Modelling environmental impacts on communities from co-incineration of hazardous industrial waste

J.-P. de Almeida[ab], J. Coutinho-Rodrigues[ac*]

[a] *Researcher at INESC-Coimbra*
Av. Antero Quental 199, 3000-141 Coimbra, Portugal
http://kreation.dec.uc.pt/projects

[b] *Assistant Professor in Geomatic Engineering*
Department of Mathematics-Faculty of Sciences and Technology-University of Coimbra
Apartado 3008, 3001-501 Coimbra, Portugal
E-mail: zepaulo@mat.uc.pt

[c] *Aggregate Associate Professor in Civil Engineering*
Department of Civil Engineering-Faculty of Sciences and Technology-University of Coimbra
Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
E-mail: coutinho@dec.uc.pt

Number of words of the main text: 4 853;
Number of illustrations: 7;
Number of tables: 2.

Coimbra, 21st April 2010

[*] *Corresponding author: Tel.: + 351 239 797 145; Fax: +351 239 797 123*

Abstract

The Portuguese Government conceived a nationwide plan for the co-incineration of hazardous industrial waste (HIW) in two existing cement plants located near the cities of Coimbra and Setúbal. This has been a problem of main concern for the populations of both cities who have demonstrated a strong opposition to the incineration of hazardous substances so close to the mentioned urban centres. This paper describes a study that was carried out to evaluate possible environmental impacts over the city of Coimbra in particular and some of its urban facilities. A computerised environmental impact modelling approach for atmospheric dispersion, using the Gaussian model and its linkage to a geographic information system (GIS) was implemented. Using actual physical information, such as the more frequent winds direction and speed, this study showed how the accidental emission of pollutants to the atmosphere by the cement plant in the north of Coimbra would affect some particular sensitive urban facilities (e.g. hospital units and pre-primary schools), and all the inhabited area in between the cement plant and the city centre. The regional Health Authority has requested the results obtained for designing a plan of ambient monitoring.

Keywords*:* Environment, Public health, Information technology.

Introduction

The importance of environmental issues related to pollution problems, like air pollution, has assumed an increasing importance both from the point of view of the public opinion and of the scientific community. Threats to the environment are considered currently much more seriously in policy making than what they were a few decades ago. In a natural or man-made disaster scenario, authorities at local, regional, national and global levels need to perform a comprehensive, intuitive and rapid assessment in the immediate aftermath of the event, which is often underestimated. Lack of adequate assessment is likely to lead to inappropriate priorities and emergency interventions, which may exacerbate, rather than alleviate, existing problems.

Hazardous air pollutants are known to have adverse effects on urban populations exposed at the micro or neigbourhood scale, and, for example, are believed to play a significant role in the rapid increase in urban asthma (Corburn, 2007, Delfino, 2002, Leikauf et al., 1995, Weisel, 2002). The European Community has recognised that, in spite of all the efforts to reduce the emissions of sulphur dioxide, suspended particles, and CFCs, some serious issues persist, such as those regarding emissions of carbon dioxide, ozone, and methane, and thus directives have been published to tackle especially the incineration of hazardous wastes (EC, 1992).

The perception of these problems has fostered the interest in studying environmental impacts using scientific methods. Those concerning the modelling of dispersion of atmospheric pollutants assume special importance in our study, especially in what concerns the construction of risk maps in urban areas.

The emission of atmospheric pollutants, either continuously or accidentally, impose risks over contiguous geographic areas, particularly on urban facilities that, due to their own nature, are more sensitive to those aggressions (e.g. hospitals, schools, rehabilitation centres for the handicapped, or elderly care houses) (vd. also Chakraborty and Armstrong, 2001). In particular, the accidental emissions may have strong negative impacts over those facilities serving people more sensitive or with reduced mobility (e.g. pre-primary school children, patients, elderly and handicapped people). A prospective study aimed to identify the consequences of an accident over the population of an urban area, particularly on the urban facilities mentioned above, is an important step to foresee the spatial distribution and the intensity of the consequences, especially on vulnerable segments of population (e.g. Corburn, 2007, Coutinho et al., 2006).

Formal models are usually used for helping a decision maker (i.e. a politician and not necessarily a scientist) in his/her needs for policy evaluation or planning. In the literature, there are a few models enabling the evaluation of the concentration in the atmosphere of any pollutant, just requiring few parameters, such as the spill source location (which can be punctual – e.g. industrial or medical waste incinerators; areal – e.g. a set of industrial units within a certain area; linear – e.g. busy roads), the wind direction and speed, amongst others (Holmes and Morawska, 2006). The problem of the dispersion modelling has been addressed by the US Environmental Protection Agency (USEPA, 1986, 2003) that has proposed some models for particular cases, such as: VALLEY, COMPLEX-I, SHORTZ, LONGZ or RTDM which may be applied for static sources emitting sulphur dioxide and particles (considered non reactive pollutants), and CALINE, HIWAY and ROADWAY, for moving sources such as traffic.

The Gaussian modelling approach (or Gauss plume model) has been the most widely used technique to describe many phenomena, including the estimation of the impact of a non-reactive neutrally buoyant contaminant (i.e. its density roughly the same as air) will move and spread in the air from the source of the spill (Astarita and Wei, 1997, Boubel et al., 1994, Chakraborty and Armstrong, 2001, Gordon, 1985, Holmes and Morawska, 2006, Mahoney, 1974, USEPA, 1986, 2003, also referred to by Kiely, 2007). This model was particularly popular in the late 1980s and early 1990s and has been also the basis for the development of other more sophisticated recent formulations, which take into account, for instance, the orography friction effect. As an example scenario, the basic formulation of the Gaussian plume model was implemented and applied to the case study described in this paper.

As this is a spatial problem, the simplicity of spatial representations is a relevant aspect. Therefore, the display of a pollutant effects on maps, besides the evaluation of impacts and the corresponding intensities, may well be a powerful tool to help decision makers in identifying hot spots and in strengthening or weakening their own convictions and judgments about a particular case. Indeed, the human brain is sensitive to the visual representation of real scenes, and visual analysis can often reveal patterns not promptly discernable by current automated analysis techniques. "Visuality and intuition" should be viewed in GIS as a distinct advantage from structured inquiries to convey patterns and concepts. According to this perspective, GIS extends the capabilities of the analytical techniques by allowing the visualisation of spatial arrangements and, in the process, restored intuition as a valid heuristic technique (Dykes et al., 2005, Longley et al., 2005, Schuurman, 2004).

As far as environmental phenomena are concerned, GIS technology has gained an increasing emphasis on environmental modelling (Goodchild et al., 1993). GIS provides indeed a logical framework to assist planning and management for communities that is safer, more sustainable and more resilient in the face of a disaster scenario (Gwilliam et al., 2006). Moreover, the possibility of knowing beforehand the spatial distribution of pollutants, enables a spatial planning of a monitoring procedure which is usually required in cases like these. Thus, the integration of analytical models, spatial data, and methods of representing numeric data directly over a map using adequate graphical metaphors, makes possible the improvement of both the representational and communicative processes (Dykes, 1997, MacEachren, 1995, Raper et al., 2002). This integration is potentially effective to overcome some of the problems that make difficult the use of some models in environmental analysis and planning (Wang et al., 2000). The incorporation of adequate analytical models and GIS technology has been indeed recognised as a promising research area in this context of environmental problems (Aspinall, 1994, Bennett, 1997, Briggs et al., 1997, Burrough, 1997, Chang et al., 2009, Coleman et al., 1994, Goodchild et al., 1993, Steyaert and Goodchild, 1994, Yates and Bishop, 1998).

In this paper, the study that was carried out to visually evaluate possible environmental impacts over a medium size city in Portugal (Coimbra, ~150 000 inhabitants), and some of its facilities, is presented. A Gaussian model representing impacts related to pollutants dispersed through the atmosphere and its linkage to GIS were implemented in order to profit from the capabilities of graphical visualisation of impacts on virtual maps. To accomplish this, a communication interface between a high level programming language, supporting the model and the GIS, was implemented.

With such a system, the authors sought to simulate the effects of a possible malfunctioning of the plant, showing who is affected in this situation (a densely populated suburban and urban area, including important hospital and school units); a particular attention was paid in this simulation to more vulnerable segments of the population (e.g. patients, children, elderly people). It should be pointed out that the aim of the study was neither the simulation of a particular kind of pollutant nor a particular quantity released by the source; in fact, the Gaussian model used (vd. section 3.1) can be applied to any kind of air pollutant.

As stated above, visualisation aspects constitute a key focus of this paper. This is principally because potential non-skilled users were taken into account in the development of the GIS-based application. Indeed, overall decision makers are not likely to be particularly acquainted with environmental models or GIS technology. As noted above, comprehensive, intuitive results are needed for a rapid first-step assessment and action in the immediate aftermath of a disaster scenario. It is precisely within this context that the regional Health Authority at Coimbra has requested the results obtained for ambient monitoring purposes in the city of Coimbra.

In section 2 the motivation for the study with real-world data is provided. The Gaussian plume model, which has been used, is briefly described in section 3.1; its computer implementation and linkage to a GIS are reported in section 3.2. In section 4, illustrative results for emissions in a "co-incineration" plant (vd. definition in section 2), due to a hypothetical accident or malfunctioning, are presented with a special emphasis on impacts over schools and hospitals. In section 5, some conclusions are drawn and future work is outlined.

1. Motivation - a real world case study

During the last years of the 20th Century and the dawn of the 21st Century, the Portuguese Governments studied the problem of the hazardous industrial wastes processing from all over the country. In the 1990s a statistical survey was performed and published showing that the amounts of total industrial waste produced in Portugal were 29.9×10^6 tonnes in 1995 and 26.4×10^6 tonnes in 1997, being the HIW values 668 062 tonnes in 1995 and 595 156 tonnes in 1997 (INE, 1999).

However, more recently, a special committee (including six Portuguese university representatives) was appointed to gather information about the production of industrial wastes in Portugal. As a result, a more recent and accurate report on the amounts of waste produced in each Portugal's Plan-Region (as shown in Figure 1 and Table 1) and by type of industrial source were presented (IR, 2003). Table 2 provides a comparison with other European countries. HIW accounts for 0.9% of the total industrial waste (29.2×10^6 tonnes), in the amount of 253.6×10^3 tonnes. The total amount resulting from used oils represents 48% of HIW productions (which corresponds to 121.6×10^3 tonnes), with predominant origin in the North and the Lisbon and Tagus Valley Plan-Regions. Other important contributions of HIW are organic chemicals (32.4×10^3 tonnes corresponding to 12.8%) and solvents (28.0×10^3 tonnes corresponding to 11.0%).

- Insert FIGURE 1 about here -

- Insert TABLE 1 about here -

- Insert TABLE 2 about here -

As a consequence of the importance of the environmental problem, a decision was made to implement an overall "co-incineration" solution (for the purpose of this work, "co-incineration" means the joint incineration of HIW, in any form, with refuse and/or sludge), which should be undertaken in two cement plants: one in the southwest of the country (Outão, nearby the city of Setúbal, south of Lisbon), and the other in the west-centre (located in Souselas, just a few kilometres north of Coimbra). As expected, this decision has been rather controversial and prompted an actual national debate. Public reluctance in accepting the incinerators as typical utilities often results in an intensive debate concerning how much welfare is lost for those residents living in the vicinity of those incinerators (Chang et al., 2009). In this case it led to a strong opposition to the government plan from environmental groups and the general public. Outão is located nearby the protected area of Serra da Arrábida; Souselas is quite close to Coimbra, a city home for one of the oldest Universities in the world (720 years old, currently with about 22,000 students), with important monuments from very different historical periods, and a very important cultural legacy (actually, a candidate for the classification as UNESCO's World Heritage). In Coimbra, the services sector is totally dominant occupying more than 75% of the population (industry is far behind, with about 20%, not causing significant pollution problems). Education is the dominant sector, followed by others, such as: public administration (a large number of regional departments of the central government); health (with a large number of hospitals providing all kinds of medical care); tourism; commerce; and law. Moreover, Souselas is a rural Coimbra Parish with many vineyards where good quality wine is produced. The actual concerns derive mainly from an eventual atmospheric dispersion of pollutants (e.g. dioxins, potentially causing cancer and other diseases), either due to an accident or a malfunction in the chimney filters.

Decisions taken by the politicians were mainly supported by the conviction that the co-incineration was the most effective way to treat HIW and there would be no impact on people, fauna, and flora. This would be accomplished namely by means of using adequate filters in the chimneys (of course those filters should be submitted to rigorous periodic replacement and maintenance operations). Nevertheless, a scientific study showing the actual consequences of such decisions was never presented. Moreover, Meneses et al. (2004) sated that, even in what concerns municipal waste incineration (which is overall less aggressive then HIW), some of the chemicals emitted travel through the combustion chamber and are not captured by pollution control devices. These are then directly transmitted to humans through inhalation, contaminating also soil, vegetation, water and biota.

Therefore, there was a strong motivation and valid justification to assess the environmental impact produced by a co-incinerator to be installed in a cement plant existing in the neighbourhood of the city. The spatial problem was represented over digital maps of the region that includes Coimbra, Souselas, and the potential source of spill (the cement plant where the planned co-incineration is meant to be installed).

In the simulations carried out, attention was drawn towards:

a) The atmospheric distribution of a pollutant over the region (the term "dispersion" means implicitly an horizontal movement and mixing of gases); though the system is able to display a plume's footprint in any direction from the source of the spill, it made sense in the particular simulation to spatially represent the plume's footprint in the most frequent downwind direction in the area – the interest was indeed in simulating the worst circumstances, which correspond approximately to the direction Souselas>>>Coimbra; this showed where the most affected areas in the region are located;
b) The evaluation of pollutant concentration in points representing urban facilities dedicated to more sensitive segments of the population, such as children, patients, and elderly people.

3. A GIS-based modelling approach

3.1 The Gaussian model

Since the study of the Gaussian modelling is beyond the scope of this paper, a brief explanation of the mathematical equation representing the model and the meaning of its parameters is given in this section. For further details and assumptions, the reader is referred to the literature mentioned throughout this section.

The Gaussian plume model has implicitly defined a reference system *XYZ* with a right-handed orientation (Figure 2) – origin *O* located in the spill source at the ground level; *X*, an horizontal axis, oriented downwind ($x = 0$ at stack); *Y*, the other horizontal axis and perpendicular to *X* ($y = 0$ at any point on the plume´s centre-line footprint); *Z*, the vertical axis perpendicular to the *XOY* plan and measured upwards from ground level ($z = 0$ at the ground level).

The concentration c of a pollutant plume at any (x, y, z) reception point can be calculated with the Gaussian diffusion equation as follows (Astarita and Wei, 1997, Boubel et al., 1994, Kiely, 2007):

$$c(x,y,z) = \underbrace{\frac{Q}{2*\pi*\sigma_y*\sigma_z*U}}_{\text{plume axis}} * \underbrace{\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]}_{\text{horizontal}} * \underbrace{\left\{\exp\left[-\frac{1}{2}\left(\frac{z-h}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{z+h}{\sigma_z}\right)^2\right]\right\}}_{\text{vertical}} \quad (1)$$

where,

c: Pollutant concentration at a given point (any property by unit of volume, e.g. μg/m^3);

Q: Emission flow rate (any property by unit of time, e.g. μg/s);

x_w, y_w: x and y components of the wind vector (m/s);

$U = \sqrt{x_w^2 + y_w^2}$: Average wind speed in the X downwind direction (m/s);

σ_y, σ_z: Horizontal and vertical diffusion coefficients (see below) as a function of the downwind distance (distance x relative to the source spill) and the atmospheric stability criteria (m);

V_s: Emission speed (m/s);

r_s: Chimney hole ray (m);

h_s: Chimney physical height (m);

P: Atmospheric pressure (kPa);

T_s: Chimney interior temperature (K);

T_a: Chimney exterior temperature (K);

Δh : Plume rise (m) = $\frac{2V_s r_s}{U}\left[1.5 + 2.68 \times 10^{-2} \times P \times \left(\frac{T_s - T_a}{T_s}\right) \times 2r_s\right]$;

h: Actual height of emission (m) = $h_S + \Delta h$ (Briggs, 1969);

x: Horizontal distance from the reception point to the source in the wind direction (m);

y: Horizontal distance from the reception point to the centreline (axis) of the plume (m);

z: Height of the reception point above ground level (m).

At the source of the spill the concentration of the pollutant is high and the Gaussian distribution has a considerable peak. The maximum value of the concentration at the centreline decreases as the plume spreads out becoming wider, and as the time increases the boundaries also extend (Kiely, 2007). The standard deviations in the transverse and vertical directions of the plume are represented by two coefficients, s_y and s_z, which depend on the distance to the source measured in the wind direction, and are also associated to the atmospheric conditions. The flexibility of the model is mainly due to the different methods which can be used to evaluate s s without affecting the model. For this purpose, the method of the atmospheric stability classes is suggested by several authors (e.g. Boubel et al., 1994, Gordon, 1985). The parameters used in this method are the wind speed (which is recorded at a standard height of 10 m above ground and denoted by U_{10}), solar radiation and cloud cover fraction at night, which are basically obtained through routine observations (Gifford, 1961, Pasquill, 1961), and can be seen for instance in Boubel et al. (1994) and Kiely (2007).

The parameters of Pasquill-Gifford were translated in terms of dispersion coefficients (Boubel et al., 1994, Pasquill, 1974) and analytical expressions (as well as graphs with curves, as shown by Boubel et al., 1994, and Kiely, 2007) were provided to calculate s_y and s_z as a function of the distance from the source and the atmospheric stability class.

In order to be able to evaluate the pollutant concentration in a given point, the emission flow rate, the effective height of the emission, the wind speed and direction, the atmospheric stability conditions, and the s s are needed. Although the wind speed is recorded at the standard height of 10 m, it can be evaluated to any height as a function of U_{10} and z (Hanna et al., 1982, Stern, 1976, Kiely, 2007). In addition, georreferenced data (e.g. the emission source(s), Census data) are related to a global reference system *X'Y'Z'* – the same as that of the underlying digital map. Therefore, in order to display the results over GIS georreferenced data, the coordinates of the reception points (in the model reference system) need to be transformed into the cartographic reference system specified in the current GIS virtual map. This is a relatively straightforward operation, which is illustrated in Figure 2, consisting of a translation (using the georreferenced coordinates of the emission source), and a rotation (equals to the wind direction angle).

- Insert FIGURE 2 about here –

3.2 Computer implementation and linkage to GIS

The computer implementation consists of a module developed in a high level computer language which implements the model described in section 3.1 above. It gives either the pollutant concentrations in a spatial area selected, or over particular sites (e.g. urban facilities). The numerical values obtained were graphically represented on a map as a new layer of the GIS environment. This is accomplished by linking the two applications (Gaussian model and GIS) in order to obtain an inter-application real time communication. The implementation was made on an *Apple Macintosh* computer and the two applications communicate through *Apple Events* technology. *MapGrafix*®, from *ComGrafix, Inc*., was the GIS software package used. Since the model was implemented externally, a different software package could have been used.

In practical terms, two applications run simultaneously in the memory of the computer. One is the GIS, which manages all the geographic information related to the geographical entities; the other is the program that implements the Gaussian model. Both graphic and alphanumeric data are stored in a data base management system. The GIS is the interface that displays the problem in its actual space.

4. Illustrative results for eventual emissions in the HIW co-incineration plant

4.1 Circumstances simulated

Some parameters of general examples, taken from the literature, were considered as real data (e.g. chimney interior and exterior temperatures). Meteorological data were obtained from the records of the closest meteorological station in Coimbra (e. g. solar radiation, cloud cover fraction at night, wind direction, and wind average speed – recorded at a standard height of 10 m above ground – were considered from 10 year routine observations). This study aims to simulate generic situations, and hence the consideration of both a particular kind of pollutant and an emission flow rate is not relevant. Thus, emission flow rates for a hypothetical malfunction scenario can be deducted from the HIW amounts expected to be processed at each co-incineration plant (INE, 1999, IR, 2003).

The source of emission considered (the cement plant's chimney in Souselas) was represented on a digital map (close to the upper border of Figure 3) using its planimetric coordinates referred to the global system of the map considered: $x_s = 549\,560.77$ m; $y_s = 4\,460\,095.15$ m. The chimney physical height (h_s) is 88 m; the actual height (h) is calculated by the respective mathematical expression (see above) defined in the system (380 m in this case). The emission flow rate (Q) considered was $4.69 \times 10^9\ \mu$g/s. The wind average speed considered was 9 m/s, and the wind direction was 175° ($y_w = -8.966$; $x_w = 0.785$) – this value belongs to the class of the most frequent wind directions in the area, which is from N-NW. The atmospheric stability class "C" of Pasquill-Gifford was considered (Gifford, 1961, Pasquill, 1961, Boubel et al., 1994-pp 302, Kiely, 2007).

4.2 Impact over a continuous area – generation of the plume's footprint

The generation of the plume's footprint is based upon the definition of a rectangle, which basically represents the continuous geographical area to be studied. The given rectangle is then divided into square cells. Both the dimension of the rectangle and cell resolution, are specified by the user as input parameters. The amounts of the pollutant concentration are then evaluated for each cell's centroid. These values were then translated into coloured classes of values for rapid visualisation purposes of the plume's footprint. In fact, taking into account the minimum and maximum values calculated, the system determines the thresholds for 100 different classes of concentration values; these in turn are assigned a specific colour from a colour palette. A "continuous" representation was then implemented as a 4-dimension cell-grid (x, y, z, c), where the colour of each cell (its 4th dimension) represents the concentration c evaluated for its centroid. Colour gradients represent graphically those amounts: dark red and red colours correspond to high concentrations; yellow and light yellow to low concentrations. (Dykes, 1997, Dykes et al., 2005, MacEachren, 1995). In this specific simulation, a $2\,800 \times 2\,400$ cell – rectangle (each cell corresponds to a 10×10 m square), representing our case study area (672 km^2), was considered. The maximum value calculated under the circumstances simulated was $6.9 \times 10^2\ \mu$g/m^3.

As illustrated in Figure 3, such graphical metaphors above were considered in order to obtain meaningful intuitive colour gradient maps.

- Insert FIGURE 3 about here –

4.3 Impact over sensitive urban facilities

The results calculated for impacts over hospital units and pre-primary schools (children aged 6 years old or less) in Coimbra are displayed in Figures 4 and 5 respectively. The wind direction is the same used in Figure 3 (approximately NW-SE). The GIS environment also supplies data such as the coordinates of the desired points and the corresponding number of affected people.

As far as impacts over facilities are concerned (vd. Figures 4 and 5), the user can choose graphical representations on the map, located on the facilities, either using circles or rectangles. In the case of circles, the radius is proportional to the total impact (*concentration* × *#persons*) – Figures 4, 6 and 7 (see also Dykes and Mountain, 2003). As far as the rectangle representation is concerned, the corresponding width represents the number of people affected, and the height represents the pollutant concentration (thus, the area is proportional to the total impact: *concentration* × *#persons*) – Figure 5. In both cases, colours and colour gradients denote classes of concentration values (Dykes, 1997, MacEachren, 1995).

- Insert FIGURE 4 about here –

The Coimbra University Central Hospital is one of the largest and best equipped hospitals in Portugal and in Europe (with 1200 beds, 12 surgery suites performing 7000 surgical treatments/year), providing all kinds of medical care and serving, in some instances, the whole central region of Portugal, or even the whole country. As shown (see the largest circle in Figure 4), it is actually located right on the straight line defined by the potential polluting source and the predominant downwind direction.

- Insert FIGURE 5 about here –

The central axis linking the location of pre-primary schools and the polluting source is almost coincident with the predominant wind direction dispersing the plume (Figure 6).

- Insert FIGURE 6 about here –

It is clear from the illustrations above that people living in between the cement plant and the city would be deeply affected in an accident or filter malfunction scenarios. In addition, the experiments performed showed that, given their particular location within the city relative to the cement plant, the sensitive urban facilities mentioned could be affected under the circumstances above.

As mentioned above, the wind direction corresponding to the results displayed in Figures 3-6 is the most frequent in this region (approximately NW-SE). According to the number of wind observations recorded for each direction in the official registry (N, NE, E, SE, S, SW, W and NW), it is also possible to calculate in a further step the probability of wind occurrence in each direction. Given a certain facility and the probability of the respective wind direction, such a map enables a quick determination of which large capacity facilities could be affected under the circumstances simulated. That maximum probabilistic impact over each pre-primary school facility in Coimbra is illustrated in Figure 7.

- Insert FIGURE 7 about here –

Given the importance of the problem and the controversy around it, and because of the public health issues, the implementation of this particular co-incineration plan of the Portuguese Government must be subjected to the definition of a set of monitoring stations for sample data capture. Indeed, whenever possible, a dispersion model should not substitute for actual monitoring data (Corburn, 2007). Nevertheless, such a model may well constitute a first step to help urban planners and public health officials – who are increasingly asked to perform health impact assessment – in determining a suitable spatial distribution of monitoring stations for data capture. Following this concept, the regional Health Authority at Coimbra has already requested the results obtained in this case study in order to determine the most suitable spatial location of such stations.

5. Conclusions

Environmental impact studies are receiving a growing attention from both the public opinion and the research community. The impacts related to pollutant emissions to the atmosphere and their dissemination are very important issues within this context.

Given a particular emission source, models, like the Gaussian approach used in this work, were developed to study pollutant dispersion in the atmosphere. Gaussian modelling provides an approach for the physical phenomenon. Data corresponding to the impacts are susceptible of being geo-referenced and displayed on dynamic maps. Thus, the computer implementation of this prototype system combines a Gaussian model with GIS technology. An accident can be simulated imposing a particular amount of pollutant released (Q in the Gaussian equation). The corresponding spatial distribution of the different concentrations can be determined; a quick visual evaluation can be performed through the metaphors conceived.

The novelty in the approach taken is the linkage between an environmental model – whatever model – and GIS for the generation and rapid visualisation of the spatial impact through dynamic maps: as input data are entered, the user can see the dynamic generation of the plume's footprint over digital geographical data. In addition, the numerical values calculated by the model can be combined with other data stored in the GIS, like Census data, economic activities and employment data amongst others, for the retrieval of further information.

It is strongly believed that this study confirmed that coupling analytical models with GIS technology is a promising area for providing sound decision support to decision and policy makers in environmental issues. Moreover, the simulation performed of hypothetical situations – though carried out with real data – shed light upon a pertinent environmental issue in Portugal; the regional Health Authority has thus requested some of the results obtained for designing a plan of ambient monitoring.

According to the results obtained for this case study, it is clear that people living in between the cement plant and the city could well be affected in an accident or filter malfunction scenarios. In addition, it showed that sensitive urban facilities, such as pre-primary schools and hospitals, could be affected under the circumstances simulated given their particular location within the city relative to the cement plant. As a result, none of the two co-incineration processes have been definitely implemented yet for the treatment of HIW.

Finally, in most cases, multiple, incommensurate and conflicting aspects are generally at stake. Therefore, decision aid models must explicitly account for the consideration of multiple criteria, reflecting economical, technical, environmental, health, and social concerns of different stakeholders. The results of this work should be of interest in order to be integrated with multiple criteria models and methods in the context of an *ex ante a priori* decision making process, which was not the case in this instance.

References

Aspinall R. (1994). GIS and spatial analysis for ecological modeling. *Environmental Information Management and Analysis: Ecosystems to Global Change* (Michener W., Brunt J., Stafford S. (Eds.)). Taylor & Francis, London, pp. 377-396.

Astarita G. & Wei J. (1997). The critical plume. *Chemical Engineering Science* **52**, No. 9, 1399-1413.

Bennett D. (1997). A framework for the integration of geographical information systems and model base management. *International Journal of Geographical Information Science* **11**, 337-357.

Boubel R., Fox D., Turner D. & Stern A. (Eds.). *Fundamentals of Air Pollution*, 3rd edn. Academic Press, USA, 1994.

Briggs G. (Ed.). *Plume Rise*. US Atomic Energy Commission, USA, 1969.

Briggs D., Collins S., Elliot P., Fischer P., Kingham S., Lebret E., Pryl K., Reeuwijk H., Smallbone K. & Veen A. (1997). Mapping urban air pollution using GIS: a regression-based approach. *International Journal of Geographical Information Science* **11**, 699-718.

Burrough P. Environmental modeling with geographical information systems. In *Innovations in GIS* (Kemp Z. (Ed.)). Taylor & Francis, London, 1997, pp.143-153.

Chakraborty J. & Armstrong M. (2001). Assessing the impact of airborne toxic releases on populations with special needs. *The Professional Geographer* **53**, No. 1, 119-131.

Chang N.-B., Chang Y.-H. & Chen H.-W. (2009). Fair fund distribution for a municipal incinerator using GIS-based fuzzy analytic hierarchy process. *Journal of Environmental Management* **90**, 441-454.

Coleman M., Bearly T., Burke I. & Lauenroth W. Linking ecological simulation models to geographic information systems: an automated solution. In *Environmental Information Management and Analysis: Ecosystems to Global Change* (Michener W.K., Brunt J.W., Stafford S.G. (Eds.)). Taylor & Francis, London, 1994, pp. 397-412.

Corburn J. (2007). Urban land use, air toxics and public health: Assessing hazardous exposures at the neighborhood scale. *Environmental Impact Assessment Review* **27**, 145-160.

Coutinho M., Pereira M., Rodrigues R. & Borrego C. (2006). Impact of medical waste incineration in the atmospheric PCDD/F levels of Porto, Portugal. *Science of the Total Environment* **362**, 157– 165.

Delfino R. J. (2002). Epidemiologic evidence for asthma and exposure to air toxics: linkages between occupational, indoor, and community air pollution research. *Environ Health Perspect* **110** (Suppl. 4), 573-589.

Dykes J. (1997). Exploring spatial data representation with dynamic graphics. *Computers & Geosciences* **23**, No. 4, 345-370.

Dykes J. & Mountain D. (2003). Seeking structure in records of spatio-temporal: visualization issues, efforts and applications. *Computational statistics and data analysis* **43** (Data Visualization II Special Edition), 581-603.

Dykes J., MacEachren A. & Kraak M.-J. Exploring geovisualization. In *Exploring Geovisualization* (Dykes J., MacEachren A., Kraak M.-J., (Eds)). 2005, **1**, pp. 3-19.

European Community 1992. Proposal for a Council Directive on the Incineration of Hazardous Wastes, Com (92). *EC Official Publications*, Brussels, March 1992.

Geymen A., Yomralioglu T. & Baz I. (2008). Developing an urban information system for local governments. *Proceedings of the Institution of Civil Engineers - Municipal Engineer* **161**, ME3, 163–173.

Gifford F. (1961). Use of routine meteorological observations for estimating atmospheric dispersion. *Nuclear Safety* **2**, 47-51.

Goodchild M. The state of GIS for environmental problem-solving. In *Environmental Modeling with GIS* (Goodchild M.F., Parks B.O., Steyaert L.T. (Eds.)). Oxford University Press, New York, 1993.

Goodchild M., Parks B. & Steyaert L. (Eds.). *Environmental Modeling with GIS*. Oxford University Press, New York, 1993.

Gordon S (Ed.). *Computer Models in Environmental Planning*. Van Nostrand Reinhold, New York, 1985, pp. 78-89.

Gwilliam J., Fedeski M., Lindley S., Theuray N. & Handley J. (2006)**.** Methods for assessing risk from climate hazards in urban areas. *Proceedings of the Institution of Civil Engineers - Municipal Engineer* **159**, No. 4, 245–255.

Hanna S., Briggs G. & Hosker R. *Handbook on Atmospheric Diffusion*.US Department of Energy, 1982.

Harvey P. A. & Reed R. A. (2002). Rapid assessment and priority setting in emergencies. *Proceedings of the Institution of Civil Engineers - Municipal Engineer* **151**, No. 4, 249–254.

Holmes N., Morawska L. (2006). A review of dispersion modelling and its application to the dispersion of particles: An overview of different dispersion models available. *Atmospheric Environment* **40**, 5902–5928.

INE, 1999. *Estatísticas do Ambiente – Resíduos Industriais 1995 e 1997* (*Environmental Statistics. Industrial Wastes - 1995 and 1997*, official report in Portuguese). INE-Instituto Nacional de Estatística, Lisboa, 1999.

IR, 2003. *Estudo de Inventariação de Resíduos Industriais*, Relatório Síntese (Report on the Industrial Wastes Production in Portugal - official report in Portuguese). Instituto dos Resíduos de Portugal, Lisboa, July 2003, ISBN 972-98996-0-6.

Kiely G. (Ed.). *Environmental Engineering,* 4th edn. McGraw-Hill International, London, 2007.

Leikauf G. D., Kline S., Albert R. E., Bater C. S., Bernstein D. I. & Buncher C. R. (1995). Evaluation of a possible association of urban air toxics and asthma. *Environmental Health Perspectives* **103** (Suppl 6), 253-271.

Longley P., Goodchild M., Maguire D. & Rhind D. (Eds.). *Geographical Information Systems and Science*, 2nd edn. 2005, Part IV, **13**, pp. 289-313.

MacEachren A. (Ed.). *How maps work: representation, visualization and design*. The Guildford Press, New York – London, 1995.

Mahoney J. (1974). Meteorological Aspects of Air Pollution. *Industrial Pollution* **15**, 409-455.

Meneses M., Schuhmacher M. & Domingo J. (2004). Health risk assessment of emissions of dioxins and furans from a municipal waste incinerator: comparison with other emission sources. *Environment International* **30**, 481– 489.

Pasquill F. Meteorological Mag**. 90**, No. 1063, 33-49, 1961.

Pasquill F. Atmospheric Diffusion, 2nd edn. Halstead Press, New York, 1974.

Raper J., Dykes J., Wood J., Mountain D., Krause A. & Rhind D. (2002). A framework for evaluating geographical information. *Journal of Information Science* **28**, No. 1, 39-50.

Schuurman N. GIS – A short introduction. Blackwell, 2004.

Stern A. Air Pollution, Vols. I, II, III, IV and V. Academic Press, 1976.

Steyaert L. & Goodchild M. (1994). Integrating geographic information systems and environmental simulation models: a status review. *Environmental Information Management and Analysis: Ecosystems to Global Change* (Michener W.K., Brunt J.W., Stafford S.G. (Eds.)). Taylor & Francis, London, 397-412.

USEPA, 1986. *Guidelines on air quality models*. Environmental Protection Agency - 450/2 – 78 – 027R, July.

USEPA, 2003. Revision to the Guideline on Air Quality Models: Adoption of a Preferred Long Range Transport Model and Other Revisions [online], Environmental Protection Agency. Available from http://www.epa.gov/EPA-AIR/2003/April/Day-15/a8542.htm [Accessed 15 January 2010].

Wang X., White-Hull C., Dyer S. & Yang Y. (2000). GIS-ROUT: a river model for watershed planning. *Environment and Planning B: Planning and Design* **27**, 231-246.

Weisel C. P. (2002). Assessing exposure to air toxics relative to asthma. *Environmental Health Perspectives* **110** (Suppl 4), 527-537.

Yates P. & Bishop I. (1998). The integration of existing GIS and modeling systems with urban applications", *Computers, Environment and Urban Systems* **22**, No. 1, 71-80.

CAPTIONS (Tables and Figures)

Table 1. Production of industrial waste (tonnes) by Plan-Region in Portugal's main land (IR, 2003).

Table 2. Production of hazardous industrial waste in Europe by country: amount produced/NGP (IR, 2003).

Figure 1. Production of industrial waste by Plan-Region in Portugal's main land (adapted from IR, 2003).

Figure 2. Gaussian model coordinate system and how it refers to a global coordinate system.

Figure 3. Pollutant emission impact on a continuous rectangular area.

Figure 4. Impacts on hospital facilities in Coimbra (using circles).

Figure 5. Impacts on pre-primary school facilities in the central zone of Coimbra (using rectangles).

Figure 6. Impacts on pre-primary school facilities in Coimbra region**.**

Figure 7. Maximum impacts on pre-primary school facilities in Coimbra central urban area.