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Planning Air Pollution Monitoring Networks in Industrial Areas by Means of Remote Sensed Images and GIS Techniques

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1. Introduction

Air pollution and its impact have become one of the most important challenge for public authorities. The quantification of emissions as well as their spatial distribution are essential for any air quality program (Aleksandropoulou & Lazaridis, 2004; Sengupta et al., 1996). The selection of the location of monitoring stations is one of the most complex task that occurs in designing air monitoring networks. Several issues, as the harmful effects of pollution on both human health and environment, must be taken into account (Allegrini et al., 2004).

The European directive 2008/50/CE of 21 May 2008 on ambient air quality and cleaner air provides criteria about monitoring network. This directive has been issued in order to improve, clarify, simplify and replace the precedents five acts:

- Council Directive 96/62/EC of 27 September 1996 on ambient air quality assessment and management;
- Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and nitrogen oxides, particulate matter and lead in ambient air;
- Directive 2000/69/EC of the European Parliament and of the Council of 16 November 2000 relating to limit values for benzene and carbon monoxide in ambient air;
- Directive 2002/3/EC of the European Parliament and of the Council of 12 February 2002 relating to ozone in ambient air and;
- Council Decision 97/101/EC of 27 January 1997 establishing a reciprocal exchange of information and data from networks and individual stations measuring ambient air pollution within the Member States.

The Directive 2008/50/CE also introduces new air quality objectives and monitoring requirements for $PM_{2.5}$. In addition to that the EU directive determines criteria for positioning monitoring stations, taking into account a detailed evaluation of environmental features on both local and regional scale.

These objectives can be pursued by territorial analysis, which can be performed using a Geographic Information System (GIS). GIS is a computer-based information system that enables storing, modelling, manipulation, retrieval, analysis and presentation of geographically referenced data (Burrough, 2001). In particular this powerful tool allows a detailed representation of the investigated territory. Different types of data can be integrated and correlated: chemical, physical, demographic and any kind of environmental information. Numeric records can be stored in a GIS, creating and developing a geo-database. All these information can be analysed and elaborated in order to derive thematic cartography. GIS gives the opportunity to integrate these thematic layers with health data and permit the evaluation of health risk towards pollution (Stedman et al., 1997). The dynamics of these processes can be moreover investigated and monitored over a long period by multitemporal integration. This last procedure consists on join up of data provided by different campaigns carried out in the same study area. The background knowledge of every territorial analysis and successive integration with atmospheric data is made up of satellite imagery retrieving and classification. This final step provides land use maps and can be derived with several classification techniques on satellite images or digital aerial imagery (Foody, 2000; Weirs et al., 2004). The integration of land use maps with concentration maps of pollutants, allows recognition of areas exposed to high pollution levels and the relative exposure during time. The successive step of this territorial analysis allows identification of sites optimal for the installation of monitoring stations following the rules provided by the directives in force. This chapter proposes a combined procedure between data concerning pollutants contents and thematic cartography. This approach can support designing of monitoring networks focused on air quality.

2. Sampling strategies

Campaigns for monitoring pollutants must be planned considering objectives of the survey and features of the investigated process. These two issues are decisive for the selection of the season and the extent of the sampling length and are critical for the choice of the passive samplers location strategy. The passive sampler system, developed by the CNR Institute of Atmospheric Pollution Research, is particularly useful for preliminary evaluations of air quality condition (Bertoni 2000; De Santis et al., 1997). Samplers can in factbe exposed for many months in selected areas of interest, and resulting concentration levels are averaged over a long period. Passive samplers use active carbon as adsorption phase, active carbon is contained in a stainless steel netting inserted in the diffusive cylindrical body. Pollutants adsorbed by active carbon are successively extracted, by solvents or by heating, and analysed with appropriate chemical techniques. Passive samplers are inserted with the open side facing to the holder, which is necessary in order to minimize wind interference. Samplers are then exposed to air for a period long enough to obtain a significant and adequate sample for the analysis. The selection of the exposure length for sampling is regulated mainly by the survey objectives: the impact evaluation of new industrial plants on the environment requires pre-, sin- and post start-up campaigns; the impact evaluation of existing industrial plants requires, instead, to plan campaigns representative of each season in order to estimate all climatic and environmental features of the investigated area. The design of monitoring networks in urban areas requires, as above, the execution of campaigns representative of all the features characterising the examined urban area. On the other hand, the scheduling of campaigns and the exposure time of samplers are obviously influenced dominantly by requirements and funds dedicated by the administrations that dispose the study. For sure, a longer exposition of passive samplers can, in accordance of observed concentrations, be more representative of the study area, as the climatic and environmental conditions are averaged.

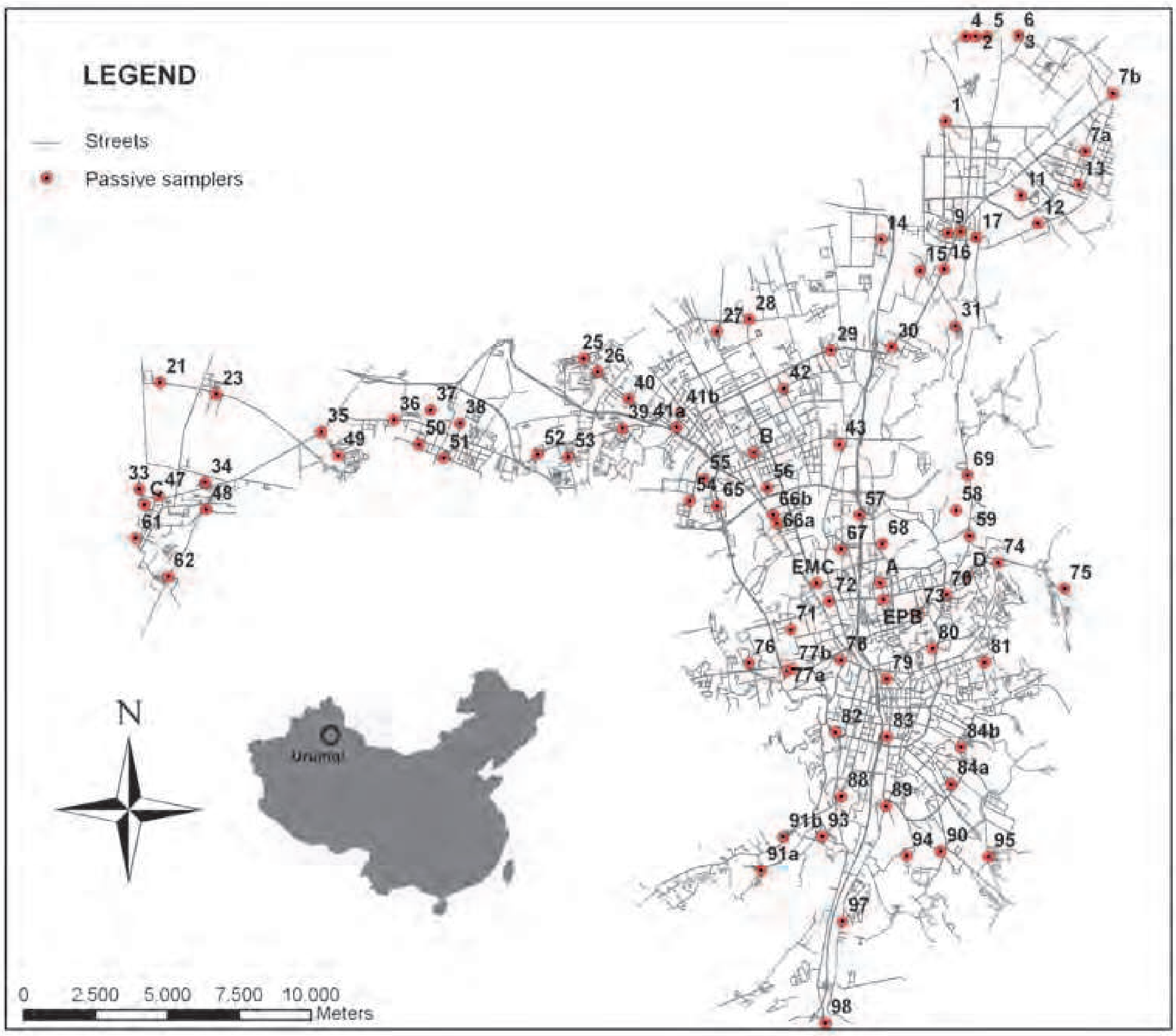

Fig. 1. Example of sampling strategy carried out in Urumqi (China, PRC).

The sampling strategy (Fig. 1) must be selected considering the objectives of the survey (Isaaks & Srivastava, 1989). Strategies can be classified into two major groups: simple and stratified. The first one is characterised by a single sampling grid. The lattice that localizes sampling sites is defined by several features: orientation; order; density. Orientation is the property that defines the alignment of grids with preferential directions of pollutant dispersion. This feature can be selected taking into account the climatic and environmental conditions of the study area and can be regulated in order to consider dominant wind directions, topography and urban characteristics in the case of cities. The order grade of the grid is referred to the distribution of sampling stations in the territory and to the distance that occurs between sites. This distance can be constant and guarantees an homogeneous distribution, or it can be random in order to investigate processes at a more detailed spatial scale. In opposition of that, the random criteria can add clustering problems to the distribution of sampling stations. Both geometric features, previously discussed, influence the final characteristic of the sampling grid. The sampling density is a descriptive parameter that defines the spatial resolution of the lattice and allows evaluation of homogeneity and spatial significance of data. Stratified strategies are instead the result of the combination between two or more simple grids. This group is more appropriate for monitoring studies with a limited number of stations. It provides a dataset relatively independent from the studied phenomena and at the same time guarantees a good coverage of the study area.

3. Representation of concentration levels of pollutants

The representation of chemical data in a spatial context requires a three step analysis of concentration levels (Fig. 2).

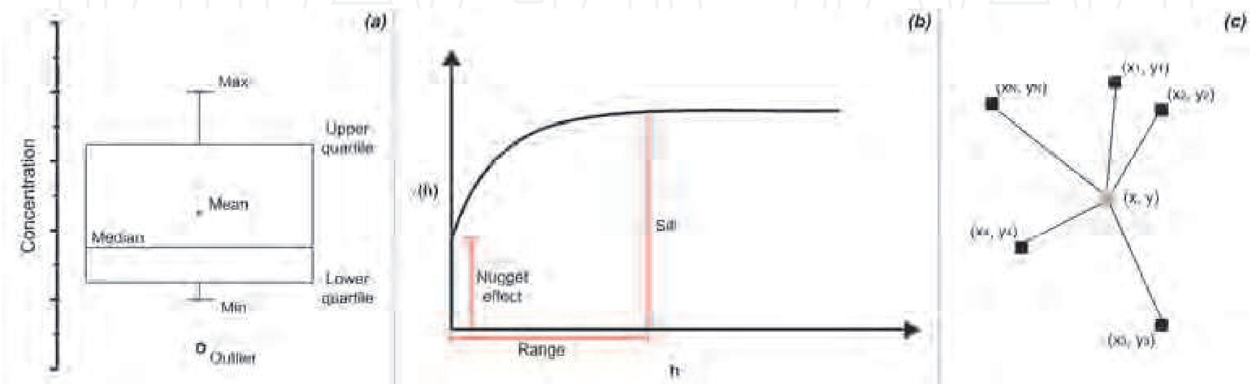

Fig. 2. Examples of statistical tools useful for the representation of concentration levels of pollutants [box diagrams (a), variograms (b) and interpolation algorithm (c)].

3.1 Descriptive analysis

This first step consists on the description, with general statistical parameters, of data obtained during the monitoring campaigns. Different statistic tests are performed (Davis, 1986), in particular to study the statistical distribution of the dataset;variograms are created to define the spatial dependence of pollutants. All these data treatments are propaedeutic to the next steps that are focused on the representation *sensu strictu*.

3.2 Interpolation criteria

The interpolation criteria that can be applied to chemical data provided by diffusive samplers can be classified into two main groups (Armstrong, 1998): deterministic (inverse distance weight, nearest neighbour, linear and polynomial regression), and probabilistic (ordinary and universal kriging). In the first case, the values in the "*unknown*" sites are calculated as linear combination between "*measured*" stations. Probabilistic criteria estimate instead the "*unknown*" value using the spatial dependence model that exists between "*measured*" sites. Kriging, in particular, requires that the investigated process, and consequently the measured dataset respects the "*normality*" and the "*stationariness*" hypothesis (Isaaks & Srivastava, 1989). A complex geostatistical treatment is necessary to support the application of kriging. The core of this probabilistic method consists in the definition of spatial dependence model. The appropriated model is selected fitting experimental variograms with theoric functions. The selection of the interpolation method depends mainly on the sampling strategy and on the number of available samples. Unfortunately there are no objective criteria that support the selection of the most appropriate interpolation method. Each case differs from the others and only the preliminary analysis and the variogram study can help the user to take decisions. It is possible to evaluate the goodness of resulting maps creating error maps, which can be calculated as the difference between "*measured*" and "*calculated*" values.

Concentration level	SO_2	O_3	NO_x	NO_2	H_2S
	µg/m³				
1st	0 – 20.8	0 – 20	0 – 13.3	0 – 13.3	0 – 2.7
2nd	20.8 – 41.7	20 – 40	13.3 – 26.7	13.3 – 26.7	2.7 – 5.3
3rd	41.7 – 62.5	40 – **60**	26.7 – **40.0**	26.7 – **40.0**	5.3 – **8**
4th	62.5 – 83.3	**60** – 80	**40.0** – 53.3	**40.0** – 53.3	**8** – 10.7
5th	83.3 – 104.2	80 – 100	53.3 – 66.7	53.3 – 66.7	10.7 – 13.3
6th	104.2 – **125.0**	100 – 120	66.7 – 80.0	66.7 – 80.0	13.3 – 16.0
7th	> **125.0**	> 120	> 80	> 80	> 16.0

Concentration Level	Benzene	Toluene	Xylenes	VOCs
	µg/m³			
1st	0 – 1.6	0 – 8.3	0 – 8.3	0 – 16.7
2nd	1.6 – 3.3	8.3 – 16.7	8.3 – 16.7	16 – 33.3
3rd	3.3 – **5**	1.7 – **25.0**	1.7 – **25.0**	33.3 – **50.0**
4th	**5** – 6.6	**25.0** – 33.3	**25.0** – 33.3	**50.0** – 66.7
5th	6.6 – 8.3	33.3 – 41.7	33.3 – 41.7	66.7 – 83.3
6th	8.3 – 10.0	41.7 – 50.0	41.7 – 50.0	83.3 – 100.0
7th	> 10.0	> 50.0	> 50.0	> 100.0

Table 1. Suitable concentration levels of pollutants for distribution maps. Bold numbers represent the reference values, that are based on annual limits indicated by legislation, when available.

3.3 Classification of pollution levels

The classification of pollution levels for each considered substance can be arbitrary, objective or derived. The first criterion can be applied using statistic parameters as equivalent classes, quartile, standard deviation or whatever the user wants to use for subdividing the range into levels. The classification with an objective criterion is instead based on selecting a reference value that can be indicated, for example, by legislation. In conclusion several derived criteria can be used as calculated indexes. It is possible to calculate ratios respect reference values or coefficients that consider health effects produced by specific pollutants (Table 1).

4. Territorial analysis with remote sensed images

The best locations for air quality monitoring stations can be found analysing the environmental patterns of the region where the network must be located, even if socio-political reasons cannot be neglected. The study of environmental patterns can be conducted using coverage and land use maps along with census maps. The availability of updated and detailed maps is very limited and to overcome this problem it is only possible to derive these thematic maps by processing remote sensed images. Remote sensors collect and record the electromagnetic energy coming from the Sun and reflected, or emitted, by the Earth surface at different wavelengths. For environmental studies the wavelength range used by sensors (passive optical sensors) is between 450 nm and 2500 nm, although there are passive sensors that can collect images in the thermal infrared wavelengths range (8000 – 10000 nm). Each surface element like soil, different types of vegetation cover, urban areas, reflects the electromagnetic energy as a function of its chemical and physical characteristics, i.e. each surface element shows a different spectral behaviour that can be considered as its fingerprints or its spectral signatures. Images collected at different wavelength intervals (different bands) can be processed in order to assign a surface element to each pixel of images and to analyse the spatial distribution of these elements. At the present time, there are many remote sensors and each of them can collect images characterised by a different spectral range (band). The number of bands, their width and their location in the electromagnetic spectrum define the spectral resolution of the image. Most of the sensors record the reflected energy in the visible range, with three spectral bands centred on blue, green and red light, one or more bands are instead reserved for the spectral range that corresponds to middle and near-infrared and generally only one band is dedicated to measure the radiation in the thermal infrared. Therefore, a remote sensing (RS) image can be composed of different number of bands: a multispectral image is represented by 3 - 7 bands while hyperspectral images can have more the 100 bands, where more than one corresponds to the thermal infrared. In theory, a higher number of bands can allow a more detailed analysis of the spectral characteristics of surface element. The availability of images collected simultaneously at different wavelength ranges, allows selection of the most appropriate set of bands useful for the specific investigation. Visible and near infrared images are, for instance, used mainly for vegetation and land cover studies while images recorded at higher wavelengths are more useful for geological applications. Moreover, images recorded in the thermal infrared can be processed in order to derive radiant temperature of the surfaces. Remote sensors used for environmental investigation can be carried aboard on satellites or aircrafts. In the first case, the geometry of the sun-target-sensor system, is determined by orbital parameters. The resultant image has consequently a fixed and constant pixel size. Aircrafts can, instead, fly at specified altitude that can be selected in order to achieve the requested spatial resolution. These images can also be collected at different day time improving the discrimination of surface elements. Nowadays, the improvement of spatial technologies makes available a wide selection of satellite images with a "*spatial resolution*" ranging between 1km and few metres and a "*pass over*" time ranging between 0.5 and 25 days. Sensors with low spatial resolution pass over the same area daily while sensors with medium or high resolution have pass over time of 3 - 16 days (Table 2).

Such a wide availability of remote sensed images with different spatial and spectral characteristics makes possible the production of thematic maps with a higher level of accuracy and with a scale controlled by the image pixel size. The selection of the most appropriate sensor must be carried out before the information extraction process and must take into account the purposes of the study averaging out between spatial and spectral resolutions. For instance, the most suitable data sets for regional scale studies are the Landsat Thematic Mapper images. Such sensor acquires images with 7 spectral bands, in the wavelength range between visible and thermal infrared, at ground resolution of 30m per pixel (Table 2). These radiometric and geometrical characteristics allow the investigation of large areas with a spectral resolution suitable for the production of land cover or land use maps with a scale ranging between 1:50.000 and 1:100.000. Image fusion techniques, that combine images with different spatial and spectral resolutions, are a very useful tool to preserve the highest content of information. Moreover, all the other multispectral instruments devoted to Earth observations, as Thematic Mapper, were designed taking into account the spectral properties of natural surfaces. Vegetation cover patterns can be easily discriminated by processing red and near infrared bands (TM3, TM4, TM5) while differences between soils moisture or rock outcrops can be detected using band TM5 and TM7. The complexity of the information embedded in multispectral images is the key that allows, using proper statistical classification algorithms, the elaboration of thematic maps for environmental applications.

	NOAA AVHRR	**Landsat 7 ETMP**	**SPOT5 HRVIR**	**IRS LISS-I**	**IKONOS**	**QuickBird**
Image bands (μm)	0.58 – 0.68	0.45 – 0.52[a]			0.45 – 0.52[a]	0.45 – 0.52[a]
	0.725 – 1.1	0.52 – 0.60[a]	0.50 – 0.59[a]	0.52 – 0.59[a]	0.52 – 0.61[a]	0.52 – 0.60[a]
	3.55 – 3.93	0.63 – 0.69[a]	0.61 – 0.68[a]	0.62 – 0.68[a]	0.64 – 0.71[a]	0.63 – 0.69[a]
	10.3 – 11.3	0.76 – 0.90[a]	0.79 – 0.89[a]	0.77 – 0.86[a]	0.77 – 0.88[a]	0.76 – 0.90[a]
	11.5 – 12.5	1.55 – 1.75[a]	1.58 – 1.75[b]	1.55 – 1.70[b]		
		10.4 – 12.5[b]				
		2.08 – 2.35[a]				
		0.52 – 0.90[c]	0.48 – 0.71[c]	0.5 – 0.75[c]	0.45 – 0.90[c]	0.45 – 0.90[c]
Spatial resolution (m)	1100	30[a]/60[b]/15[c]	10[a]/20[b]/5[c]	23[a]/70[b]/5.8[c]	4[a]/1[c]	2.4[a]/0.5[c]
Revisit time (day)	0.5	16	2-3	24	3	3
Swath Width (km)	3000	185	60	70[a,c]/142[b]	11	16.6

Table 2. Characteristics of the most commonly used satellite sensors for Earth Observation.

The definition of land use and land cover classes has been object of several studies but nowadays the scientific community is converged on the CORINE classification system (Bossard et al., 1999), where the detail of classification can be selected according to the study purposes as well as the representation scale. CORINE Land Cover (CLC) is a geographic land cover/land use database encompassing most of the European countries. CLC describes land cover (and partly land use) according to a nomenclature of 44 classes organised hierarchically in three levels. The first level (5 classes) corresponds to the main categories of the land cover/land use (artificial areas, agricultural land, forests and semi-natural areas, wetlands, water surfaces). The second level (15 classes) covers physical and physiognomic entities with a higher level of detail (urban areas, forests, lakes, etc), finally level 3 is composed of 44 classes. Image classification techniques can help to study air quality and its effects on human health. The classification procedures, devoted to the production of the land use and the land cover maps for air quality studies, support the discrimination between spectral classes related to urban and industrial areas. These classes can be used, by means of integration with data coming from different sources (i.e. census data), to estimate population density or other socio-economic parameters. For example, classes identified in industrial sites could be combined with the number of persons working as well as the type and the amount of pollutants introduced in the atmosphere.

5. Integrated analysis with GIS

As mentioned before, the GIS is a complex database system in which data coming from different sources can be archived. The unique constraint is that data must be georeferred, i.e. stored with their geographical coordinates (Fig. 3). The creation of a GIS, designed to be a decision tool in planning an air quality network, foresees the input of: point data, derived from chemical analysis of atmospheric pollutants or from census archives; linear data, like railways or highways networks as well as traffic fluxes associated to relative feature; surfaces data, derived from remote sensed image processing or other thematic maps. The statistical analysis, the data retrieval and the representation procedures are implemented in a GIS. All these features make GIS as a very powerful tool, which can provide several types of new information. For example, surface information can be derived from point data using interpolation procedures. The geodatabase can be queried in order to extract new calculated values, as areas where pollution levels are higher then a certain value and where the main roads are closer than 50 metres. Data stored in a GIS can be periodically upgraded by the users in order to supply a better overview in monitoring environmental processes. The dynamism of GIS allows processing of multi-temporal data using multivariate statistical analyses. Once pollutant concentrations, collected in different seasonal campaigns, are stored into a GIS, substances can be treated singularly or combined together. The built-in routines can either retrieve seasonal distribution maps or calculate maps of ratios (i.e. benzene/VOCs) or compute multi-temporal maps. Moreover, the areas with concentration values above the average can be highlighted using queries. These results can also be resumed in different summary maps, one for each pollutant (i.e. NO_x, NO_2, O_3 and VOCs respectively). Through the summary maps it is possible to describe the distribution of pollutants all over the monitoring period without loosing information of the single monitoring campaign. Subsequently, from each summary map, areas with values above average for more than two campaigns can be extracted and plotted together in a new map that can be named "*occurrence map*". These areas can be furthermore classified using special tags that allow identification of the recurrence number and of the type of pollutant.
For instance it is possible to attribute the tag "$2rNO_x$" to the areas that registered a NO_x concentration levels above the average values for at least two monitoring campaigns (Fig. 4). This kind of analysis, iterated for each pollutant, can be used to verify the significance of peak values and/or spatial trends. For this purpose a "*multiple-occurrence map*" can be created selecting properly the pollutants to be monitored. All the thematic maps, thus computed, can be overlaid to the land cover and land use maps obtained by remote sensed image classification procedures. This approach permits the correlation between pollution patterns, physical features and processes occurring in the investigated area (Fig. 5). Pollutant distribution can be easily investigated taking into account its possible origins or carriers, such as transportation fluxes, industrial plans, urban wastes, morphology or hydrological networks.

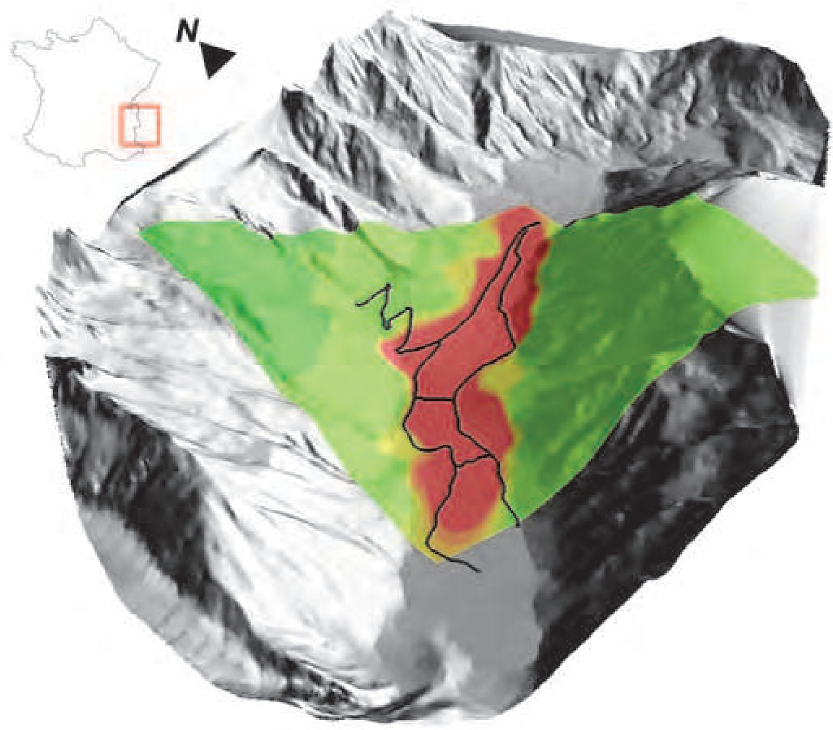

Fig. 3. Example of data integration in a GIS. Concentration levels (colours) of one pollutant are over imposed on a shaded relief (grey tones) obtained from a digital elevation model. Black lines represent the major road network. The study area is Chamonix (France).

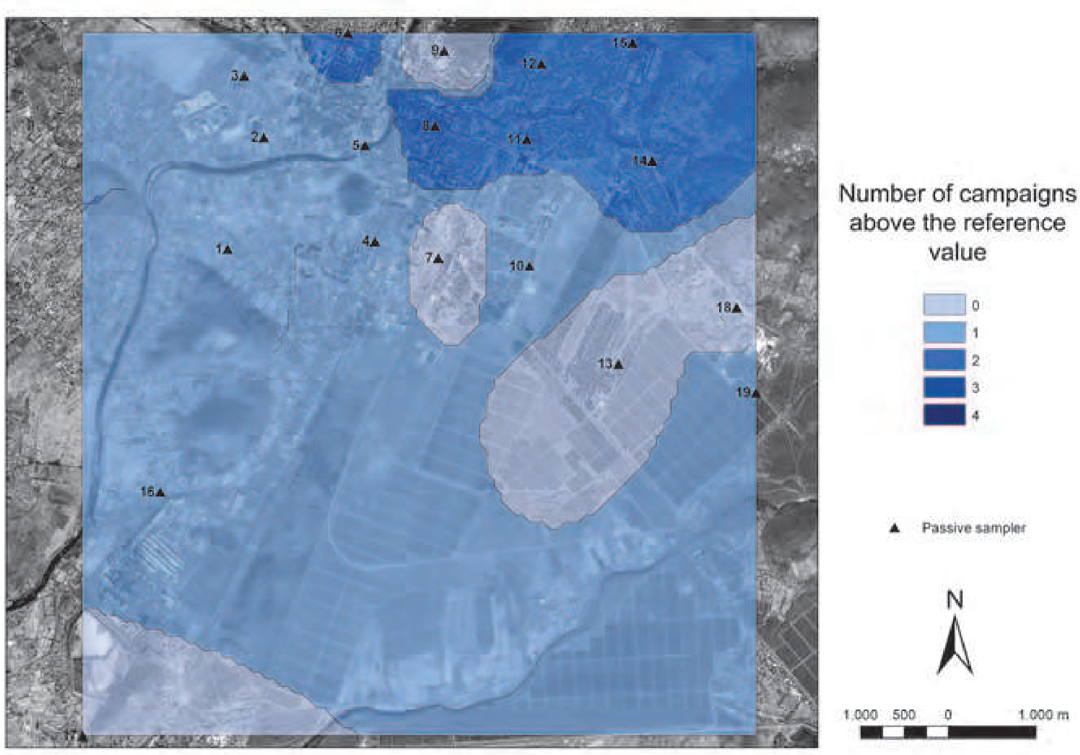

Fig. 4. Example of occurrence map where colours represent the number of campaigns that exceed a reference value defined by legislation or by statistics.

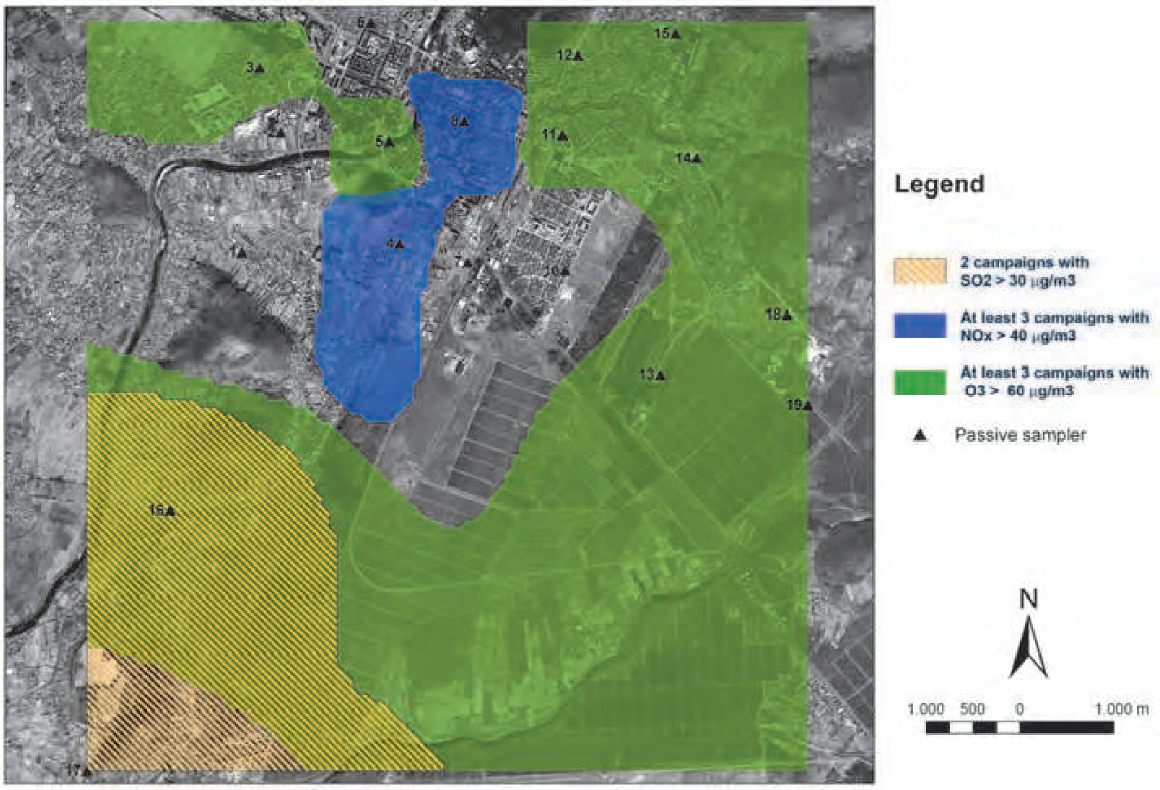

Fig. 5. Example of multiple occurrence map where colours represent areas where pollutants exceeded a reference value for a specified number of campaigns.

In urban areas, the use of very high resolution images can also allow overlaying of supply networks to land cover map as well as to pollutant distribution map. This interactions has been turn out to be a very useful tool to identify the most suitable site for monitoring stations network following the European criteria.

6. Practical applications

6.1 Gela case study

RS – GIS integrated approach was tested in 2005 when an oil enterprise, owner of a refinery plant located in Gela (Southwestern Sicily, Italy), charged CNR – IIA for upgrading its air quality monitoring network. The aim of this study was the identification of the minimum number of monitoring stations, their location, their type and their instrumental equipment in accordance with the Italian and the European legislation. Gela refinery is located in Sicily, 1 km SE of the city of Gela, in an industrial area 500 km^2 wide. Considering the wind direction, the distribution of inhabited areas, it was decided to investigate an area of about 22 x 22 km thus including both the urban areas of Gela and Niscemi (Fig. 6).
A Landsat 5 Thematic Mapper multispectral image (July 20th 2004) was selected to obtain a 1:50.000 land use map; this scale factor was also used to prepare all the cartographic layers of the developed GIS. The identification of different land covers (urban area, bare soils and different kind of vegetation covers) was carried out using the false colours combination of visible and near infrared bands (RGB = TM 4-3-2) provided by Landsat TM. This classification was obtained following the CORINE land cover classification criteria. In details, the performed procedure consisted in a first step where a preliminary classification

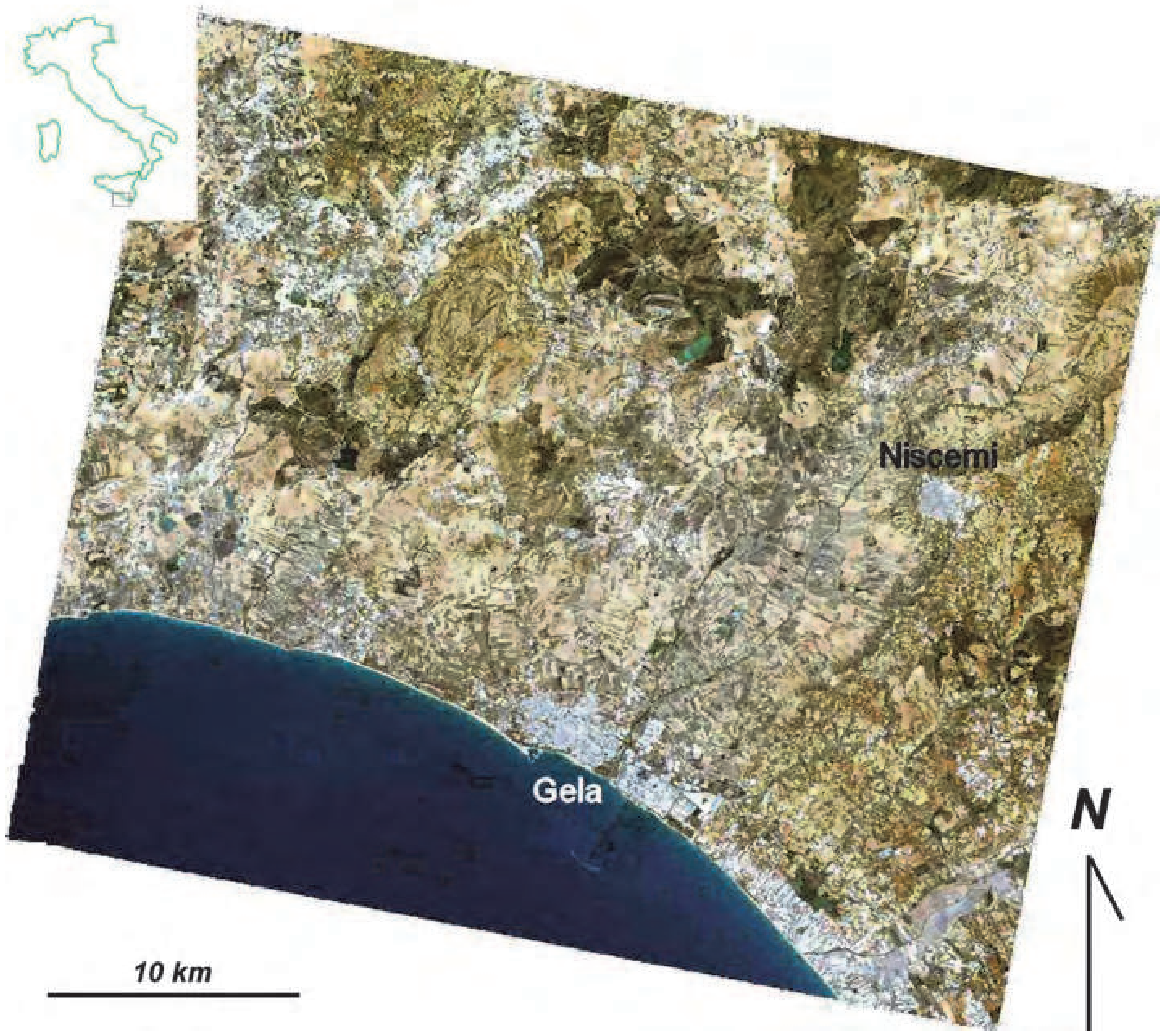

Fig. 6. Location map of Gela and Niscemi (south-western Sicily, Italy).

based on 6 classes (CORINE level 2) was obtained using a maximum likelihood algorithm. The following step was based on the principal component analysis of the original multispectral image combined to the classification of the resulting components. In this new classified image it was possible to discriminate clearly the urban area (in red) from the industrial areas: refinery in blue and dumping ground in magenta (Fig. 7). Both thematic maps were included in the GIS prepared for this case study. Moreover, this discrimination between different land-use classes (agricultural, natural and pasture areas) supported the assignment to each area of a specific weight, successively useful for estimating the value of each parcel and consequently the type of monitoring station that must be located, as stated by the European criteria on air monitoring network.

In addition to the territorial analysis this study included preliminary assessment of air quality using diffusive samplers: 4 seasonal campaigns were performed from January 2005 to November 2005, and the considered substances were NO_x, NO_2, SO_2, O_3, benzene, toluene, xylenes, and VOCs. Diffusive sampler is a device that collects samples of gas or vapour pollutants from air at a rate controlled by physical processes such as diffusion through a static air layer or permeation through a membrane. The main advantage of diffusive sampling is the length of the exposure period (it ranges from weeks to months

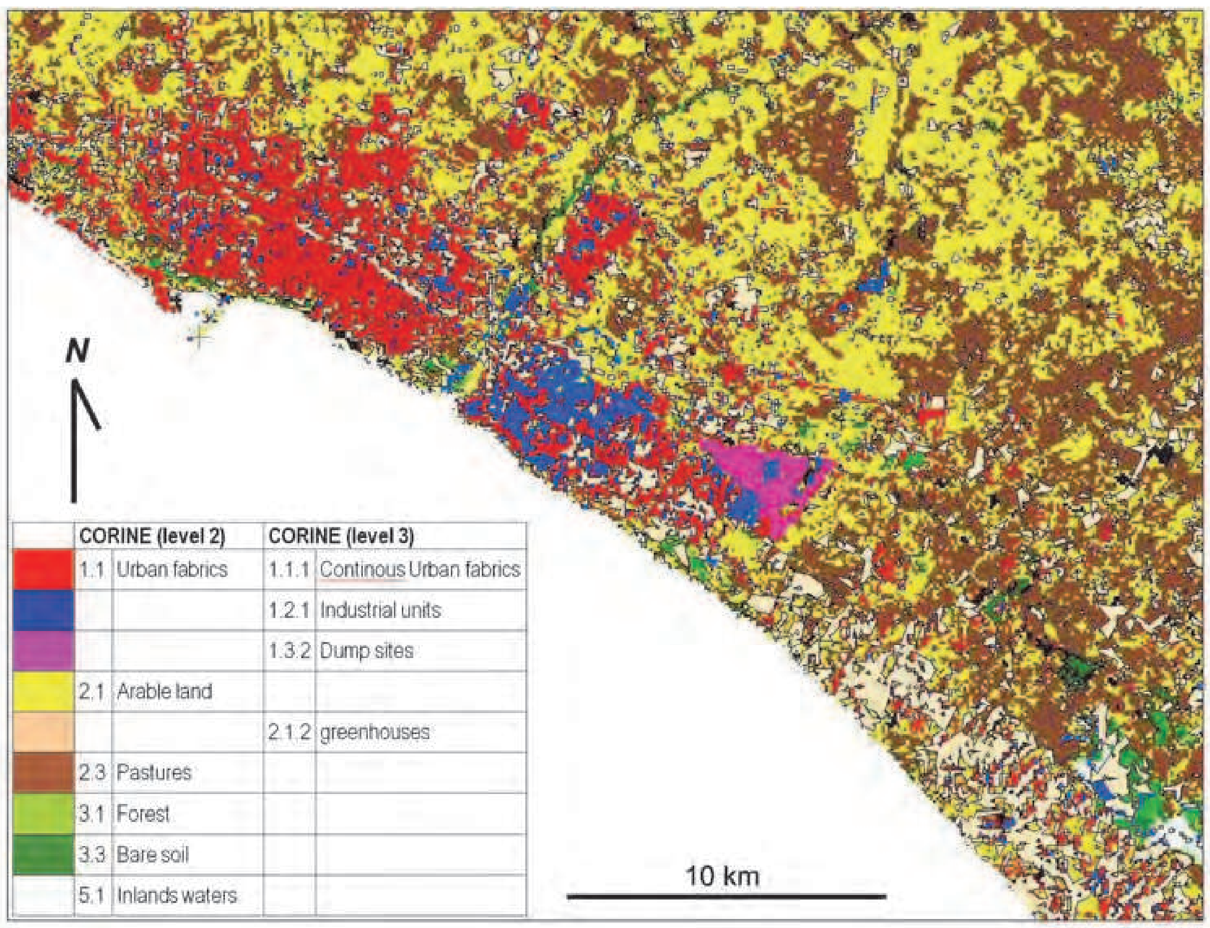

Fig. 7. Final classified image of the Gela area. Red pixels represent urban areas, blue areas are occupied by refinery facilities and dumping ground in magenta.

depending on observed concentrations) that allows long term sampling campaigns. In this study the selected sampling strategy for positioning diffusive samplers was the "*Stratified Random Sampling*" strategy. This option was adopted because this is an effective and practical method to ensure a uniform coverage of the study area. The study area was divided into a regular square grid with a cell dimension of 2.5 km and samplers were randomly placed within each cell. More than one sampler was placed in the cells located in the inhabited areas (Gela and Niscemi), in order to better assess the effects of pollutants on human health. In conclusion 72 diffusive samplers were distributed in the study area and the exposure time for each seasonal campaign was 30 days. In addition to that the quality of data was supported by samplers used as replicates and blanks. Furthermore, the installation of diffusive samplers was supported by a GPS survey in order to use chemical data in a GIS geodatabase. Pollutants concentration data, obtained by IIA chemical laboratories using chromatographic techniques, were interpolated over the whole study area using the geostatistical tools on the developed GIS. In this case study concentration maps were obtained using an "*Inverse Distance Weight*" algorithm, where the values at the "*unknown*" sites are calculated using relationship based on the distance between "*measured*" stations. The greater the distance, the lower is the effect of measured points on the unknown site. The interpolation process produces a continuum of values placed on the whole study area.

Concentration level	SO_2	O_3	NO_x	NO_2	H_2S
	$\mu g/m^3$				
1st	0 – 20.8	0 – 20	0 – 13.3	0 – 13.3	0 – 2.7
2nd	20.8 – 41.7	20 – 40	13.3 – 26.7	13.3 – 26.7	2.7 – 5.3
3rd	41.7 – 62.5	40 – **60**	26.7 – **40.0**	26.7 – **40.0**	5.3 – **8**
4th	62.5 – 83.3	**60** – 80	**40.0** – 53.3	**40.0** – 53.3	**8** – 10.7
5th	83.3 – 104.2	80 – 100	53.3 – 66.7	53.3 – 66.7	10.7 – 13.3
6th	104.2 – **125.0**	100 – 120	66.7 – 80.0	66.7 – 80.0	13.3 – 16.0
7th	> **125.0**	> 120	> 80	> 80	> 16.0

Concentration level	Benzene	Toluene	Xylenes	VOCs
	$\mu g/m^3$			
1st	0 – 2.7	0 – 8.3	0 – 8.3	0 – 16.7
2nd	2.7 – 5.3	8.3 – 16.7	8.3 – 16.7	16 – 33.3
3rd	5.3 – **8**	1.7 – **25.0**	1.7 – **25.0**	33.3 – **50.0**
4th	**8** – 10.7	**25.0** – 33.3	**25.0** – 33.3	**50.0** – 66.7
5th	10.7 – 13.3	33.3 – 41.7	33.3 – 41.7	66.7 – 83.3
6th	13.3 – 16.0	41.7 – 50.0	41.7 – 50.0	83.3 – 100.0
7th	> 16.0	> 50.0	> 50.0	> 100.0

Table 3. Applied concentration levels of pollutants for the Gela case study. Bold numbers represent the considered reference value, that are based on annual limits indicated by legislation, when available.

For a better result, a pollutant map requires the use of a chromatic scale that can effectively represent the concentration values; therefore the colour scale adopted was calibrated in order to immediately visualize the reference limits imposed by national and European directives (Table 3). This approach turned out to be an objective and flexible criterion, and the maps thus obtained were easily compared and immediately figured out also by non-technical users. Since maps were produced from digital data, any modification of ranges or limit can be easily performed and, for more detail local analysis, it was also possible to represent concentration values following statistical criteria. In conclusion of that, considering all the monitored compounds and each seasonal campaign, 32 concentrations maps were created and integrated in the GIS combined to thematic layers obtained by the previously described territorial analysis. This large amount of maps was unfortunately not easily accessible and information were synthesized in new thematic layers. The first step was to create a "*multitemporal map*" or a summary map overlapping the seasonal campaign maps of each pollutant. Being the product of a series of queries and not the result of numerical calculations on the original concentration values of pollutants, these maps allowed the simultaneous view of the pollutant distribution during the year, maintaining, however, information relating to individual campaigns. From the summary maps for each pollutant, using crossover functions, areas with concentration values higher than the 4th class for more than 2 campaigns were selected. Since the values of the classes were decided on the basis of current legislation and not on the basis of the statistical distribution of individual pollutant, the 4th class represents the threshold that can be assimilated as reference value for each pollutant.

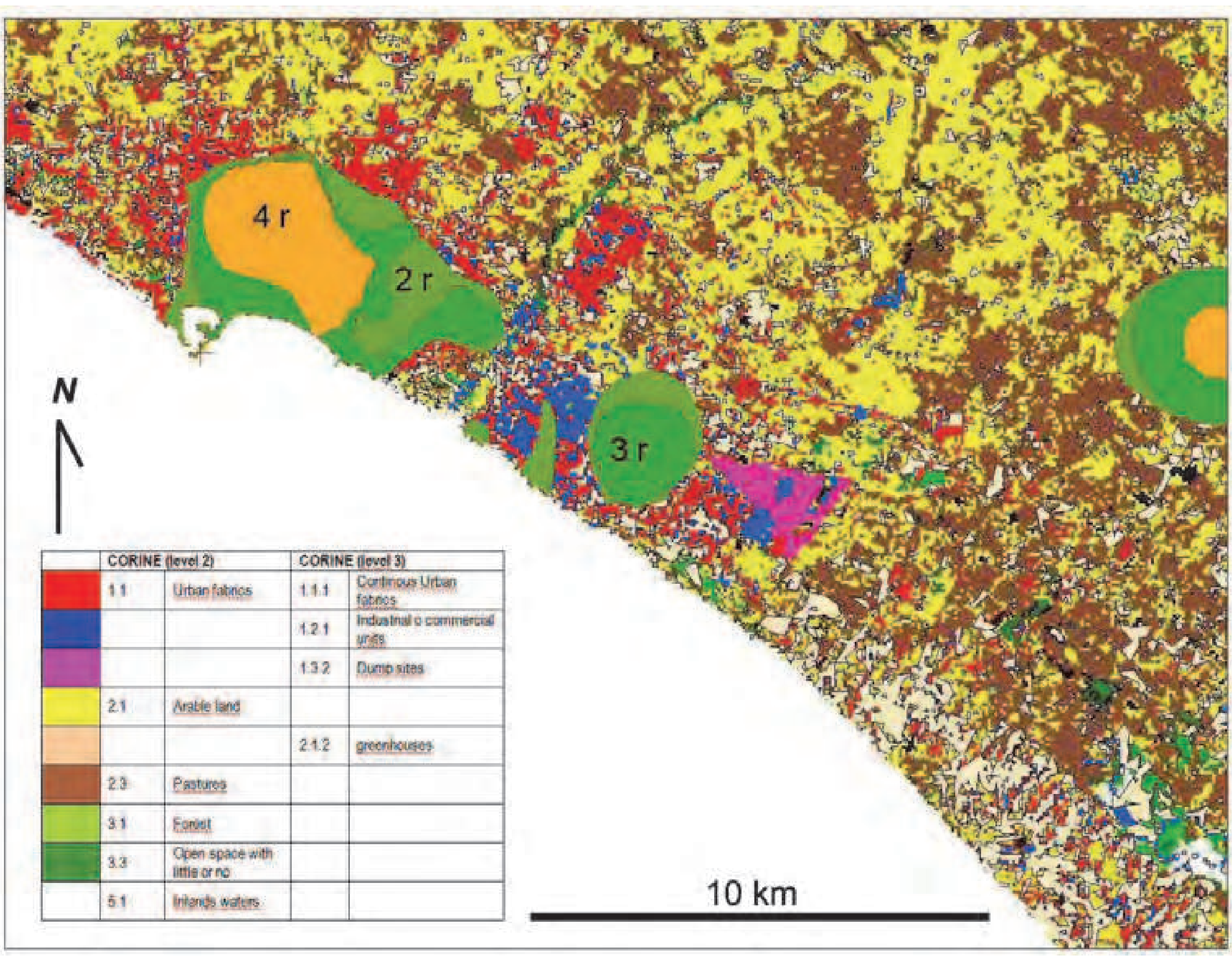

Fig. 8. Occurrence map of NOx in Gela. Orange (4r), dark (3r) and light green (2r) areas show where nitrogen oxides exceed the reference value for 4, 3 or 2 campaigns.

These areas were classified taking into account the number of occurrences, named as "*occurrence map*", highlighting how many times the concentration values were above the reference value and where. Querying the GIS iteratively and performing multi-temporal and multi-pollutants analyses, NO_x, O_3 and VOCs were found to be the most significant compounds that affect air quality in the study area. In conclusion all these maps were collapsed in a single final synthetic map named as "*multiple occurrence map*", where the occurrence maps of these compounds were overlaid. This "*multiple occurrence map*" evidences sites where the effects of pollutants are more relevant. Merging this map with the land cover /use maps, derived by satellite image processing, it was finally possible to evaluate the effect of pollutant on environment and on human activities and health The orange area "*4r*", is the area where the concentration of NO_x was higher than the law limits during the 4 seasonal campaigns. In the land use map this area corresponds to an urban area (Fig. 8).

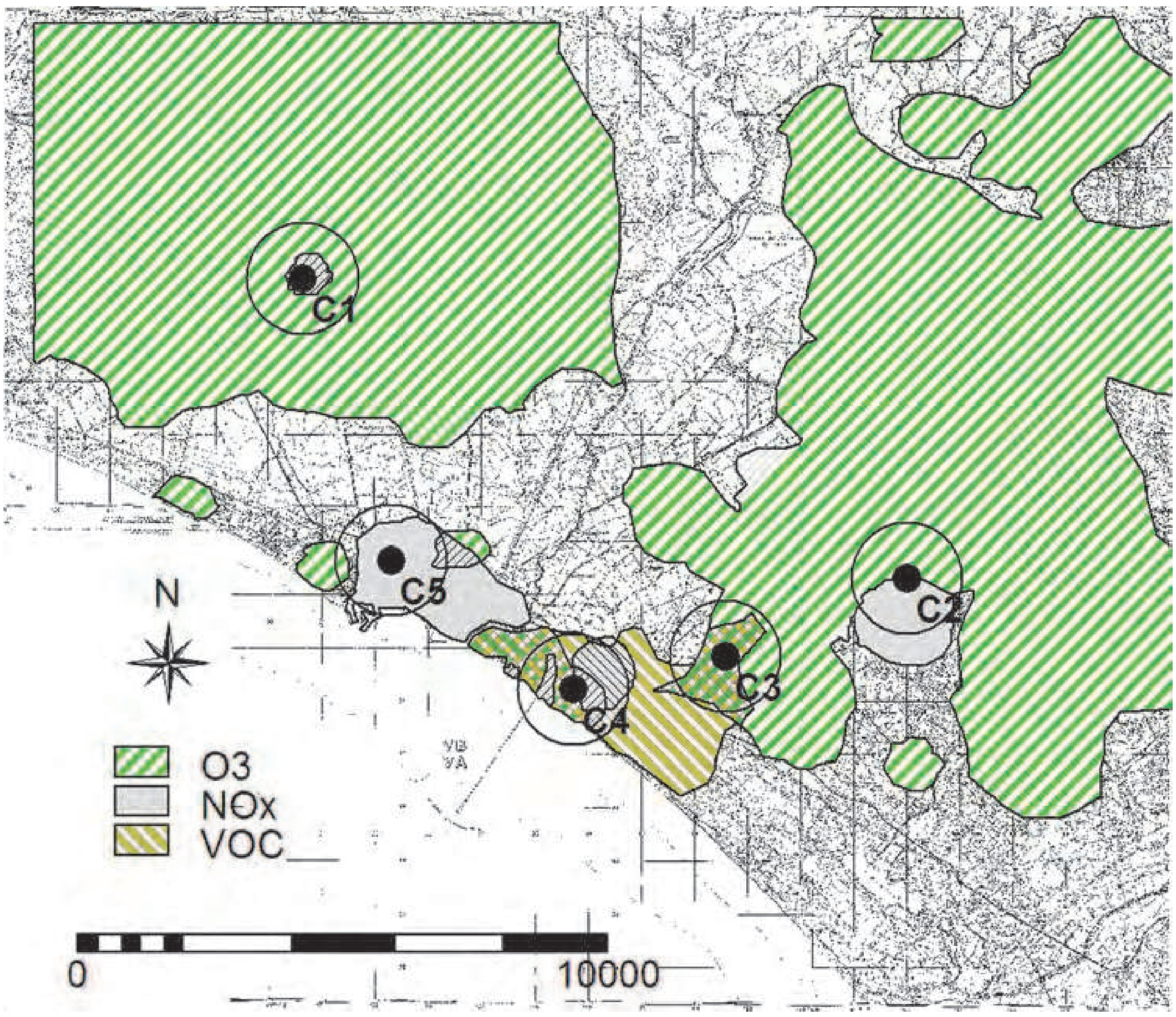

Fig. 9. Localization of monitoring stations in the Gela areas.

The final aim of the study was the selection of the location of new continuous monitoring stations. Giving the environmental asset of the study area: urban areas, industrial plants, agricultural lands, the European Directive suggests at least 3 continuous sampling points. For the sake of a better assessment of the risks for human health, 5 station monitoring network were proposed and this proposal was accepted by the oil company. Based on EUROAIRNET criteria (Larssen et al., 1999), the monitoring stations (Fig. 9) were classified according to the type of pollutant source (urban traffic, industrial, and background) and the characteristics of the area in which they are located (residential, industrial, rural - agricultural).
Furthermore, an additional result obtained overlapping the map of multiple occurrences and the land use map was the identification of the most suitable areas for the location of this 3 different types of monitoring stations taking into account also the logistics and accessibility of sites (power supply, roads network, etc.).

6.2 Scarlino case study
The situation of the industrial area of Scarlino, an industrial area close to coast in Tuscany (Italy), has always been one of the most delicate in Italy from the environmental point of

view, considering the type of industries and the proximity of the industrial area to the city. For this reason the municipality has commissioned to the CNR-IIA a preliminary assessment of air quality aimed to optimize the air quality monitoring network according to the European criteria. In the study area the former monitoring network covered only the industrial area of Scarlino and was focused on monitoring mainly sulphur dioxide (13 stations), that is the most significant pollutant in the emissions of the local industries activities. Few stations were equipped for monitoring nitrogen dioxide (2 stations) and total suspended particulate matter (3 stations). Moreover, this network appeared to meet outdated methodological criteria and not to be consistent with recent EU directives. The study was therefore focused on defining the possible relocation and on retraining the network set up, based on the new criteria established by current legislation. The European criteria require a preliminary evaluation of the air quality in the area of interest; to achieve this result a 4 seasonal monitoring campaigns on NO_x, NO_2, O_3, SO_2, H_2S and VOCs were carried out in the area surrounding the industrial plant (12 x 9 km). Investigated substances were sampled using diffusive samplers that were exposed for 30 days as described above.

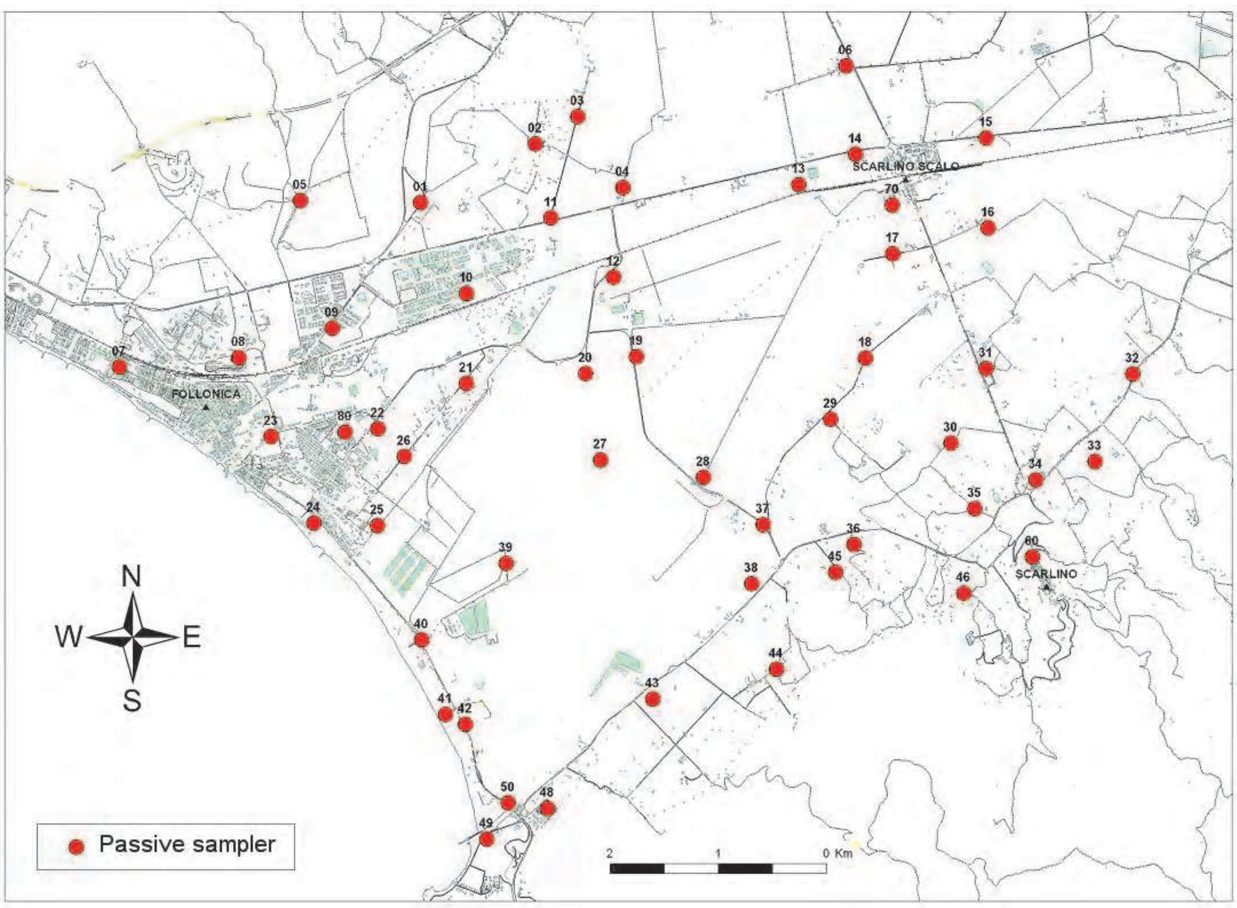

Fig. 10. Location map of passive samplers in the Scarlino area.

Considering the territorial feature of the study area, 52 passive samplers were positioned according to a stratified random strategy: systematic or large-scale and random on local scale. The area was divided with a regular grid (1 x 1 km), and in each cell a sampler was randomly placed. The sampling grid was constructed to take into account the morphology of the study area, the urban fabric and layout of industrial sites. (Fig. 10). Geographic coordinates of each sampler were collected in order to input the concentration value in the GIS geo-database. The quality of data was ensured placing samplers as replicates and blanks. The values of pollutants concentrations, as stated in the previous case study, were measured at the CNR-IIA chemical labs and included in the developed GIS in order to be statistically processed and spatially interpolated. In this case interpolation was constrained by territorial features as morphology, obtained by the digital elevation model, and by the coastline, defined using satellite imagery (SPOT, September 12th 2006).

The land cover/use map of the study was extracted processing both panchromatic and multispectral bands of a SPOT satellite image acquired on January 7th, 2005. The high spatial resolution, 5 meters for panchromatic band and 10 m for multispectral bands, allowed us to analyse territories with enough detail to realize thematic maps with a scale larger than 1:50.000, and therefore sufficiently accurate for the study purposes. The SPOT image was georeferenced to the 1:25.000 topographic map that represented the base of the GIS. The first stage of image processing was devoted on improving the contrast of each individual spectral band and on increasing the chances of visual interpretation of the image. The integration between bands with different spatial resolution aimed to increase the spatial detail and then to obtain a better detection of the land cover/use classes. In details, the contrast enhancement was performed emphasizing multispectral bands by linear stretching and the band integration was achieved using a pan-sharpening technique which allowed to obtain a synthetic image having the spatial resolution of the panchromatic band (5m/pixel) but preserving the spectral information of the multispectral images (Saroglu et al., 2004; Švab & Oštir, 2006). The final synthetic image has been classified by object-oriented methodology that allows the image interpretation not only based on their spectral characteristics but also on object geometric features and on the mutual relation between these objects. This technique allowed the accurate discrimination between classes of land use characterised by a similar spectral behaviour, in particular between the urban and the industrial zones, but avoiding the possibility of interpretation errors usually associated with pixel-oriented techniques (Yu et al., 2006). Furthermore, the image classification was carried out with an iterative procedure that creates polygons, firstly matched with an higher CORINE land cover class (level 2), and starts to segment the polygon-classes into sub-polygons assigned to a lower level of the CORINE land cover system (level 3). After the segmentation procedures, the classification algorithm k-Nearest Neighbours (k-NN) was used to associate the land cover classes to each polygon. The last step of this phase consists in the integration of this land cover/use maps to the developed GIS.

Similarly to the previous case study, distribution maps of pollutants were obtained using the Inverse Distance Weighting interpolation method. Considering the threshold values specified by regulations, the same 7 classes of the Gela case study were used to represent the distribution maps of the monitored pollutants (Table 3). Using the spatial analysis tool implemented in a GIS, pollutant concentration maps were overlaid to the land cover map and synthesized as already described. It was noted that the concentration values of SO_2, NO_2, benzene, toluene, xylenes were always lower than the 4th class; the occurrence maps emphasized also that in the study area there are no occurrences if the 4th class is considered; even when 3rd class is considered, the occurrences showed a small extent pattern. A Further analysis of the pollutants distribution was then carried out computing the ratio between NO_2 and NO_x, in order to evaluate the areas in which the primary pollutants provide a major contribution i.e. the areas where the ratio tends to lower values. This calculation was performed for each campaign and NO_2/NO_x distribution maps were derived.

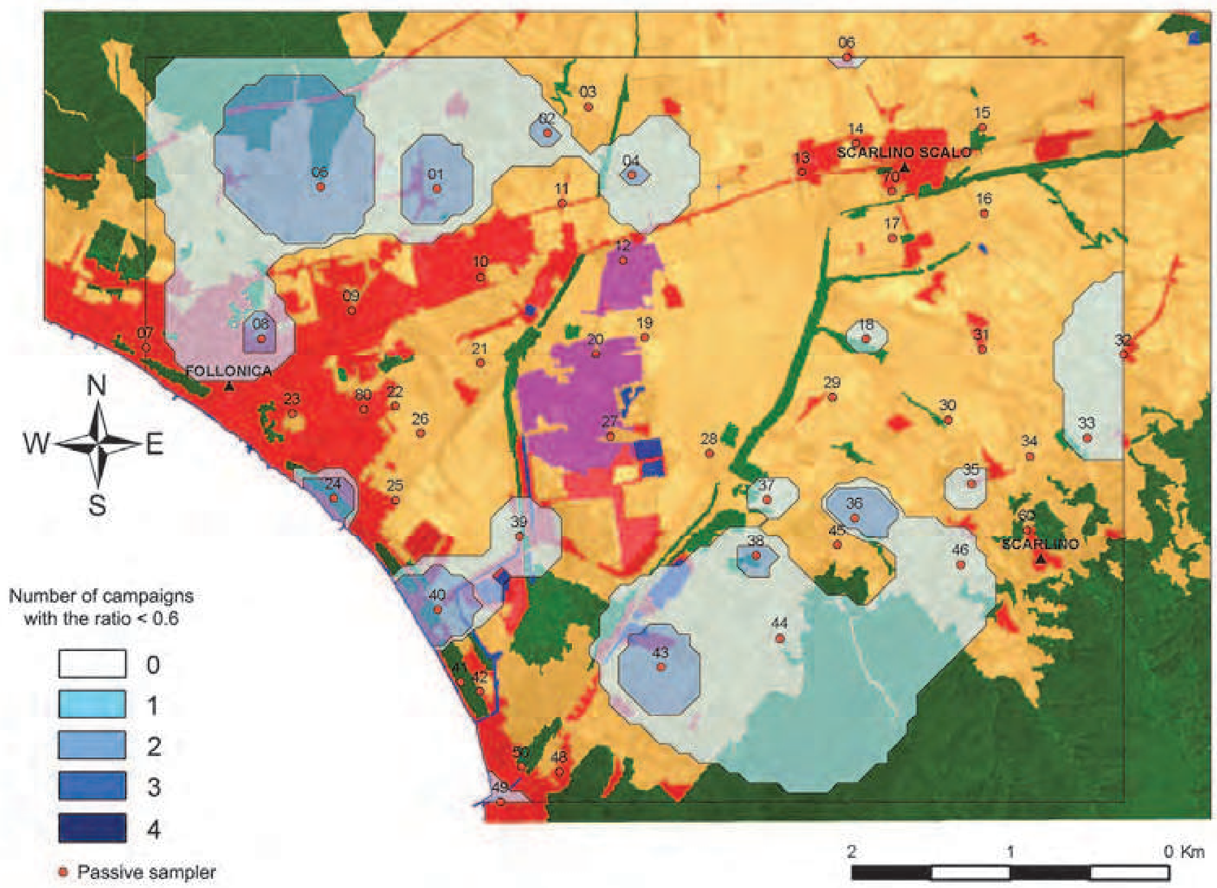

Fig. 11. Occurrence map of the ratio NO_2/NO_x below 0.6 in the Scarlino area overlaid on the land use map. Red areas are urbanized, magenta are industrialized, green are vegetated and brown are rural districts.

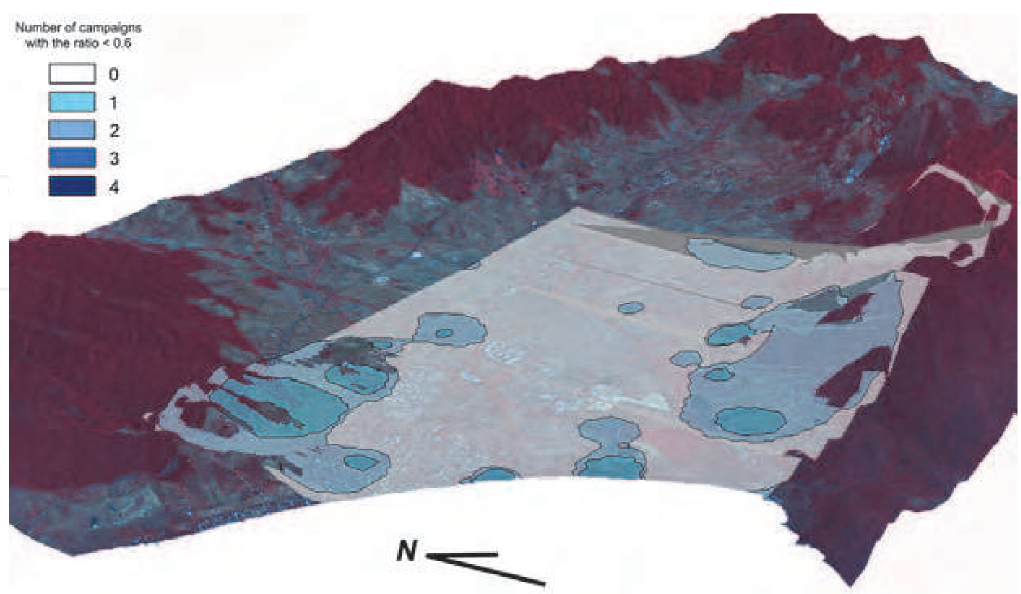

Fig. 12. Integration of NO_2/NO_x < 0.6 occurrence map on the digital elevation model associated with a remote sensed image. Red areas represent vegetated hills.

A "*ratio occurrence map*", that indicates how many time the ratio assumed values less than 0.6, was created and overlaid on the land use map (Fig. 11). This map showed the presence of a lower concentration of secondary pollutant in the areas where vegetation is largely present. As a final step, a Digital Elevation Model (DEM), with 10m grid, was derived by the 1:10.000 map provided by technical services of the Municipality. The ratio maps on the DEM clearly shown that these areas correspond with those at higher elevation above sea level (Fig. 12) . The ratio occurrence map, the land use map and the DEM were used as input data for querying the GIS in order to select the most suitable site for the three air quality monitoring stations according to EUROAIRNET criteria (Larssen et al., 1999). The final cartographic product (Fig. 13) shows the localization of monitoring stations that can be defined by a 500m buffer area. The final map presents three possible locations for monitoring stations: one traffic station (A) where two occurrences of NO_2/NO_x ratio less than 0.6 were found (the lower is the ratio, the higher is the amount of primary nitrogen oxide associated to vehicular emissions); one rural station (B) located inland in the valley at the same distance between the industrial and urban area; one industrial station (C) near the industrial hub.

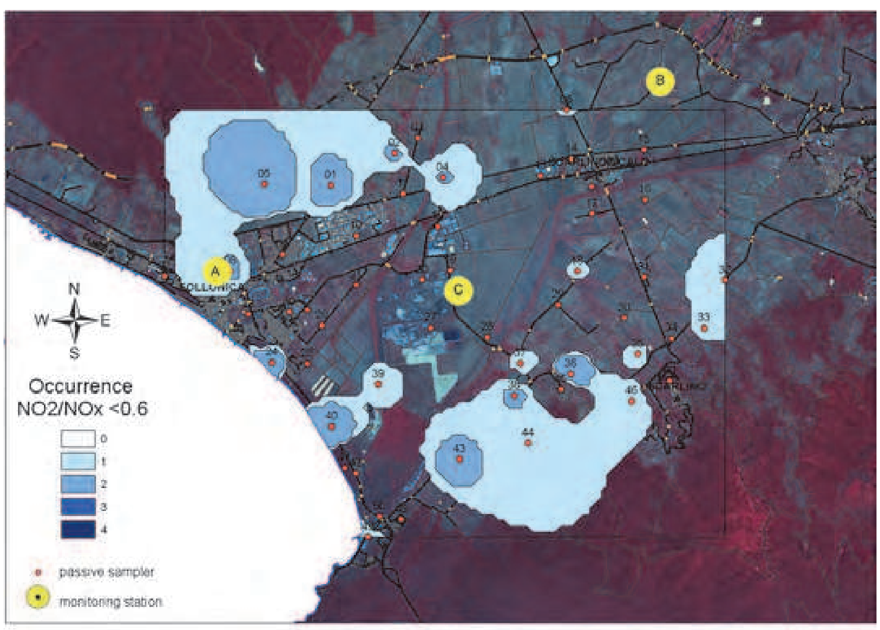

Fig. 13. Location map of monitoring stations in accordance to results obtained during the seasonal campaigns.

7. Conclusions

This chapter presents a combined approach (Fig. 14) for designing monitoring networks of air quality based on integrating Remote Sensing and GIS techniques, following the criteria indicated by European directives. The current EU legislation (Directive 2008/50/EC) on air quality monitoring for the preservation of human health sets still very generic criteria at macro-and micro-scale, but contains an new approach which requires a definition of the spatial and temporal distribution of air pollutants through a preliminary assessment of air quality. The Directive also classifies the monitoring stations according to their purposes (Traffic, Background and Exposure) and the characteristics of the area in which they are located (urban, suburban, industrial, rural).

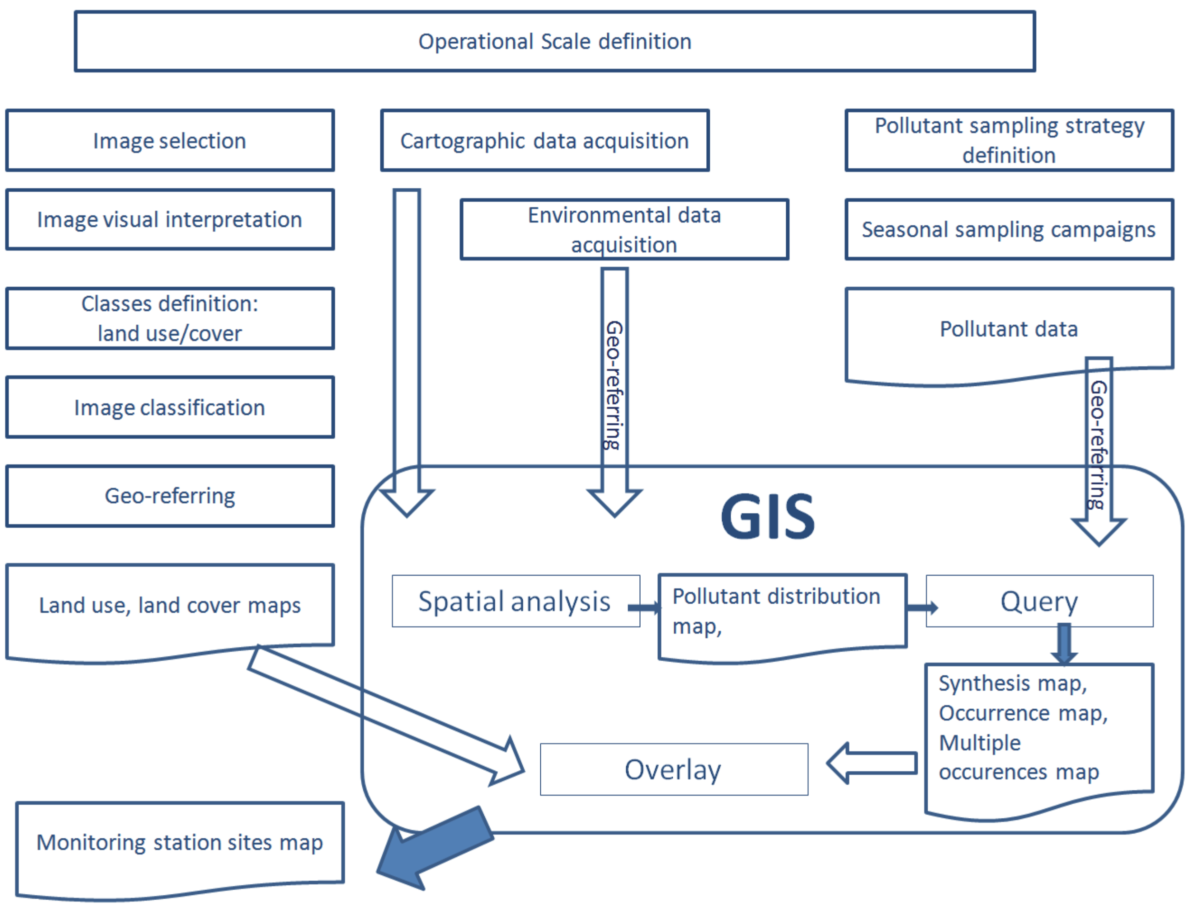

Fig. 14. Flow chart of the proposed approach based on integrating GIS technique and Remote Sensing.

The traffic stations should be placed along main streets, taking into account its type and dimension, the distance from buildings and the mean traffic flow. These stations should be equipped for monitoring nitrogen oxides, nitrogen dioxide, carbon monoxide, benzene, toluene and xylenes. The background stations, which support observations on long-range transport of pollutants, must be placed outside the major urban areas, possibly in rural areas, where only photochemical pollution occurs and where the distance from possible emitting sources is more than tens of km. The stations should be provided with equipment for the measurement of nitrogen oxides and ozone. The exposure stations are aimed to establish the level of exposure of population to pollutants. They should be located at sites with high population density and in adequate number according to the number of inhabitants and their distribution. These monitoring station must be equipped in order to monitor all those pollutants affecting human health protection, such as nitrogen oxides, carbon monoxide, nitrogen dioxide, sulphur dioxide, polycyclic aromatic hydrocarbons (pah) , benzene, toluene, xylenes, PM_{10} and $PM_{2.5}$. Moreover, the EU directive combined to such a preliminary study on air quality, focused on investigating the spatial distribution of pollutant during different seasons, foresees a territorial analysis of the area of interest at local and regional scale. The GIS technique can cater to these requests but it is necessary that all pollutant and environmental data must be georeferenced. Having georeferenced data available it is possible to use interpolation tools and consequently to generate pollutant distribution maps. GIS supports query and overlapping of such maps and land use/cover maps, derived by remote sensing image processing. The final goal of this approach is to provide smart information that can be integrated with legal and socio-economical features of the study area. The approach here described may represent a flexible, effective and quick methodology to develop management strategies concerning air pollution, such as the definition of control areas or the localization of monitoring stations.

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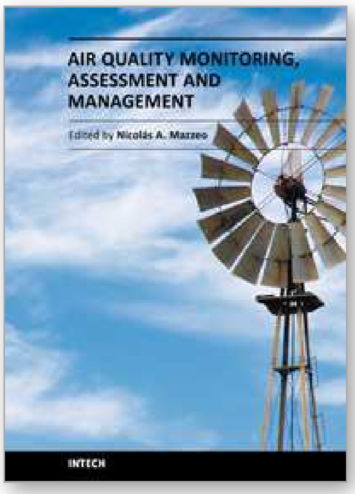

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