Design of an Air Pollution Monitoring Network for Tarragona (Spain)

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1 Introduction

The location of measurement stations for air pollution has been given an special attention in specialized literature since the Clean Air Act was passed in the United States[1]. Thus, for instance, the United States Environmental Protection Agency (USEPA in what follows) claimed the optimization of the measurement points to be needed as early as in 1975 [3] stating that:

> Much more consideration, in both manpower and monetary resources, should be applied to the issue of siting monitoring facilities than is currently the common practice ... It is considered inconsistent to undertake a monitoring effort involving resources in the tens of thousands of dollars without investigating the far smaller effort involved in ... proper siting of the monitoring instruments.

As it is evident, the criteria for the design of every network depend on its objectives. Some of these objectives were summarized by USEPA[3] as follows[2]:

- Establish a comparison basis between the present and future air quality in order to assess the effectiveness of air pollution control measures.
- Provide a basis to determine long term trends. Particularly, to determine the influence of global strategies of air pollution abatement.
- Constitute a source of information during severe air pollution episodes in order to take emergency actions.
- Allow the determination of the degree of fulfillment of emissions regulations.

[1] In fact, the optimal siting of measurement points for any kind of physical or chemical variable has received great attention since the seventies [1,2].

[2] Other objectives, more specific than the listed here can influence in the location of measurement networks. A good example is the experimental air pollution measurement network of the Saint Louis region, designed mainly to be used as an experimental site for the calibration of atmospheric transport and diffusion models [4].

- Provide data bases for research purposes.

Obviously, in each particular case any of the measurement stations can accomplish several of these functions. In fact, the criteria described in the bibliography for the siting of these stations [5,6,7], are usually closely related to the mission assigned to the station.

In a completely general case, the process of defining a measurement network for air pollution can be decomposed in three phases. First of all, one must determine the optimal number and location of the stations. After, one can specify the measurement equipment. Finally, the frequency and programming of measures are to be determined.

In the case of automatic measurement stations, as the described here, the last phase can be suppressed. In effect, given that the cost of each measure is very low, they can be taken continuously, as opposed with other cases, where the cost of the measure limits its frequency[3].

In general, the most common chemical compounds responsible for atmospheric pollution are sulphur dioxide, nitrogen oxides, hydrocarbons, suspended particulate matter, carbon monoxide and ozone[4]. Everyone of these pollutants has its own requirements for accurate measurement. Thus, for example, sulphur dioxide is generated mainly as a product of combustion of fossil fuels. Once emitted it is oxidized to sulfate after several hours in the atmosphere[5] and, therefore, an important part of the sulphur originally emitted is incorporated into the particulate matter. As a consequence of the kinds of its sources, sulphur dioxide is emitted usually from large stacks and other elevated points. One expect then to find the maximum concentrations shortly downwind from the source. On the other hand, it is well known that the combination of sulphur dioxide and particles produces worse effect on human health than any of them separately. This forces to install the measurement stations for sulphur dioxide further than expected given

[3]This is the case, for instance, of some kinds of groundwater essays, that require the introduction of special kinds of sounding into a well.

[4]Also lead has to be taken into account in urbane regions of countries where vehicle fuel still contains lead alkiles.

[5]The rate of oxidation of sulphur dioxide is rather complex to determine, and depends on factors such as the presence of potential catalyzers (like nitrogen oxides or particles that behave as strong oxidizers), solar irradiation, etc.

that particulate matter shows a long transport distance from stacks[6] The consequence is that one must look for representative areas to determine the location of monitoring stations.

This brief discussion already allows the identification of two basic types of stations. The first type will be called proximal[7] while the second kind will be called regional[8]. The selection of the location for proximal stations is conditioned to the configuration of the source one wants to control, as well as to the local topography. The optimal positions for these stations are those where the maxima of concentration at ground level occur[9].

Contrarily, regional stations are used to evaluate the level of immision in a vast region. Their positions must therefore be representative of this region. As a consequence, its location cannot be close to any important air pollution source[10].

2 Description of the scenery and demography

The geographical region considered for the study is shown in figure 1. As one can see, this region is limited by the coast line, the Universal Transverse Mercator (UTM) projection X-coordinates 342300 m and 362300 m and the Y-coordinate 4566900 m, all of them belonging to zone 31.

In the study one has considered three industrial nucleus responsible for air pollutant emissions: the so called Northern Polygon (labelled as PN

[6]The only exception for this rule occurs when one wants precisely to measure the source term from a large emission point.

[7]This is the name used by Liu *et al.* On the other hand, these station are called type A by Ott and traffic corridor or street canyon stations (in urban applications) by Ludwig *et al.*

[8]This is the name proposed by Ludwig *et al.* These stations are also called type C by Ott *et al.* or neighborhod stations also by Ludwig *et al.* (when its objective is the measure of the exposure of the population). When the main objective is the measure of the background levels of air pollution, these stations are called type E by Ott and regional by Ludwig *et al.*, while Liu *et al.* proposed the name of urban for this kind of stations.

[9]A more detailed description of the considerations for the location of proximal stations is given by Ludwig and Keoloha [8] or by Noll *et al.* [9]

[10]Several examples of this kind of location techniques can be found in Nakamori *et al.* [10] or Houghland and Stephens [11].

Figure 1: Region subject to study. Notice the three main industrial sources. Adapted from sheets 33-17, 33-18, 34-17 and 34-18 of series L of the Nueva Cartografía Militar de España, composed and published by the Servicio Cartográfico del Ejército.

in figure 1), the Southern Polygon (PS) and the industry located inside Tarragona (PT).

The Northern Polygon, besides Francolí river, occupies an extension of approximately 3 km^2. It is placed among the villages of El Morell, La Pobla de Mafumet and Constantí, some 8 km from Reus (and 4 km from its airport), 7 from Tarragona, 12 from Salou and Valls and 18 from Cambrils.

The Southern Polygon has an extension of 14 km^2. It is located among Tarragona, cape Salou and Mediterranean motorway. It is less than a kilometer away from Tarragona and Vilaseca de Solcina, 2 km from Salou, 4 from Reus and 5 from Cambrils. This polygon is crossed by Tarragona-Salou motorway, national route CN-340 and the railway lines Barcelona-Cádiz and Barcelona-Madrid.

This region presents a distribution of population, summer resorts and industry that makes it almost unique in Spain for what refers to air pollution study. In effect, the two previously described industrial polygons host a series of petrochemical factories (among them two refineries) that yield about 35production. On the other side, Salou[11] is a very important summer resort, with a floating population estimated in 500000. Finally, Tarragona has the largest population in the region and, in addition, a very important set of roman ruins[12] that have been severely affected by anthropogenic sulphur sources.

Table 1 shows the extension and population of each of the urban nuclei included in the area studied. The population values given correspond to 1986 census [12].

3 Methodology

The methodology used in the realization of the study is sketched in figure 2. As one can see, this methodology is divided in three main stages.

In the first phase an inventory of pollutant emissions in the zone studied

[11]Salou depends administratively on Vilaseca de Solcina. That's why it does not appear in the tables as an independent village.

[12]Tarragona, then called Tarraco, was the capital of the roman province Tarraconensis between 27 B. C. and 411. This province was, roughly, most of the north east of the actual Spain

Urban nucleus	Extension (km^2)	Population
Tarragona	62.24	107356
Constantí	30.45	5690
Els Garidells	3.03	182
El Morell	5.96	2234
Els Pallaresos	5.54	475
Perafort	9.65	503
La Secuita	17.60	942
Renau	8.30	47
El Catllar	26.39	891
La Pobla de Mafumet	6.20	816
Vilallonga del Camp	9.24	1165
Vilaseca de Solcina	36.71	17512
La Masó	3.59	285
La Selva del Camp	35.18	3369

Table 1: Demography of the region studied. Notice that the population of Vilaseca de Solcina does not include the floating population of its summer resort Salou.

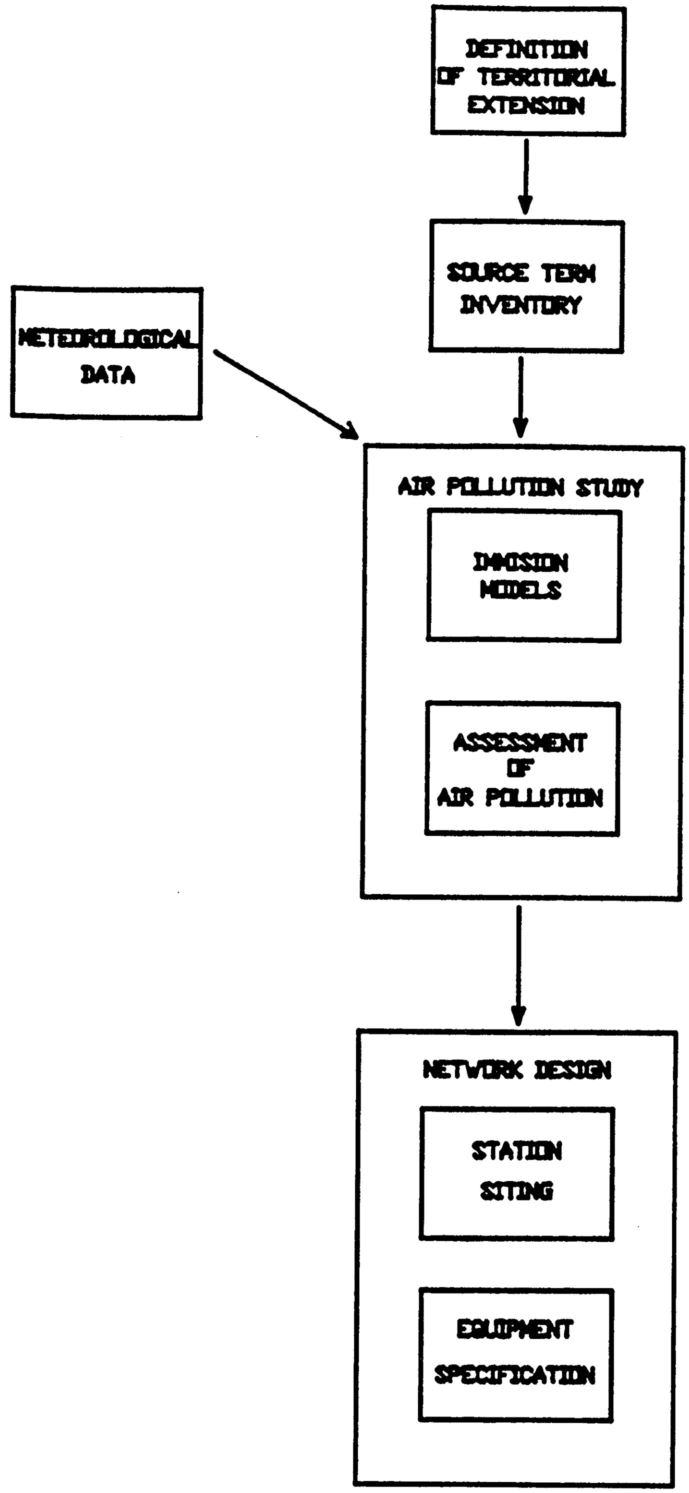

Figure 2: Scheme of the methodology used in the study.

Emission type	Number
Fugitive emissions	123
Relief valves	134
Venting points	122
Stacks	52
Torchs	18

Table 2: Summary of the inventory of pollutant emissions in the area studied.

was elaborated. The inventory of industrial sources was based on a poll distributed among the industries located in the area studied. This part of the inventory contains information about some 449 sources. Table 2 shows a summary of the number of industrial emission points considered in each of the categories that were used to classify them. On the other hand, the source terms due to urban traffic, interurban transport and other sources received specific treatments. Thus, for instance, the values for transport emission were estimated using USEPA's emission factors [13].

The second part of the project consisted on an air pollution study. This objective was accomplished by incorporating both, emission and meteorological data, into a set of models of air transport and diffusion of pollutants. The objective was to determine the immision levels for about twenty different contaminants[13].

The contamination study was conducted to determine year-averaged values of air pollution as well as the values due to severe episodes. These can be provoked either by specially unfavourable meteorological conditions (such as low mixing layer height) or by accidental emissions (such as relief valves, for instance). Two mathematical models were used in this study. The first one is a climatological model based on Pasquill-Guifford's [14] model[14]. In addition to the classical model, the used for this study takes

[13]In fact in the poll distributed among the industries appeared some 113 different chemical compounds. To ease the interpretation of these data, the compounds were classified into twenty-nine categories, attending to their chemical affinity and pollutant potential.

[14]These models are also called, improperly, gaussian. This is due to the fact that, in their

into account the effect of the following phenomena:

- Plume rise due to thermal and buoyancy effects [15].
- Aerodynamic emissary effect and building effect [16].
- Ground and boundary layer effects [17].
- Topography effect [18].
- Particle depletion [19,20]. Gaseous contaminants depletion was not considered because the scenery studied was too small for this effect to be accountable for some reduction in immision levels [21,22].

On the other side, the air pollution due to urban sources was determined using a box model [23] specially adapted to the conditions of the scenery. These kinds of models are based in the integration of the advection-diffusion equation over the area studied, given the initial wind field. Also in this case both year-averaged and episodic values were calculated.

For what refers to the location of measurement stations, the third phase of the study, one used a model adapted from a model described previously by Liu *et al.* [24] and used by USEPA to locate the renewed carbon monoxide control network in Las Vegas, Nevada [25]. The algorithm is based in the optimization of the surface area covered by the stations allocated, using an heuristic procedure for the sequential siting of each of them.

Figure 3 shows an scheme of the method. The first stage consists in the elaboration of a relation of all the points inside the area studied that can host a station. These will be called the candidate points. The candidate points are after ordered according to a merit factor[15]. The algorithm proceeds then in a greedy adding algorithm, choosing at each step the first

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simplest version, they model the plume of air pollutants as a bidimensional normal distribution. Nevertheless, the normal distribution was first described by Abraham de Moivre, in *Doctrine of Chances* (1716). He discovered it when trying to find an approximation to the binomial distribution, published some three years before by Jacques Bernoulli in his posthumous book *Ars Conjectandi*. The normal distribution was later rediscovered independently by Karl Friedrich Gauss (for whom receives its name) and Pierre Simon, Marquis de Laplace.

[15]This merit factor will, in general, be the immision level at the point. In this case, therefore more than one merit factors were used. This point shall be discussed later on.

candidate point still available[16]. Once chosen, a station is established at this point. The algorithm proceeds then to eliminate from the list of candidates the chosen point and all the points covered by it. In this sense, a point is said to be covered by another when the spatial correlation coefficient between them is greater than a fixed threshold. When no candidates remain in the list, one concludes that the number of stations already located is the minimum and their locations are also optimal.

The spatial correlation coefficient is a natural generalization of the discrete correlation coefficient, also used in other science and technology fields (such as the study of turbulence from eulerian references, for example). This function allows the obtention of the correlation coefficient between series of observations of the same variable in two different points as a function of the distance between them. The correlation coefficient between points s_0 and $s_0 + \delta s$ is then:

$$r(s_0, s_0 + \delta s) = \frac{COV[C(s_0), C(s_0 + \delta s)]}{\sqrt{VAR[C(s_0)]VAR[C(s_0 + \delta s)]}} \qquad (1)$$

Where $C(s)$ is the merit factor used, $VAR[x]$ is the variance of random variable x and $COV[x, y]$ is the covariance between random variables x and y.

From the previous definition is immediate that, the fraction of variance of point s_0 explained by the network is given by the maximum correlation coefficient, as follows:

$$\Psi(s_0) = max_i[r(s_0, s_i)] \qquad (2)$$

Where the subscript i indicates the stations of the network.

Of course, the results of the application of this method depend on an adequate distribution of candidate points. As it shall be described later, in the case described here the candidate points were uniformly scattered in the area studied, which guaranteed their representativeness. On the other hand, the method is quite robust with respect to slight modifications

[16]In practice, and to avoid points that are not representative of their region, an additional condition is to be satisfied. In effect, a point cannot be chosen to host a measurement station unless it covers (in a sense that shall be defined later) at least a fixed neighboring area.

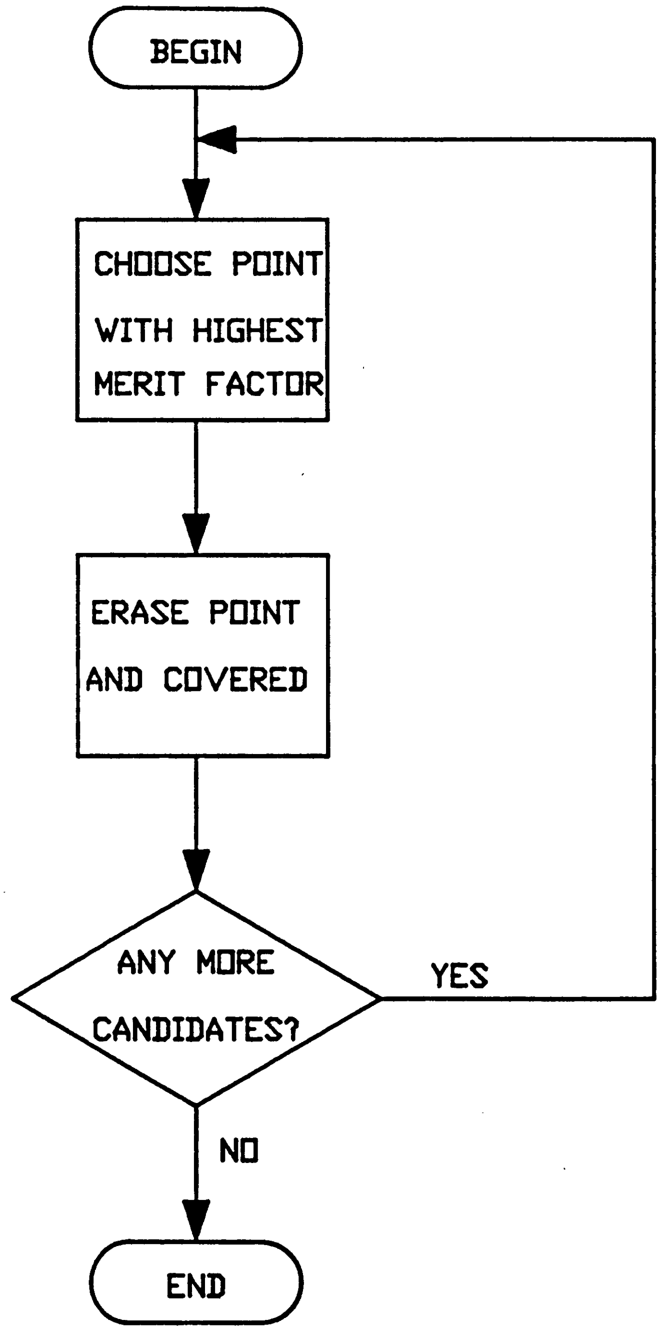

Figure 3: Scheme of the methodology used for the siting of measurement stations.

in source terms, diffusion parameters and station location. Therefore, the network designed will still be a good one should some of these circumstances change in a small amount.

4 Application and results

For the case of Tarragona, the area studied was divided in 121 squares, each 2 km of side. The center of each of these squares was considered a candidate to host a measurement station. Nevertheless, the station can be placed in any point inside the square. As it has been previously stated, the method is robust enough to allow this manipulations. On the other side, this allows the installation of stations in urban nuclei. This presents several advantages from the practical (maintenance, accessibility, etc.) and from the health point of views [26,27].

For what respects to merit factors, the following parameters were used:

- Concentration at ground level (immision level) of sulphur dioxide, taking into account all of the sources included in the inventory.
- Immision level of sulphur dioxide suppressing the two largest emission points of the included in the inventory. This was done because, using the first merit factor, these two points drive the method to the installation of a proximal station to control them. On the other side, this merit factor is useful to find regional stations.
- Aromatic hydrocarbons immision level. These are pollutants typical of both, urban and industrial atmospheres.
- Immision levels of unsaturated hydrocarbons classified as highly pollutant (basically ethylene). These are pollutants typical of a petrochemical complex like the studied.

Neither nitrogen oxides nor particles were use as merit factors. This is due to the fact that both of them are strongly correlated with sulphur dioxide, because all of them are generated mainly in combustion.

Finally table 3 shows the number and location chosen for the stations of the network, as well as the parameters monitored at each station. Also, figure 4 shows the location of the stations in the area studied. One can see that in each station are monitored particles and nitrogen oxides even though these were not design parameters. This is due mainly to legal and standardization requirements[17]. On the other side, ozone detectors were assigned to the stations of Tarragona and Salou because this is a typically urban pollutant, whose effect on human health is becoming more and more worrying as studies are published [28].

5 Conclusions

Looking at the results obtained one can conclude that the network designed has a lot more equipment that the network that will result using standard designing techniques. thus, for instance, USEPA guidelines [29] will assign between two and three stations for a region like the studied. This overequipment is due to the particular circumstances given in the region and, in particular, to the presence of petrochemical industry, heavily pollutant.

On the other side, the correlation coefficients obtained with the network designed are rather high. See, for example, the explained variance isolines for sulphur dioxide in figure 5. This is due mainly to the dominance of several of the emissions above the others. This fact guarantees that the network designed will allow and accurate monitoring of air pollution in the area studied.

Finally, even when the network has been designed with year-averaged concentrations, it has also been tested in numerical simulations with severe air pollution episodes. In this way it has been proved that the network presents very favorable characteristics for the monitoring of this kind of pollution.

[17]Thus, for example, spanish legislation defines emergency states as a function of the product of concentrations of sulphur dioxide and suspended particles. This implements the synergic relationship between these pollutants.

Location	Parameters measured
El Morell-La Pobla de Mafumet	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons Ethylene
Tarragona	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons Ozone
La Secuita	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons
Bonavista	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons Ethylene
Salou	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons Ozone
Constantí	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons
San Salvador	Sulphur Dioxide Nitrogen oxides Suspended particles Aromatic hydrocarbons

Table 3: Location and equipment of the stations.

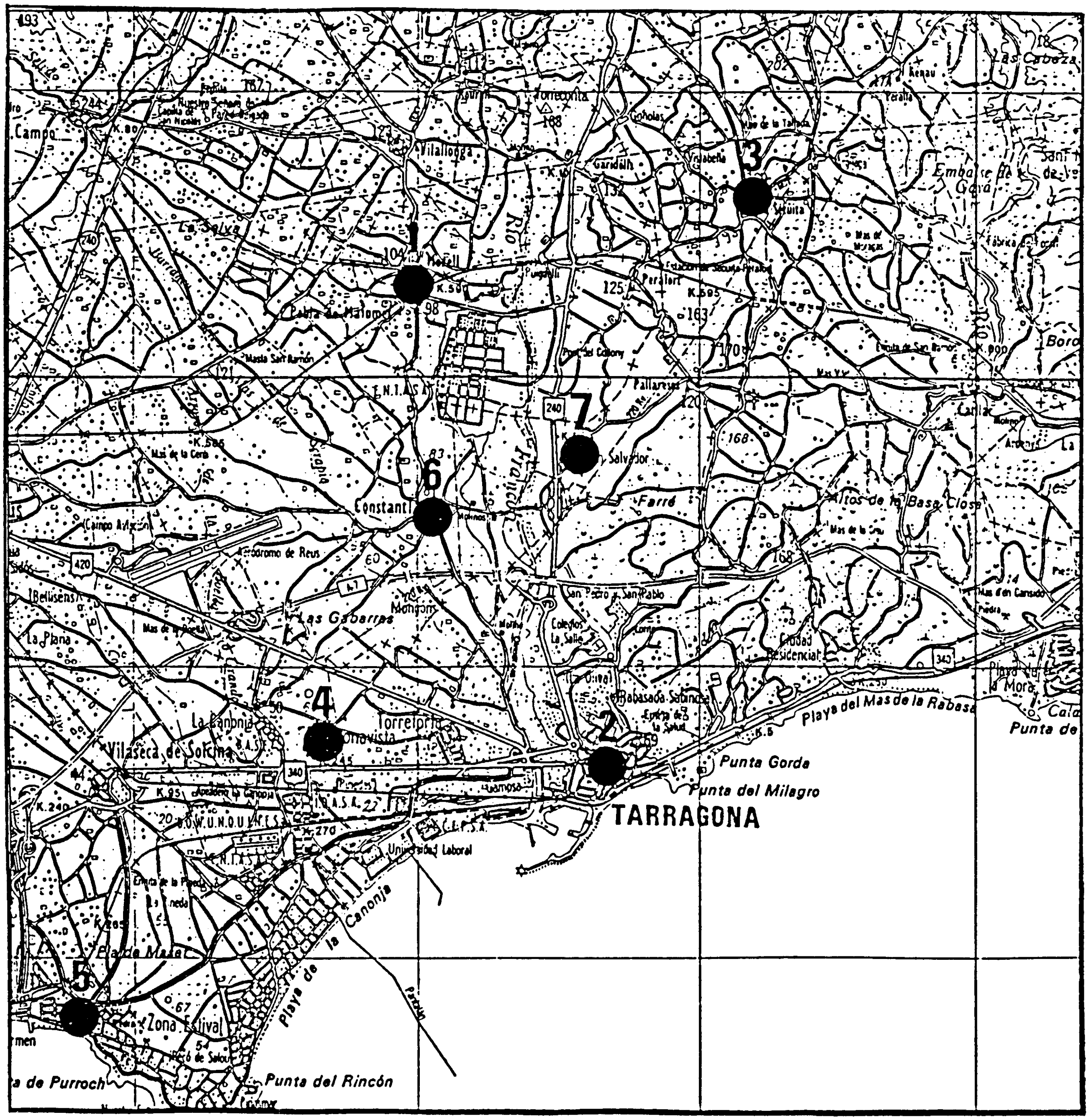

Figure 4: Location of the stations of the network.

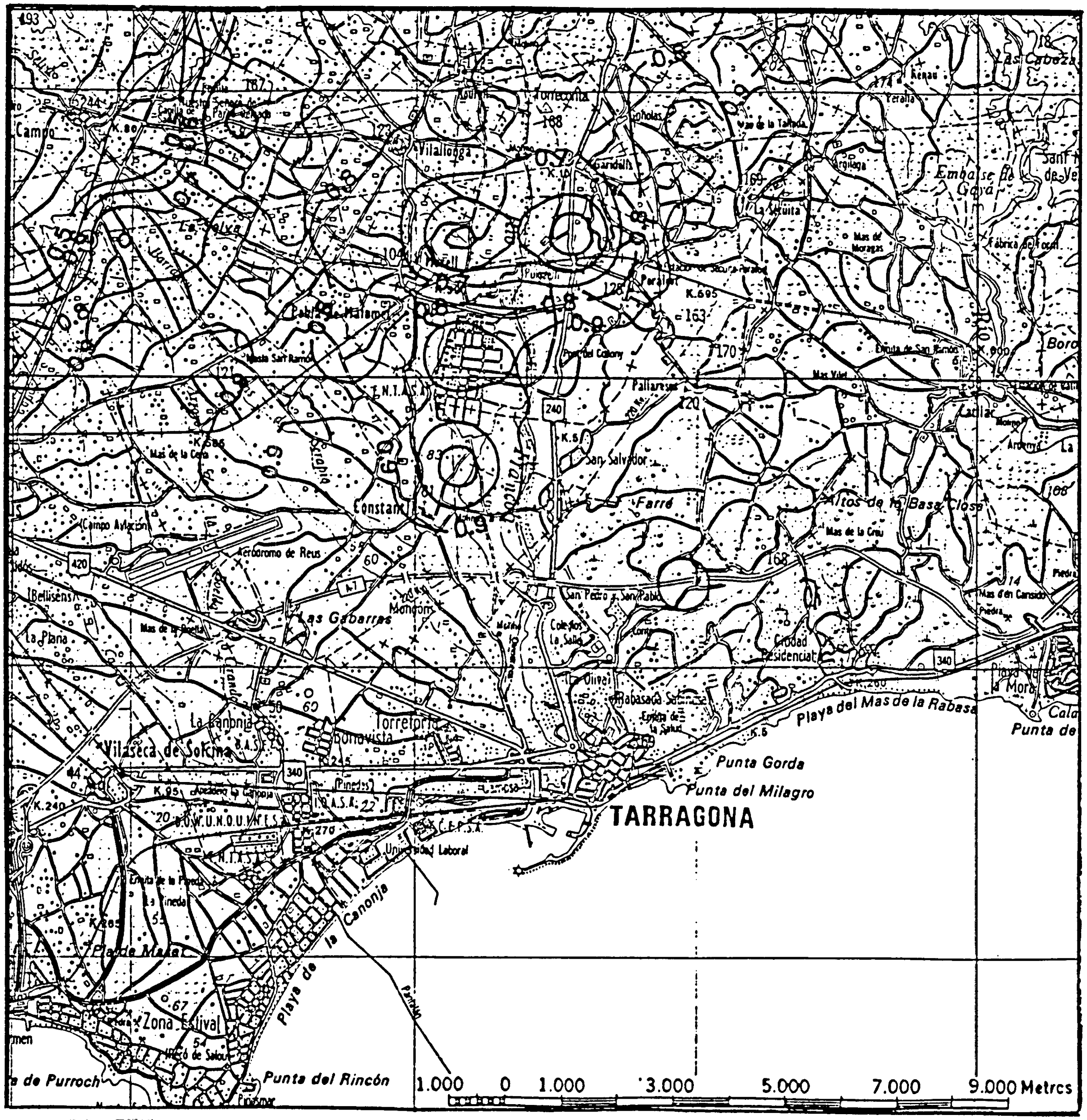

Figure 5: Isolines of explained variance for sulphur dioxide.

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