Technical cooperation office for the environment, lead smelting in Egypt – baseline study (Private Lead Smelters in Greater Cairo), Cairo; 1996.
[7] Office of Air Quality Planning and Standards, Office of Air and Radiation, U.S. Environmental Protection Agency. Compilation of air pollutant emission factors, fifth ed., AP-42. North Carolina: Research Triangle Park.
[8] Labib Mounir W, Khalil Mohammed H. 1999–2000 lead emissions inventory trend report for the Greater Cairo area. Cairo Air improvement project; May 2001.
[9] Labib Mounir W, Safar Zeinab, Khalil Mohammed H, Abdel Rahiem Ahmed G. Comparative study of lead emissions inventory in the Greater Cairo area for Y 1999 and Y 2000. In: Environment 2001 international conference, Cairo; October 2001.
[10] Compilation of air pollutant emission factors, fifth ed., AP-42, U.S.
[11] Locating and estimating air emissions from sources of lead and lead compounds, May 1998, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards. North Carolina: Research Triangle Park.
[12] Labib Mounir W, Safar Zeinab, Khalil Mohammed H. Lead emissions inventory in the Greater Cairo area for 2000 and 2001. In: AWMA symposium in San Francisco, USA; November 2002.
[13] Abou El-Azm Mawaheb, Labib Mounir, Abou El-Soud Ahmed, Saleh Ashraf, Hagag Mohamed. Recent trends in particulate matter and lead levels in the Greater Cairo Area, Paper # 426, AWMA, USA; June 2008.
[14] Labib Mounir W. Lead emission inventory in the Greater Cairo area from 1999 through 2007. Paper # 139. USA: AWMA; June 2009.
[15] Lowenthal Douglas H, Gertler Alan W. Division of atmospheric sciences, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, World Bank; May 2011.